Enabling Robust Distributed Real-Time Hybrid Simulation Method and Expanding Its Applications in Floating Wind Turbine Systems

Mehmet Cinar

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ENABLING ROBUST DISTRIBUTED REAL-TIME HYBRID SIMULATION
METHOD AND EXPANDING ITS APPLICATIONS IN
FLOATING WIND TURBINE SYSTEMS

by

Mehmet Cinar

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering (Civil)
Civil and Construction Engineering
Western Michigan University
December 2018

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ACKNOWLEDGMENTS

Firstly, I would like to express my gratitude to my advisor, Dr. Xiaoyun Shao, for all her guidance, assistance, and encouragement throughout my graduate studies. Additionally, I would like to thank the other members of my thesis committee, Dr. Upul Attanayake and Dr. Houssam Toutanji.

I would also like to extend a special thanks to my predecessors Bilal Ahmed Mohammed and Mohamed Ismail Ahmed for their support and training, as well as Bilal Alhawamdeh and Emad Zaghalil for their immense help in experimental setup.

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Mehmet Cinar, M.S.E.
Western Michigan University, 2018

Real-time hybrid simulation (RTHS), which integrates physical experiment and numerical simulation, plays an essential role in understanding the time-dependent behavior of structures when subject to hazardous loadings. On the other hand, RTHS might not yield accurate results for complex structural systems due to experimental and computational limitations. Distributed real-time hybrid simulation (dRTHS), which takes the advantage of distributed laboratory facilities using network communications, was proposed and proven to address some limitations in RTHS. During dRTHS, Internet delay due to the network communication is added to the actuator delay in RTHS, which may cause inaccurate results or even unstable tests. To enable the robust dRTHS environment and expand its applicability to FWT structural systems, this study presents the implementation of the four delay compensation methods in dRTHS, and the application of dRTHS to the FWT prototype. Firstly, delay compensation methods were utilized in dRTHS, and the method yield the best compensation results were identified through dRTHS experiments. Next, a dRTHS was applied to a FWT prototype structure during which the structural responses under wave and wind loads were simulated. The responses verified the feasibility of applying dRTHS to FWT structural response evaluation under hazardous loadings and the robustness of the dRTHS platform developed and tested in this study.
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1 INTRODUCTION

1.1 Seismic Experimental Methods in Civil Engineering

Earthquake is a natural disaster that may cause structural collapse, casualties and big economic toll. This makes earthquake an essential design aspect to be considered by structural engineers. To design and build structures which are resistant to seismic forces and their secondary effects, engineers need to be able to predict and evaluate seismic response of structures.

However, imposing an earthquake excitation on a real structure is uneconomical and almost impractical (Mohammed, 2017). Therefore, practical physical testing methods, like shake table testing and recently developed hybrid simulation methods, play an essential role in understanding seismic behavior of structures.

Along with shake table testing, the following subsections further introduce substructuring concept and its application in hybrid simulation methods. Specifically, real-time hybrid simulation (RTHS) and distributed real-time hybrid simulation (dRTHS) are the focus herein. Applications, differences, strengths and weaknesses of these experimental methods are discussed to provide an insight about the methods used in this study.

1.1.1 Shake Table Testing

Shake table testing is the most popular physical testing method in earthquake engineering, during which prototype structures are fabricated and installed on shake table and their dynamic responses under seismic loading are evaluated directly by subjecting the structure under real seismic motions imposed by the shake table. This testing method provides realistic data on the response of the whole structure such as conditions of damaged components, collapse mechanisms and post-earthquake capacities. However, shake table testing is not always feasible due to its limitations, such as huge cost associated with the construction of a
prototype structure specimen and the requirement of large geometrical and loading capacities to test the general large-scale civil structural systems.

1.1.2 Hybrid Simulation Methods and Substructuring

Hybrid simulation, which enables obtaining seismic response of the whole structure by combining the responses of physical and numerical substructures, creates a chance to overcome the cost and capacity limitations of shake table testing.

Hybrid simulation solves governing equations of motion (EOM) of a whole structural system at each time step by combining the responses of the numerical and physical substructures that are obtained from numerical simulation and physical testing, respectively. In general, substructures which are difficult to numerically model within the whole structural system are selected as physical substructures that are tested using hydraulic loading equipment and the remaining part of the structural system are considered as numerical ones whose dynamic responses will be numerically simulated using analytical models. Such combination of numerical simulation and physical testing provides an effective approach for seismic evaluation of whole structural systems. Moreover, hybrid simulation addresses cost and capacity limitations of shake table enabling the testing of large-scale structures through substructuring.

Schematic diagram of a hybrid simulation of a three-story shear frame building is shown in Figure 1-1, where the EOM is solved to determine structural displacement responses at each time step based on the restoring force values from the two substructures, the displacement response of the physical substructure, the predefined mass and damping properties of the building model and the ground motion input. In addition, the velocity is also controlled in RTHS, which are highlighted red in the Figure 1-1 and discussed in section 1.1.2.1. The command displacement is then applied on to the experimental substructure using actuators and hydraulic controller. The measured displacement response and the restoring force values are fed back to the EOM for next time step calculation. This step-by-step simulation requires time-stepping integration algorithm to solve the EOM, which is discussed in section 3.3.
1.1.2.1 Real-Time Hybrid Simulations (RTHS)

Recent hardware development in hybrid simulation testing systems provides an opportunity of combining numerical simulation and physical testing at the real earthquake rate to achieve real-time hybrid simulation (RTHS). RTHS allows a more realistic seismic response evaluation of structural systems with rate-dependent dynamic behavior compared to the traditional slow-rate hybrid simulation (i.e., Pseuedodynamic testing) method.

RTHS, executed in real-time, requires simulation process to be completed within the duration of defined time step. In addition, RTHS differs from the slow hybrid simulation in loading of physical substructure through controlling of both displacement and velocity, as shown in Figure 1-1 (versus displacement control only in the slow hybrid simulation) (Hashemi, et al., 2013). On the other hand, numerical substructure model in RTHS is usually limited to computationally inexpensive models (i.e., simplified numerical models) to accommodate the
maximum permissible time step (usually at the order of 0.001 sec or smaller) and realize the real-time processing system (Margareh, et al., 2014).

In RTHS, command displacement values are imposed to the physical substructure through an actuator controlled by a hydraulic pump system. However, there is an inevitable time delay in the actuator to achieve the command displacement, defined as “actuator delay”, which induces asynchronized responses between those measured from the physical substructure and those simulated of the numerical substructure. Without proper compensation of such delays, RTHS will yield significant errors in its simulation results or sometimes become unstable. Therefore, it is important to compensate actuator delay during RTHS and to study the effectiveness of different time delay compensation methods in RTHS environment to achieve stable testing and reliable test results.

1.1.2.2 Distributed Real-Time Hybrid Simulation (dRTHS)

Limited laboratory resources, e.g. limited computational power and/or impossibility of testing two physical substructures simultaneously at one site, are challenges to perform large-scale RTHS of complex structural systems. For example, real-time processors used to simulate the responses of numerical substructures at each time step might not be faster enough to allow the simulation being finished within the permissible time, or there is more than one critical substructure of a complex system required to be tested physically. These RTHS challenges may be addressed if more than one physical and/or numerical substructures are tested/simulated in real-time at geographically distributed laboratories with necessary information being transferred among them using network grid. This type of RTHS is referred to as the distributed real-time hybrid simulation (dRTHS) and the successful implementation of dRTHS will greatly expand the RTHS testing capabilities as needed for more and more complex structural systems being built in this modern era. Not only it will allow seismic response evaluation of complex structural system that has several critical substructures requiring physical testing to be conducted at different laboratories, it will also provide a way to fully utilize the computation power located in different laboratories to improve accuracy of the numerical simulations in RTHS.
dRTHS relies on the network communication to transfer data between simulation of numerical substructures and testing of physical substructures at each time step so that the dynamic response of a whole structural system can be captured. However, network delay in transferring data between the computers, called the “Internet Delay”, is added onto the actuator delay during a dRTHS. This combined delay from both sources will result in the same adverse effects (i.e., inaccurate test results and unstable tests) as the actuator delay on RTHS, only being more severe considering that the Internet delay is usually much larger than the actuator delay. Time delay compensation methods are, therefore, more critical for dRTHS experiments compared to RTHS tests. Whether or not the existing time delay compensation methods developed for RTHS can be successfully implemented in dRTHS requires systematic investigation and evaluation.

1.2 Physical Testing of Floating Wind Turbine (FWT) Systems

Wind energy, as one of the renewable and clean energy sources, is considered as an alternative to cope up the fossil fuels limitations as well as climate changes. Wind energy, which can be transformed into the electricity by means of wind turbines, is a promising energy option for several countries where most of them have long-term plans to take the advantage of clean and renewable energy. For example, the United States (U.S) is planning to supply 20% of the electricity demand from wind energy in 2030 (U.S. Department of Energy, 2008). Therefore, finding the regions with large wind energy potential is an issue considered worldwide to optimize the exploitation of the wind resources.

Until now, on-land wind turbines have been used to generate electricity worldwide for many years. However, on-land wind turbines have disadvantages like noise pollution and space limitations. Besides, deep water regions have vast wind energy potential, where large wind resources are known to be available in water deeper than 30 m for many countries (Jonkman, 2007). Hence, several countries have plans to move their wind farms to deep water locations for finding the wind fields with high energy potential and capturing the wind energy using wind turbine systems (Koo, et al., 2014).
However, recent researches show that fixed wind turbines, which use monopiles to fix the turbine to the sea floor, are not economical in deep sea regions (Karimirad, 2014). To overcome this challenge and take the advantage of the vast energy potential, floating platform concepts have been proposed for deep sea regions to provide the stability of the wind turbine (Koo, et al., 2014). The wind turbines being supported and stabilized with floating platforms are called as floating wind turbine (FWT). Compared to the fixed wind turbine, FWT has the potential to capture the wind energy economically using the floating platform and anchored lines instead of uneconomical monopiles. To utilize the wind energy potential with minimum costs, optimized design of the FWT structures is essential but the dynamics and the responses of the FWT systems are still not very well understood since the coupled dynamics between the turbine and the floating platform are very complex (Koo, et al., 2014). There is a strong need of more experimental studies that may help advancing design methodology of the FWT systems.

Recently, there have been several studies conducted to evaluate the response of FWT systems against wave and wind loads utilizing physical testing methods including both scaled testing and RTHS. In scaled testing method, prototype models are scaled down to create FWT specimen following the geometrical similarities and the scaling methods, where the scaling is a big challenge for FWT systems since the specimen shall be properly scaled for both aerodynamic and hydrodynamic loads. On the other hand, RTHS can overcome this scaling challenge by using the substructuring method, where the aerodynamic loads are numerically simulated in full-scale and then applied to the scaled physical substructure. Seeing the advantages of RTHS in capturing accurate responses of systems through combination of numerical simulation and physical experimentation, researchers attempted RTHS to FWT systems. Hence, the feasibility of dRTHS for FWT systems shall be investigated since dRTHS may allow more realistic analysis than RTHS with its capability of providing multiple facilities.
1.3 Objective and Scope

RTHS and dRTHS were proposed to address the experimental challenges in earthquake engineering through combinations of numerical simulation and physical testing, and the substructuring techniques. Although RTHS has been applied to some researches to study the seismic responses of structural systems and to understanding FWT responses when subject to both wave and wind loads, dRTHS’s application in earthquake engineering is limited and no dRTHS has been implemented in FWT research yet. One major issue hindering the broad application of dRTHS is the large time delay due to both actuator and internet communication as discussed previously. On the other hand, several delay compensation methods have been proposed for RTHS that could be used by dRTHS. Therefore, the objectives of this thesis work are two folded as follows.

The first objective is to investigate existing time delay compensation methods developed for RTHS when they are applied to dRTHS experiments. Four delay compensation methods were examined on a three-story shear frame model when subject to seismic excitations. The model was first numerically simulated with a delay model and the four compensation methods. It was found out that the delay compensation methods improved the accuracy of response results when no delay compensation was adopted. Then, the model was divided into the substructures, and both virtual and physical dRTHS experiments were carried out using the selected the compensation methods and their compensation effects were compared and discussed.

The second objective of this study is to create a dRTHS environment to analyze FWT systems. FWT prototype was created based on the FWT model in the references and wave and wind loads were generated following recommended values in literatures. The dynamic responses of the FWT prototype when subject to wind and wave loads were numerically simulated first. Then, virtual dRTHS tests were conducted by substructuring the prototype model into two numerical parts where responses under wind and wave loading are separately simulated in two real-time computers. The applicability of dRTHS method on FWT systems
was demonstrated comparing the responses of the FWT prototype in vdRTHS with the numerical simulation results.

1.4 Thesis Outline

This thesis explores the implementation of delay compensation methods in dRTHS method and investigates the applicability of dRTHS on FWT systems.

Chapter 2 presents the reviewed literature on distributed hybrid simulation methods and the experimental methods currently employed for FWT systems. Developments in distributed hybrid simulation (dHS) and dRTHS methods and the challenges confronted in experimental studies on FWT systems were explained.

Chapter 3 contains the theoretical background related to the delay compensation methods selected in the study, dRTHS experimental method and dynamic response evaluation of FWT systems. Numerical models of the building and FWT models was presented where the substructuring method and the numerical integration algorithms used in dRTHS tests are also discussed.

Chapter 4 comprises the numerical simulations of the delay compensation methods. Dynamic responses of the shear frame building model are numerically simulated to provide the reference results. Optimization of the adaptive parameters in the two adaptive delay compensation methods are discussed next. Then, numerical simulations using the delay compensation methods are introduced and the performance of the methods is discussed through comparison of the results with the reference responses.

Chapter 5 contains the investigation of the delay compensation methods when they are implemented in dRTHS experiments. An overview of the experimental system is presented first. Then, vdRTHS and dRTHS experiments are described and the performance of the delay compensation methods are discussed comparing both results with the numerical simulation results.
Chapter 6 presents the implementation of a dRTHS environment to capture the dynamic responses of the FWT model when subject to simultaneously wind and wave loadings. The properties of the prototype FWT model, wind and wave loading histories, and the numerical simulation procedure are discussed. Then, the numerical simulation and dRTHS tests carried out on the FWT model are explained and the applicability of dRTHS to FWT system is demonstrated by the dRTHS results.

Chapter 7 summarizes the findings of the study and provides recommendations for the future works of dRTHS.
2 LITERATURE REVIEW

2.1 Introduction

This chapter begins with the presentation of past studies on distributed hybrid simulation (dHS) and distributed real-time hybrid simulation (dRTHS). Developments in distributed hybrid simulation, including communication protocols, simulation coordinators and numerical simulation programs, are introduced first. dHS experiments, which are facilitated by these developments, are explained next. Then, past dRTHS studies are discussed and the test results, delay compensation method and communication protocols are reviewed.

To apply dRTHS method to FWT experiments, experimental studies on floating wind turbine (FWT) systems are reviewed herein. Different methods to capture dynamic responses of FWT systems when subject to wind and wave loadings, such as scaled testing, numerical simulation and real-time hybrid simulation (RTHS), are explained next. Both scaled testing and numerical simulations have limitations in accurate reproducing the FWT’s responses. RTHS, which combines numerical simulation and physical testing, was recently applied to FWT experiments to address the challenges and limitations in FWT experiments and simulations. Numerical and physical models in recent RTHS FWT experiments are outlined at of the end this chapter.

2.2 Distributed Simulation

In this section, the studies and developments in dHS and dRTHS are reviewed. Conducting the distributed simulation in real-time is taken as basis in this distinction.

2.2.1 Distributed Hybrid Simulation (dHS)

Developing dHS platform, which broaden testing facilities’ capacities by utilizing facilities from other sites within one experimental procedure using network grid, was proposed and attempted by several researchers. dHS platforms that were developed and utilized in dHS experiments together with their components are exemplified in Table 2-1.
### Table 2-1 Past Studies on Distributed Hybrid Simulation

<table>
<thead>
<tr>
<th>Author</th>
<th>Integration Algorithm</th>
<th>Delay Compensation</th>
<th>Numerical Substructures</th>
<th>Physical Substructures</th>
<th>Numerical Simulation Programs</th>
<th>Simulation Coordinator</th>
<th>Communication Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spencer et al. (2004)</td>
<td>Not Specified</td>
<td>Not Specified</td>
<td>Two bay single story steel frame (NCSA)</td>
<td>Left column at UIUC Right column at CU</td>
<td>OpenSees, FedeasLab</td>
<td>Code written in MATLAB</td>
<td>NTCP</td>
</tr>
<tr>
<td>Mosqueda et al. (2008)</td>
<td>Operator-Splitting Integration Algorithm</td>
<td>Event-Driven Controller (Modified Version of Polynomial Interpolation/Extrapolation Algorithm)</td>
<td>One column at Boulder, Purdue and Illinois</td>
<td>One column at Berkeley and Buffalo</td>
<td>OpenSees, FedeasLab, Java</td>
<td>Java-based multi-threaded coordinator</td>
<td>NTCP</td>
</tr>
<tr>
<td>Takanashi and Fenves (2006)</td>
<td>Operator-Splitting Integration Algorithm</td>
<td>Not Specified</td>
<td>Single column bridge pier</td>
<td>Lead-rubber seismic isolation bearing</td>
<td>OpenSees</td>
<td>OpenFresco</td>
<td>TCP</td>
</tr>
<tr>
<td>Mueller (2014b)</td>
<td>Not Specified</td>
<td>Not Specified</td>
<td>Reinforced concrete frame structure</td>
<td>Left column at HIT Right column at WMU</td>
<td>LabVIEW, NICON, OpenSees</td>
<td>UI-SIMCOR</td>
<td>NICON (HIT), Internet (WMU)</td>
</tr>
</tbody>
</table>
Until today, researchers have been continuously developing communication protocols and testing system tools to leverage geographically distributed testing facilities. Firstly, NEESgrid, the *system integration component* of Network for Earthquake Engineering Simulation (NEES) project, was brought into use of the NEES community and it demonstrated the potential of dHS method to earthquake engineers (Spencer, et al., 2004). NEESgrid provided integrated tools and components as well as creating network for seismic researchers across the U.S to perform dHS collaboratively. The network and the components enabled multi-site dHS environment to develop complex and accurate models when subject to seismic loadings.

First dHS experiment, named Multi Site Online Simulation Testbed (MOST), was conducted by utilizing the NEESgrid Teleoperation Control Protocol (NTCP) platform (Spencer, et al., 2004). NTCP, a component of NEESgrid, provides an opportunity for remote laboratories to control physical experiment and/or numerical simulation (Pearlman, et al., 2004). A simulation coordinator, a code written in MATLAB, organized the experiment providing communication between the test sites and the simulation computers and tackling the problems such as lost network connections and invalid responses. A two-bay single-story steel frame was used as a structure and public experiment was conducted where the left and right columns were tested at University of Illinois at Urbana-Champaign (UIUC) and University of Colorado, Boulder (CU), respectively. The numerical simulation was carried out at the National Center for Supercomputing Applications (NCSA), also in Urbana-Champaign. The experiment lasted for more than 5 hours where the simulation was terminated when only a few steps were left to accomplish (at step 1493 out 1500) since the simulation coordinator did not tolerate the transient network failure at that step.

Mosqueda et al. (2008) carried out the Fast-MOST experiment taking the advantage of modified NTCP by means of simulation coordinator and event-driven controller, which was used to compensate delay, where significant improvement was achieved such as the required time per step was reduced to 0.66 second from 13.2 second.
After the NTCP, development of UI-SIMCOR provided support for several simulation programs enabling the coordination of various simulation software among several laboratories (Kwon, et al., 2007). Besides, UI-SIMCOR provided an opportunity of using the Transmission Control Protocol/Internet Protocol (TCP/IP) and the NEES Hybrid Communication Protocol (NHCP). UI-SIMCOR, a designated coordinator, directs time-stepping integration algorithm and communication. In dHS configurations using UI-SIMCOR, the coordinator communicates with both substructures whose responses are simulated by finite element programs and/or physical testing. The coordinator enables defining components easily to represent substructures in hybrid simulation (Nakata, et al., 2014). However, duration of the simulation in complex models might be challenge since the command displacements and restoring forces must be transferred at each time step.

As well as UI-SIMCOR, OpenFresco, the finite element software, has been utilized as a simulation coordinator during dHS tests. The finite element software simulates numerical substructures inside and only communicates with the physical laboratory, which removes the burden of network communication with numerical substructures and provides an opportunity for hybrid simulations with large numbers of degree of freedom. But then, functionality of simulation is limited by the capacity of finite element software (Nakata, et al., 2014). Schellenberg et al. (2009) introduced the full version of OpenFresco.

University of California (CU), Berkeley and Kyoto University carried out a dHS employing OpenFresco to couple the simulation of a single column bridge-pier with a physical substructure, which is two lead rubber seismic isolation bearings supporting a girder (Takanashi and Fenves, 2006).

Western Michigan University (WMU) and Harbin Institute of Technology (HIT) utilized UI-SIMCOR and OpenSees, and carried out DHS to determine the effects and characteristics of seismic ground motions on column failure and collapse mechanisms (Mueller, 2014b). As shown in Figure 2-1, the prototype structure was divided into three substructures (one
numerical substructure and two physical substructure), where WMU conducted the physical testing and Harbin Institute of Technology (HIT) carried out the numerical simulation and the other physical testing, synchronically. WMU used the Network Interface for Controller (NICON) to impose excitation commands to the physical specimen by means of hydraulic actuators (Kammula, et al., 2014; Zhan and Kwon, 2015). HIT utilized OpenSees to conduct the numerical simulation and the Network Interface for Console Application (NICA). UI-SIMCOR was used as the computational driver and NICA served to achieve data transfer between UI-SIMCOR and OpenSees.

Figure 2-1 Connection Diagram Between WMU and HIT (Mueller, 2014b)
2.2.2 Distributed Real-Time Hybrid Simulation (dRTHS)

dRTHS, which shows great potential for evaluation of large-scale complex structural systems at real-time, has not been extensively investigated yet. So far there have been numbered studies reported in literature, which are summarized in Table 2-2.
<table>
<thead>
<tr>
<th>Author</th>
<th>Integration Algorithm</th>
<th>Delay Compensation</th>
<th>Numerical Substructures</th>
<th>Physical Substructures</th>
<th>Numerical Simulation Programs</th>
<th>Simulation Coordinator</th>
<th>Communication Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim et al. (2012)</td>
<td>Runge-Kutta method</td>
<td>Smith predictor</td>
<td>Two story shear frames with lumped masses and rigid beams</td>
<td>MR damper located between the ground and first story</td>
<td>QuaRC</td>
<td>Not Specified</td>
<td>TCP</td>
</tr>
<tr>
<td>Ojaghi et al. (2014)</td>
<td>Newmark explicit integration method</td>
<td>Polynomial extrapolation method, Modified Darby algorithm</td>
<td>Case A: Three story structure (Oxford) Case B: Three story structure (Bristol) &amp; braces (Oxford) Case C: -</td>
<td>Case A: Laterally loaded ground floor column (Bristol) Case B: Shear type steel damper (Oxford) Case C: One story test rig to represent first story columns (Bristol) &amp; two-story test rig to represent second and third story columns (Oxford)</td>
<td>Not Specified</td>
<td>IC-DHT</td>
<td>UDP/IP</td>
</tr>
<tr>
<td>Margareh et al. (2014)</td>
<td>Not Specified</td>
<td>Retarded delay differential equations</td>
<td>Two stories partitioned into two numerical substructures</td>
<td>Instructional two-story building</td>
<td>MATLAB</td>
<td>xPC target platform</td>
<td>Ethernet</td>
</tr>
</tbody>
</table>
Kim et al. (2012) conducted a dRTHS between the University of Connecticut (UCONN) and University of Illinois at Urbana-Champaign (UIUC), at a rate of 500 Hz. Two-story shear frame building was selected as the numerical substructure where Magneto-Rheological (MR) fluid damper was the physical substructure and tested physically. The command signal was generated by a Q8 Multi-Q board running QuaRC software (Quanser, 2009) in the physical test. Besides, parametric analytical study was carried out on the same MR damper model to evaluate the robustness of the dRTHS framework to network delay, where the Smith Predictor was implemented in the numerical model for compensating the network delay. It was shown that less than 5% error in network delay can be achieved, which proved that the Smith Predictor provides the stability of dRTHS. Smith Predictor requires the numerical simulation of the physical substructure to predict the restoring force, which is not considered in delay compensation methods investigated in this thesis. Single site (SRTHS) and geographically distributed multi-site (MRTHS) real-time hybrid simulations were conducted and the displacement, force and energy results were compared to show excellent agreement.

Ojaghi et al. (2014) carried out robust and repeatable dRTHS experiments introducing a middleware developed to connect test sites, named Interdependent Channel–Distributed Hybrid Testing (IC-DHT), and a new high-level network protocol named Data Handling Protocol (DHP). Three-story building models with braces was investigated against ground motion in three different cases, as shown in Table 2-2.

Since the longer delays were inevitable in the dRTHS and polynomial delay compensation methods are limited to provide accurate responses for the additional communication delay in dRTHS (Ojaghi, 2011), a delay compensation method was applied estimating two-stage jerk (rate of change of acceleration) in the study. In this approach, the same numerical model was simulated in three versions. The main numerical model controlled the test while the other two versions, which ran one and two steps ahead of the main numerical model, respectively, to estimate the jerk of two and three-steps ahead of the main numerical model. These two models used the current measured force, which is delayed by one and two time-steps for the models, respectively. Then, the polynomial extrapolation equation is applied to estimate the
desired displacement of two time-steps ahead using the jerk estimated at the first step ahead of the current one. Lastly, the actual delay was estimated comparing measured and estimated desired displacement by means of the modified Darby algorithm (Darby, et al., 2002). The delay was compensated properly where it was stated that the method is relatively insensitive and predicts accurate delay values at large time-steps.

Lastly, Margareh et al. (2014) developed a dRTHS platform utilizing the MATLAB/xPC real-time system and the Ethernet cards. A case study of dRTHS was conducted substructuring a four-story structure into two parts where the xPC target platform was utilized to provide communication between the two target computers. The Internet delay and the actuator delay was considered and retarded delay differential equations (RDDE) were used to evaluate the model, where the delay during dRTHS tests was assumed as constant. In this study, faster simulation data transfer was provided when compared to other dRTHS studies.

### 2.3 Experimental Methods of Floating Wind Turbine Systems

Researches investigating FWT structural systems and their responses under normal working load and extreme loading conditions were carried out because FWT is an important and economical alternative of exploiting the renewable energy at deep sea regions. Ocean basin, wave basin, laboratory facilities and numerical simulation programs have all been utilized to evaluate the dynamic responses of FWT structures when subject to wind and wave loadings either separately or simultaneously. In this section, experimental methods of FWT are presented in two parts which are focused on (1) the scaled testing and numerical studies; and (2) RTHS.

To help with the discussion later on, the components of a FWT system are shown in Figure 2-2. Blades capture the wind and transmit the wind energy to the hub, then to the nacelle, where the electricity is produced by means of a generator. Tower carries the nacelle, rotor and blades. While the platform, the weight and the mooring lines provide stability of this FWT structure. The weight, also called as ballast, is used to lower the center of gravity
(COG) of the structure below the center of buoyancy (COB) as much as possible to increase the distance between COG and COB, which yields larger restoring moment and increases the stability (Al-Solihat and Nahon, 2015a; Karimirad, 2014).

To clarify the terms mentioned in reviewed studies, degrees of freedom (DOF) of FWT platform are shown in Figure 2-3, which includes translational surge, sway and heave motion and rotational roll, pitch and yaw motion.
2.3.1 Scaled Testing and Numerical Simulation

Scaled model testing is one of the existing methods to dynamically evaluate FWT responses and it also provides an economical and efficient way to advance FWT technology through relatively quick and easy experimental procedure. When compared to large-scale experiments, scaled testing has the advantages of reduced costs associated with building and loading the test specimens, and less experimental risks while providing relatively real and accurate response data (Martin, et al., 2014). Table 2-3 lists the studies reviewed on scaled testing studies.

To perform scaled experiments on FWT that yield realistic responses, a series of scaling methods need to be applied to meet the accurate modeling demands of wave and wind loads and FWT aerodynamics, which is a significant challenge (Martin, et al., 2014). Froude scaling, utilizing a Froude number and geometric similarities when applied to the prototype structure, is the most favorable scaling method. Froude number for wave and wind is expressed as:

Figure 2-3 DOF of FWT Platform (Withee, 2004)
\[ Fr = \frac{C}{\sqrt{gL}} \]  

(2.1)

where \( C \) is the wave/wind speed, \( g \) is the gravity acceleration, \( L \) is the characteristic length, which is same for both wind and wave Froude numbers. To maintain the scaling relationship, the wave and wind Froude numbers of the scaled model are set to equal to the Froude number of the prototype model. By means of Froude scaling, hydrodynamic and inertial parameters can usually be scaled properly, but scaling of aerodynamic parameters is a challenge generally due to the diminished Reynolds number, which is formulated in equation 2.2.

\[ Re = \frac{\rho VL}{\mu} \]  

(2.2)

where \( L \) is the characteristic length, \( V \) is a characteristic velocity, \( \rho \) and \( \mu \) are the density and the dynamic viscosity of the fluid/air, respectively. If aerodynamic parameters are insensitive to Reynolds number, accurate Froude scaling can be achieved in FWT specimens. On the other hand, Reynolds scaling is generally applied to aerodynamic parameters and applying Reynolds scaling to FWT prototypes is impractical for wave loaded floating body, like the platform of a FWT (Martin, et al., 2014).
### Table 2-3 Scaled Testing Studies on Wind Turbine

<table>
<thead>
<tr>
<th>Authors</th>
<th>Wind turbine</th>
<th>Scale</th>
<th>Testing facility</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martin et al. (2014)</td>
<td>5 MW</td>
<td>1:50</td>
<td>Offshore Basin</td>
<td>Establish a unified scaling methodology for Froude scale model testing of FWT under combined wind and wave loading</td>
</tr>
<tr>
<td>Viselli et al. (2015)</td>
<td>20kW</td>
<td>1:8</td>
<td>Gulf of Maine Offshore</td>
<td>Decrease the risks of full-scale experiment of new FWT platform design by demonstrating full-scale design, construction techniques and deployment methods successfully in intermediate-scale testing</td>
</tr>
<tr>
<td>Utsunomiya et al. (2009)</td>
<td>2 MW</td>
<td>1:22.5</td>
<td>Deep Sea Wave-Basin</td>
<td>Develop a FWT with spar platform by examining the scaled FWT subjected to environmental loading</td>
</tr>
<tr>
<td>Utsunomiya et al. (2013)</td>
<td>1 kW HAWT</td>
<td>1:10</td>
<td>Sea</td>
<td>Develop a cost-effective, floating off-shore wind turbine</td>
</tr>
</tbody>
</table>
Scaled testing was adopted in FWT researches to take the advantage of capturing relatively accurate response while reducing probability of risks and costs of large-scale experiments. For instance, Martin et al. (2014) conducted tests on scaled FWT specimens with three different platforms in an offshore basin, which are tension-leg platform (TLP), spar-buoy and semi-submersible. Scaled wind and wave loads were evaluated together with the loads applied on the tower and the mooring lines. Froude scaling was applied to the FWT specimen, but the scaled model provoked a poor aerodynamic performance with low Reynolds number, low lift forces and high drag forces.

Hall et al. (2014) pointed out that modifications in FWT specimen geometry, like changing blade dimensions, may yield correctly-scaled lift and drag forces. However, these modifications will affect other response characteristics of FWT, which makes accurate scaling still a great challenge in scaled testing.

On the other hand, numerical simulations were utilized to provide an opportunity to estimate FWT dynamics responses and validate results from scaled FWT experiments. For instance, Utsunomiya et al. (2009) carried out experiments on scaled FWT specimen to investigate the responses of FWT with spar platform under different environmental loading cases (i.e., regular and irregular waves, steady wind, turbulent winds and currents). Meanwhile, numerical simulation was conducted utilizing a numerical code, and the natural periods (in the prototype scale) and the responses at each motion were compared to those of the experiment, where the results were validated. Moreover, Viselli et al. (2015) performed tests on an intermediate-scaled specimen of a new FWT platform design with concrete semi-submersible hull and a composite tower. They also performed numerical simulation of the full-scale FWT structure using the Fatigue, aerodynamics, structures and turbulence (FAST) code (Jonkman and Buhl, 2005). A favorable match of the experimental and simulation results was obtained which proved that scaled testing may be able to demonstrate the full-scale design and the construction techniques while reducing the risks of full-scale experiments.
However, accuracy of numerical simulations is sometime limited depending on the computer programs and they are not considered to be capable of replacing experiments of FWT yet. International Towing Tank Conference Specialist Committee (ITTC) states that physical hydrodynamic model testing is required to verify new designs of FWT structures since some physical phenomena, e.g. extreme wave loads, viscous loads or wave-current interaction on floating moored structures, are still not fully modeled numerically (ITTC, 2017). For example, Utsunomiya et al. (2013) conducted tests on a scaled FWT specimen with hybrid spar foundation, which consists of precast concrete segments at the lower portion of the foundation and steel part at the upper portion. Spar foundation motions were simulated in FAST and general good agreement between the numerical and experimental results was observed, except for the discrepancy between yaw angular velocity values. It was found out that this discrepancy was due to errors in calculating the eccentricity of the center of the mass of the rotor-nacelle assembly. In such cases where a structure is hard to model and/or simulate numerically, there is a need of utilizing RTHS and dRTHS during which critical part of the structure is selected as the physical substructure and tested, which may overcome the aforementioned limitations in numerical simulations.

Besides the normal working loading FWT structures are experiencing daily, FWT structures shall be designed for survival in harsh environmental conditions. Table 2-4 lists two studies where numerical simulations have been utilized to investigate the behavior of offshore wind turbine (OWT) structures, i.e., bottom-fixed wind turbine and FWT, against hazardous loading and extreme conditions.

Karimirad and Moan (2011) carried out several simulations on a 5 MW NREL baseline wind turbine with different simulation durations to determine the extreme structural responses using turbulence model for 100-year environmental condition with the mean wind speed of 36 m/s and the period of 13 sec. It was found out that 20 1hour simulations are sufficient to predict the 3hour extreme bending moment by means of extrapolation. Besides, Wei et al. (2016) conducted simulations on an OWT with a jacket structure using the FAST code where hurricane loads are applied. The structural responses were found to be not so sensitive on hurricane directions.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Wind Turbine</th>
<th>Numerical Simulations</th>
<th>Software</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karimirad and Moan (2011)</td>
<td>5 MW NREL baseline wind turbine</td>
<td>Coupled aero hydro-elastic time domain dynamic response analysis</td>
<td>HAWC2, SIMO/RFLEX</td>
<td>Determine responses of FWT structure against extreme loads to meet with the demands Ultimate Limit State (ULS) conditions, which considers coupled wave and wind induced motion and structural response in harsh environmental conditions.</td>
</tr>
<tr>
<td>Wei et al. (2016)</td>
<td>5 MW OWT with jacket structure</td>
<td>Nonlinear static analysis of the structure for hundreds of synthetic hurricane events within a catalog designed to characterize potential hurricane activity in the future</td>
<td>FAST</td>
<td>Develop an analysis framework for assessing hurricane risk to understand the effect of wind and wave directionality and jacket orientation on structural demands and capacities.</td>
</tr>
</tbody>
</table>
2.3.2 Real-Time Hybrid Simulation (RTHS)

So far there have been numerous studies utilizing RTHS for FWT dynamic response evaluations, which might address the challenges in numerical simulations and scaled testing methods and provide realistic responses of FWT structures subject to various loading conditions. Table 2-5 lists two RTHS experiments, where the latter one is a comprehensive study that contains four different study related to RTHS.

ITTC (2017) states that the main advantage of RTHS is to solve Froude-Reynolds scaling problems, as the aerodynamic loading is numerically evaluated at full-scale and then subjected to Froude scaling before being applied to physical experiment. This two-step process in RTHS enables the validation of hydrodynamic coefficients, such as viscous drag coefficients and the ratio of maximum drag force to maximum inertia force (Berthelsen, et al., 2016). Therefore, expanding capabilities of RTHS and creating dRTHS environment for experiments of FWT structures is believed to move the experimental FWT testing methods into the next level.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Wind turbine</th>
<th>Scale</th>
<th>Numerical Substructure</th>
<th>Physical Substructure</th>
<th>Testing Facility</th>
<th>Software</th>
<th>Hardware</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azcona et al. (2014)</td>
<td>6 MW</td>
<td>1:40</td>
<td>Full-scale rotor</td>
<td>1:40 scaled 6 MW FWT with a ducted fan at the top of the tower and semi-submersible platform</td>
<td>Wave Tank</td>
<td>FAST $\rightarrow$ Simulate the full-scale rotor LabVIEW $\rightarrow$ Generate signals to control the power applied to the ducted fan</td>
<td>Power Supply and Electronic Speed Controller (ESC) with a Programming Card $\rightarrow$ Generates Power for the Ducted Fan</td>
<td>Implement an alternative method to deal with the out of scale aerodynamic loads in scaled testing</td>
</tr>
<tr>
<td>Norwegian Marine Technology Research Institute (MARINTEK)</td>
<td>5 MW</td>
<td>1:30</td>
<td>Full scaled nacelle, blade and rotor</td>
<td>1:30 scaled braceless semi-submersible 5 MW FWT</td>
<td>Ocean Basin</td>
<td>RIFLEX $\rightarrow$ mooring line responses SIMO $\rightarrow$ hydrodynamic loads and motion responses AeroDyn $\rightarrow$ aerodynamic load TurbSim $\rightarrow$ Modelling of wind loads SIMA $\rightarrow$ synchronizing numerical simulations in the workbench</td>
<td>Wave Probes $\rightarrow$ Measures Wave Elevation Strain Gauges $\rightarrow$ Measures moments and forces at the base of tower Accelerometer, Gyro meter $\rightarrow$ Evaluates the motion of physical substructure</td>
<td>Develop and verify RTHS setup, utilize RTHS test results to calibrate numerical model and research the sensitivity of the actuated aerodynamic components</td>
</tr>
</tbody>
</table>
Azcona et al. (2014) carried out experiments on a 1:40 scaled 6 MW wind turbine with semi-submersible platform, where the rotor was substituted with a ducted fan at the top of the tower to represent the total wind thrust by rotor. Numerical simulation of the full-scale rotor in turbulent wind was performed in synchronicity with the experiment and the simulated aerodynamic thrust was sent to the fan to apply Froude scaling in real-time. Then, wave loading, which was produced by wave maker, and scaled aerodynamic thrust loading were applied on the FWT specimen with a ducted fan, and the displacement and velocity responses of FWT platform for 6 DOF was captured using the acquisition system. These responses were scaled up and sent to the numerical simulation of the rotor as an input to calculate the aerodynamic thrust for next time-step. Combined irregular waves and turbulent wind tests, static wind tests and free decay experiments were carried out and the results were compared with the computational results. Realistic aerodynamic thrust values were obtained which validated the performance, versatility and feasibility of the method for the representation of the scaled aerodynamics. To the author’s humble knowledge, it may be counted as the first application of RTHS in this field.

MARINTEK designed and developed a RTHS setup, where the setup was verified first (Sauder, et al., 2016), RTHS tests were then conducted (Bachynski, et al., 2016) and the results were used to calibrate the numerical model (Berthelsen, et al., 2016). Firstly, MARINTEK investigated the feasibility of the developed RTHS setup through decay tests and repeated wind tests. In the RTHS setup, braceless 1:30 scaled FWT model was selected as the physical substructure and the numerical substructure consisted of the components of the FWT assembled on the top of the tower, which were nacelle, blade and rotor as introduced in Figure 2-2. Wind loads were numerically modeled and calculated, then the Froude scaling was applied to the wind loads before they were imposed to the physical substructure. Decay tests were carried out along 6 DOFs which were not RTHS tests since there was no numerically simulated wind loading. Then, only wind load was applied and the repeatability of the RTHS tests were investigated. Moreover, polynomial extrapolation method was utilized in these tests to compensate the delay (Carrion and Spencer, 2007). The results verified that the RTHS setup can perform repeatable RTHS tests properly.
Next, MARINTEK carried out RTHS tests, named as the real-time hybrid testing (ReaTHM), using the verified setup to prove the applicability of RTHS to overcome the Froude-Reynolds scaling conflict mentioned for the scaled testing method (Bachynski, et al., 2016). As shown in Figure 2-4, measured platform motions were transferred to the numerical model in RTHS where numerical simulation was carried out to find the aerodynamic forces. These aerodynamic forces were applied by actuator to the physical model and at the same time, hydrodynamic forces were generated by wavemaker and input to the physical model. So, the overall displacement responses under both forces were obtained and were fed back to the numerical model to determine the aerodynamic forces for the next time step.

![Figure 2-4 Real-time Hybrid Testing (ReaTHM) for a FWT in a Wave Basin (Bachynski, et al., 2015)](image)

The platform motions and accelerations were measured by means of gyrometers and accelerometers. The results were sampled at 600 Hz and several RTHS tests, discussed in the next paragraph, were conducted. TurbSim software (Jonkman, 2009) was utilized to generate the wind input.

Decay tests, where different wind loadings were applied, in surge and pitch motions were conducted and the increase in pitch natural period was observed when FWT operates on high wind speed values. Then, regular wave tests were conducted with different environmental wind conditions. The results showed that the aerodynamic effects did not affect the motion of the FWT significantly. Lastly, irregular waves were applied to the RTHS setup for two conditions: (1) without wind (2) with turbulent wind. Heave responses were observed to be damped when the wind load is present. The tests showed the significant effect of the wind loads on FWT, which indicated the advantages of RTHS and dRTHS in FWT experiments by applying the correctly-
scaled aerodynamic loads. Moreover, the test results can be utilized to calibrate the numerical FWT model, which is explained next (Berthelsen, et al., 2016).

RTHS, which eliminates the uncertainties about the physical modelling of wind loads is an ideal alternative to calibrate the hydrodynamic coefficients in numerical models. To take the advantage of RTHS and improve the agreement between simulations and experiments, full-scale numerical model of the FWT was calibrated using the RTHS test results (Sauder, et al., 2016). Decay and irregular wave test results were evaluated to determine the viscous drag coefficient of the numerical model. Then, the same RTHS tests were carried out numerically using the determined drag coefficient to adjust the damping ratio obtained during RTHS tests. After the calibrations, good agreement was achieved with the experimental results. In the numerical simulations, platform motions and mooring line responses were solved synchronically. SIMO (2015) was utilized to determine the hydrodynamic loads and motion responses, where RIFLEX (2015) calculated the mooring line responses. SIMA (2015), a simulation workbench, was used to conduct the simulation. The studies of MARINTEK presented a comprehensive research on the applicability of RTHS on FWT systems, where the RTHS setup was verified, RTHS tests were conducted and the results were used to calibrate numerical models, respectively.

Moreover, in order to reduce the actuated components in RTHS tests if they have negligible effects on FWT system, Bachynski et al (2015) carried out a sensitivity study on the components of aerodynamic loads. The numerical simulations were carried out on a FWT model removing the gyroscopic moments, inertial loads caused by the rotation of the blades and aerodynamic loads individually and the results were investigated. In the sensitivity study, TurbSim (Jonkman, 2009) was used to model wind numerically where AeroDyn (Moriarty and Hansen, 2005) was used to calculate aerodynamic loads, as shown in Figure 2-5. SIMO (2015) was used to model the rigid body hydrodynamics where RIFLEX (2015) conducted the finite element analysis and sent the position of the wind turbine elements and velocity values. Numerically simulated blade loads were modified by removing the aerodynamic components, where the modifications were called “ReaTHM” modifications, and introduced to AeroDyn. The results showed the limited effects of gyroscopic moments on the FWT structural response, where the removal of the actuation of them may be considered to reduce the complexity of the RTHS setup.
Figure 2-5 Floating Wind Turbine Simulation Using SIMO-RIFLEX-AeroDyn Including ReaTHM Modifications (Bachynski, et al., 2015)
2.4 Summary

This chapter provided the literature review for distributed hybrid simulation and the experimental methods of FWT systems. dHS literature were reviewed first, where the results indicated the importance of the simulation coordinators, which may enable conducting distributed hybrid simulation for complex models. dRTHS experiments, which was conducted fewer times than dHS, were reviewed and discussed next. The necessity of delay compensation methods and their limitations in long delays, which is expected in dRTHS, were emphasized and a delay compensation method from the literature was presented, where both dHS and dRTHS highlighted the importance of compensating delay. Moreover, it was observed that the communication protocol may change the data transfer rate and the robustness of the dHS.

Next, experimental FWT studies were reviewed and the advantages, challenges and limitations of three testing/simulation methods were explained. Scaled testing, which reduces the risk and cost of large-scale FWT experiments but has challenges in aerodynamic scaling, where RTHS may be utilized to numerically simulating the aerodynamic loads and applying them to the specimen to yield more accurate responses compared to scaled testing. Computational limitations of numerical simulations were also noted in the literatures, which justifies that RTHS and dRTHS methods shall be applied to FWT systems and the applicability of dRTHS shall be investigated. Lastly, RTHS studies, where their results light the road of implementing dRTHS application in FWT system, were reviewed and presented in detail. The results also demonstrate the advantages of RTHS in scaling and numerical simulations. Moreover, RTHS results can be used to improve the accuracy of numerical models by calibrating their parameters against the test results.
3 THEORETICAL BACKGROUND

3.1 Introduction

Theoretical background of dynamic response evaluation of structural systems, distributed real-time hybrid simulation (dRTHS) method and the delay compensation methods used in dRTHS are discussed in this chapter. This chapter begins with the definition of equations of motion (EOM) of multi-degrees-of freedom-(MDOF) structural systems, which are utilized to model the shear-type structure and the floating wind turbine(FWT) structure, the two prototype structures considered in this research.

Then, substructuring method and integration algorithms, two essential steps in dRTHS, are presented. Both explicit and implicit algorithms are explained with their respective pros and cons. The Newmark’s explicit integration algorithm, which was adopted in both studies but with different parameters, is presented next including a detailed step-by-step derivation of the integration algorithm.

Lastly, four delay compensation methods those compensation effects are being compared for dRTHS are explained including their theoretical basics and operating mechanisms during real-time hybrid simulation (RTHS) and dRTHS.
3.2 Dynamic Behavior of Building and FWT Structures

3.2.1 Equation of Motion of Shear-Type Structures

Dynamic response of an idealized structural system subject to dynamic excitation can be defined using three components, namely mass, stiffness and damping (Chopra, 2012). Shear-type building frame structures are idealized structural model where the beams and the floors are assumed as rigid in flexure, the mass is lumped at the floors and the translation degree of freedom (DOF) is considered only at each floor.

The three-story shear frame building model with a story height of 1.3 m was adopted as a prototype structure in the study (see Figure 3-1) to investigate the effectiveness of the four delay compensation methods implemented in dRTHS. \( k, c \) and \( m \) are initial stiffness, viscous damping coefficient and mass of each floor, respectively. \( u \) is the displacement response of each story when subject to a dynamic loading. Subscripts 1~3 are used to represent the story level.

![Figure 3-1 Three-Story Model (3-DOF)](image)

Figure 3-1 Three-Story Model (3-DOF)
The three-story nonlinear shear frame model is idealized as an MDOF structure and the EOM describing its dynamic responses when subjected to the external excitation force vector $\ddot{u}_g(t)$ is expressed as:

$$m \dddot{u}(t) + c \dot{u}(t) + f_s(u, \dot{u}) = p(t) = -m \ddot{1}u_g(t)$$  \hspace{1cm} (3.1)

where $m$ is the diagonal mass matrix and $\dddot{u}(t)$ is the acceleration response vector of the MDOF structure at the instant time $t$. $\dot{1}$ is a vector of order N, which is number of floor mass in system. $p(t)$, $\dot{u}(t)$ and $f_s$ are the external force, the velocity and the restoring force vectors, respectively. $c$ is the damping matrix, which is defined using the Rayleigh damping formula with the first two modes:

$$c = a_0 \cdot m + a_1 \cdot k$$ \hspace{1cm} (3.2)

where $a_0$ and $a_1$ are Rayleigh damping coefficients which are expressed as:

$$a_0 = \frac{2\zeta \omega_1 \omega_2}{\omega_1 + \omega_2}$$ \hspace{1cm} (3.3)

$$a_1 = \frac{2\zeta}{\omega_1 + \omega_2}$$ \hspace{1cm} (3.4)

where $\omega_1$ and $\omega_2$ are natural frequency at first and second mode, respectively, as used in the previous studies at the Laboratory of Earthquake and Structural Simulation (LESS), and $\zeta$ is the damping ratio. Moreover, $k$, the initial stiffness matrix used to determine $c$, is expressed as:

$$k = \begin{bmatrix}
k_1 + k_2 & -k_2 & 0 \\
0 & k_2 + k_3 & -k_3 \\
0 & -k_3 & k_3
\end{bmatrix}$$ \hspace{1cm} (3.5)

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$k_{1,2,3}$ represents initial stiffness of the shear-type building at each floor. $c$ is calculated using the initial stiffness matrix, where detailed calculations and results are shown in Chapter 4. Matrix form of the EOM is shown in equation 3.6.

$$
\begin{bmatrix}
m_1 & 0 & 0 \\
0 & m_2 & 0 \\
0 & 0 & m_3
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_1 \\
\ddot{u}_2 \\
\ddot{u}_3
\end{bmatrix}
+
\begin{bmatrix}
c_1 + c_2 & -c_2 & 0 \\
0 & c_2 + c_3 & -c_3 \\
0 & 0 & c_3
\end{bmatrix}
\begin{bmatrix}
\dot{u}_1 \\
\dot{u}_2 \\
\dot{u}_3
\end{bmatrix}
+
\begin{bmatrix}
f_{S1} \\
f_{S2} \\
f_{S3}
\end{bmatrix}
=
\begin{bmatrix}
p_1(t) \\
p_2(t) \\
p_3(t)
\end{bmatrix}
$$

(3.6)

### 3.2.2 Equation of Motion of FWT Structures

In the study, a FWT prototype, which does not include the rotor, nacelle and the blades, is modeled as a 6 DOF rigid body following the reference model (Lee, 2005), where the rigid body motions are shown in Figure 3-2. This approach is generally used in FWT systems to correlate nacelle and rotor motions not only with tower, but also with the floating platform (Jonkman and Sclavounos, 2006).

![Figure 3-2 Coordinate System and Modes of Rigid Body Motion (Withee, 2004)](image)

Dynamic response of the FWT structure subject to wave and wind excitations can be evaluated at each time step by solving the following EOM (Lee, 2005):
\[(M + A)\ddot{u} + C \dot{u} + Ku = p(t)\]  

(3.7)

where \( M \) is the mass matrix, \( A \) is the added mass matrix, \( C \) is the damping matrix and \( K \) is the hydrostatic restoring stiffness matrix of the FWT structure. \( p(t) \) and \( u \) are the excitation force and the displacement response vectors, respectively.

In addition to normal FWT structure mass same as for the on-land structures, added mass is included when evaluating the response of offshore structures which accounts the inertia effect from the surrounding fluid when FWT structure is moving. Added mass is neglected in onshore structural models because the systems are placed in the air and the density of the air is very small when compared to the density of water.

For the rigid body FWT structure with 6 degrees of freedom (DOF), which is shown in Figure 3-2, the mass matrix is expressed as (Karimirad, 2014):

\[
\begin{bmatrix}
  m & 0 & 0 & 0 & mz_g & -my_g \\
  0 & m & 0 & -mz_g & 0 & mx_g \\
  0 & 0 & m & my_g & -mx_g & 0 \\
  0 & -mz_g & my_g & I_{11} & I_{12} & I_{13} \\
  mz_g & 0 & -mx_g & I_{21} & I_{22} & I_{23} \\
  -my_g & mx_g & 0 & I_{31} & I_{32} & I_{33}
\end{bmatrix}
\]

(3.8)

where \( I \) is the mass moment of inertia of the FWT system about surge, sway and heave axes which are represented using subscripts 1~3. \( m \) is the total mass of the FWT structure and \( z_g, y_g \) and \( x_g \) are the coordinates of the center of the mass (COM) of the FWT structure in the -z,-y and -x directions, respectively.

Added mass matrix of FWT structures with cylindrical buoy draft is formulated as follows (Lee, 2005):
where $r$ is the platform radius, $T$ is the length of platform (draft), and $\rho$ is the density of water. Mooring lines, which were fixed to the sea ground and used to restrain the motions of FWT systems, are considered when calculating the hydrostatic restoring force matrix. Hydrostatic restoring stiffness matrix $K$ of a FWT structure is determined considering the contribution from both the platform $K_{\text{hyd}}$ and the mooring lines $K_{\text{lin}}$, where $K_{\text{hyd}}$ is expressed as (Al-Solihat and Nahon, 2015a):

$$
K_{\text{hyd}} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & K_{\text{hyd}}^h & K_{\text{hyd}}^h & 0 \\
0 & 0 & -W + F_B z_b & K_{\text{hyd}}^r + K_{\text{hyd}}^h & 0 \\
0 & 0 & -K_{\text{hyd}}^r & -K_{\text{hyd}}^h & (W - F_B) y_f \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
$$

(3.10)

$$
K_{\text{wp}}^h = \rho g A_c
$$

(3.11)

$$
K_{\text{wp}}^r = \rho g I_{xx}
$$

(3.12)

$$
K_{\text{wp}}^p = \rho g I_{yy}
$$

(3.13)

$z_b$ is the center of buoyancy (COB), $I_{xx}$ and $I_{yy}$ are the area moment of inertia of the platform in -x and -y direction, respectively. $W$ is the weight of the system, which is equal to buoyancy force, $F_B$. 

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$A_c$ is the water-plane area where $y_f$ and $x_f$ are the center of buoyancy of FWT in -x and -y direction, respectively. $y_f$ and $x_f$ are zero for symmetric FWT structures.

Equation 3.14 stands for the hydrostatic restoring stiffness matrix of mooring lines, $K_{lin}$ (Al-Solihat and Nahon, 2015b). The parameters of $K_{lin}$ are shown in Figure 3-3. $T$, $L$ and $EA$ are the tension force, the length, the longitudinal stiffness of the mooring lines. $D$ is the distance between the water level and the top of the mooring lines.

![Figure 3-3 Mooring System (Al-Solihat and Nahon, 2015b)](image-url)
In floating platforms, rigid body natural frequencies are not zero due to the hydrostatic restoring forces and mooring stiffness (Karimirad, 2014). Instead of eigenvalue analysis, the following formula is applied to find the natural frequencies of the FWT structure:

\[
\omega_j = \sqrt{\frac{(\mathbf{K}_{\text{lin}})_{jj} + (\mathbf{K}_{\text{hyd}})_{jj}}{(\mathbf{M}_{jj} + \mathbf{A}_{jj})}}
\] (3.15)

where \(\mathbf{M}_{jj}\), \(\mathbf{A}_{jj}\), \((\mathbf{K}_{\text{lin}})_{jj}\) and \((\mathbf{K}_{\text{hyd}})_{jj}\) are the diagonal terms in the mass, added mass, hydrostatic and mooring stiffness matrices used to find \(\omega_j\), the natural frequency of the \(j^{th}\) motion. Surge, sway, heave, roll, pitch and yaw motions are sequentially numbered from 1 to 6 in the equation. For FWT with non-negligible mooring stiffness value, pitch natural frequency value is calculated as follows (Karimirad, 2014), where \(I_{55}\) is the pitch mass moment of inertia:

\[
\omega_{55} = \sqrt{\frac{(\mathbf{K}_{\text{lin}})_{55} + (\mathbf{K}_{\text{hyd}})_{55}}{(\mathbf{I}_{55} + \mathbf{A}_{55})}}
\] (3.16)

The structural damping matrix is calculated following the Rayleigh damping method, which is shown in equation 3.2 where \(\mathbf{m}\) includes the mass \(\mathbf{M}\) and added mass matrix \(\mathbf{A}\), and \(\mathbf{k}\) includes \(\mathbf{K}_{\text{hyd}}\) and \(\mathbf{K}_{\text{lin}}\).
3.3 Distributed Real Time Hybrid Simulation (dRTHS)

dRTHS, which allows accurate evaluation of complex structural systems, takes the advantages of substructuring to combine large-scale experiments on physical substructure and numerical simulation of analytical substructure to obtain the whole structural responses when subject to excitations such as earthquake, wave or/and wind loadings. During dRTHS, numerical model of the whole structural system is utilized to solve the EOM at each time-step using an integration algorithm. In this section, substructuring method and the integration algorithm used in the dRTHS tests are presented and discussed.

3.3.1 Substructuring

dRTHS is a combination of numerical simulation and physical experimentation of structural components within a structural system in real-time, where the structural components herein are called substructures. These substructures are simulated and tested synchronically where the responses of the substructures are transferred to each other in real-time to obtain the dynamic response of the whole structure (see section 1.1.2.2). Physical substructure is subjected to dynamic loading induced by hydraulic loading equipment and the response is measured and sent to the numerical substructure in real-time where numerical simulation of the whole structure is being carried out to solve EOM at each time step.

3.3.1.1 Substructuring of the 3DOF Shear Frame Building Model

The three-story shear frame building model is divided into two substructures in the study, namely physical and numerical substructures, as shown in Figure 3-4. First story was selected as the physical substructure where the upper two stories were selected as the numerical one.
Equations of motion of the whole structure, physical and numerical substructures are shown in equations 3.17-3.19.

\[
\begin{bmatrix}
m_1 & 0 & 0 \\
0 & m_2 & 0 \\
0 & 0 & m_3 \\
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_1 \\
\ddot{u}_2 \\
\ddot{u}_3 \\
\end{bmatrix}
+ \begin{bmatrix}
c_1 + c_2 & -c_2 & 0 \\
0 & c_2 + c_3 & -c_3 \\
0 & -c_3 & c_3 \\
\end{bmatrix}
\begin{bmatrix}
\dot{u}_1 \\
\dot{u}_2 \\
\dot{u}_3 \\
\end{bmatrix}
+ \begin{bmatrix}
f_{s1} \\
f_{s2} \\
f_{s3} \\
\end{bmatrix}
= -\begin{bmatrix}
m_1 \\
0 \\
0 \\
\end{bmatrix}
\dddot{u}_g
\] (3.17)

\[m_1 \dddot{u}_1 + c_1 \ddot{u}_1 + c_2 \ddot{u}_2 - c_2 \ddot{u}_1 + f_{s1} = -m_1 \dddot{u}_g\] (3.18)

\[
\begin{bmatrix}
m_2 & 0 \\
0 & m_3 \\
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_2 \\
\ddot{u}_3 \\
\end{bmatrix}
+ \begin{bmatrix}
c_2 + c_3 & -c_3 \\
-c_3 & c_3 \\
\end{bmatrix}
\begin{bmatrix}
\dot{u}_2 \\
\dot{u}_3 \\
\end{bmatrix}
+ \begin{bmatrix}
f_{s2} \\
f_{s3} \\
\end{bmatrix}
= -\begin{bmatrix}
m_2 \\
m_3 \\
\end{bmatrix}
\dddot{u}_g
\] (3.19)

### 3.3.2 Integration Algorithm

Since earthquake poses random loading effects on structures and which is difficult to be expressed in EOM using general functions, time-stepping integration algorithms are required to solve the dynamic EOM of structures when subject to seismic excitations. These algorithms solve the structural responses (i.e., displacement, velocity, acceleration) at every time step based on the ground motion input. In general, integration algorithms are divided into two categories, which are explicit and implicit.
In explicit integration algorithm, response of the next time step is calculated using the responses of the current and previous time steps. This feature makes explicit algorithms a simple and efficient solution for hybrid simulations. However, explicit integration algorithm may have stability requirements. For example, the Newmark’s explicit integration method, which was utilized in this thesis, is stable if and only if the time step size is smaller than the upper limit, which is shown in equation 3.20.

\[
\Delta t < \frac{T_n}{\pi}
\]  

(3.20)

where \( T_n \) is the shortest period of the structure. The shortest period might be very small for the structures with many DOFs, which may cause irrational upper limits.

In implicit integration algorithms, response of the next time step is calculated using responses of the next, the current and the previous time steps and iterative procedure is sometimes required in these algorithms. For this reason, command displacement values can overshoot the true displacement values during the iteration process. Moreover, implicit algorithms are computationally expensive since they require iterations.

The model investigated in the study, the shear type frame building model with 3 DOFs, is a simple structure model that can be solved using an explicit integration algorithm. In the study, the Newmark’s explicit integration algorithm (Newmark, 1959), defined as the simplest explicit integration algorithm method (Schellenberg, et al., 2009), was utilized and its step-by-step calculations are presented in next subsection. Besides, the incremental form of the Newmark’s explicit integration method was used to solve the EOM of the FWT model, which is presented in section 3.3.2.2.

**3.3.2.1 Newmark’s Explicit Integration Algorithm**

Newmark’s integration methods, which use time-stepping method to determine the displacement response of a structural system, are based on equations 3.21 and 3.22:
\[
\dot{u}_{i+1} = \dot{u}_i + [(1 - \gamma) \Delta t] \ddot{u}_i + (\gamma \Delta t) \dddot{u}_{i+1} \tag{3.21}
\]
\[
u_{i+1} = u_i + (\Delta t) \dot{u}_i + [(0.5 - \beta)(\Delta t)^2] \ddot{u}_i + [\beta (\Delta t)^2] \dddot{u}_{i+1} \tag{3.22}
\]

where \(\dddot{u}_{i+1}\), \(\dddot{u}_{i+1}\), and \(\dddot{u}_{i+1}\) are acceleration, velocity and displacement at \(i+1^{th}\) time step, respectively and \(\Delta t\) is the step size of the integration. \(\gamma\) and \(\beta\) are the parameters used to determine the variation of the accelerations at each time step.

\(\beta\) was set to zero and \(\gamma\) was set to 0.5 in the study, and the integration algorithm was performed in two steps in the investigation of delay compensation methods in dRTHS, which are named as prediction and correction steps.

Firstly, prediction step was performed at each time step to determine the desired displacement and velocity values, which are \(\dddot{u}_{i+1}\) and \(\dddot{u}_{i+1}\), respectively. The desired displacement and velocity values are expressed as follows, where equation 3.22 is rewritten to find the \(\dddot{u}_{i+1}\) which is shown in equation 3.23.

\[
\dddot{u}_{i+1} = u_i + (\Delta t) \dot{u}_i + [(0.5) (\Delta t)^2] \ddot{u}_i \tag{3.23}
\]
\[
\dddot{u}_{i+1} = \dot{u}_i + [(0.5) \Delta t] \ddot{u}_i \tag{3.24}
\]

where \(\dddot{u}_{i+1}\) and \(\dddot{u}_{i+1}\) are desired displacement and velocity vectors, respectively. Since \(\beta\) was set to zero in the study, \(\dddot{u}_{i+1}\) is equal to the \(\dddot{u}_{i+1}\) when the equation 3.22 is rewritten. Moreover, the substituting equation 3.24 into equation 3.21 provides the equation 3.25, which is used in the correction step after finding \(\dddot{u}_{i+1}\).

\[
\dot{u}_{i+1} = \dddot{u}_{i+1} + (0.5 \Delta t) \dddot{u}_{i+1} \tag{3.25}
\]
To find $\ddot{u}_{i+1}$, $\dot{u}_{i+1}$ and $\ddot{u}_{i+1}$ are first used as inputs to compute the restoring force vector $f_s$ at each time-step, where $f_s$ is computed using Bouc-Wen hysteresis loop model, as discussed in Chapter 4. Then, the effective force vector, $p_{eff}$, is calculated at each time step using $\ddot{u}_{i+1}$ and $\dot{u}_{i+1}$.

$$p_{eff} = p_{i+1} - f_s(\ddot{u}_{i+1}, \dot{u}_{i+1}) - cu_{i+1}$$  \hspace{1cm} (3.26)

where $c$ is the damping matrix, $p$ is the excitation force vector and the $f_s$ is the restoring force vector of the structure.

Then, the following equation are obtained by substituting equations 3.23, 3.25 and 3.26 into 3.1 (EOM):

$$m_{eff}\ddot{u}_{i+1} = p_{eff}$$  \hspace{1cm} (3.27)

where effective mass matrix $m_{eff}$ is constant and calculated before the start of the simulation, as shown in equation 3.28.

$$m_{eff} = m + (\gamma \Delta t)c$$  \hspace{1cm} (3.28)

where $m$ is the mass matrix, and $c$ is the damping matrix. After $\ddot{u}_{i+1}$ is solved by equation 3.26, $\dot{u}_{i+1}$ is updated at the correction step, as shown in 3.25. Then, $u_{i+1}$ and $\dot{u}_{i+1}$ are in turn used in the next time step calculation.

### 3.3.2.2 Integration Algorithm used in FWT Model Analysis

The Newmark’s explicit integration method in the incremental form was used to solve the EOM of the FWT model, which is a linear multi-degrees of freedom (MDOF) system. Linear acceleration method was adopted where $\beta = 1/6$ and $\gamma = 0.5$, where $\gamma$ was set to the same value as used in solving the three-story model.

Firstly, initial parameters were determined as shown in equation 3.29~3.31:
\[ \mathbf{K} = \mathbf{K} + \frac{\gamma}{\beta \Delta t} \mathbf{C} + \frac{1}{\beta (\Delta t)^2} \mathbf{M} \]  
\[ (3.29) \]

\[ \mathbf{a} = \frac{1}{\beta \Delta t} \mathbf{M} + \frac{\gamma}{\beta} \mathbf{C} \]  
\[ (3.30) \]

\[ \mathbf{b} = \frac{1}{\beta} \mathbf{M} + \Delta t (\frac{\gamma}{2 \beta} - 1) \mathbf{C} \]  
\[ (3.31) \]

where the \( \mathbf{K} \), \( \mathbf{C} \) and \( \mathbf{M} \) are the stiffness, damping and mass matrices of the FWT model, respectively. Note the total mass matrix of the FWT system is used here, which includes the mass matrix of the structure and the added mass matrix as discussed in section 3.2.2. \( \Delta t \) is the time step which is 0.001 sec in the FWT response simulation. Then, the time-stepping calculations were carried out using the incremental values.

Firstly, incremental force vector, \( \Delta \mathbf{P}_i \), is determined at each time step using equation 3.32 and 3.33:

\[ \Delta \mathbf{P}_i = \mathbf{\phi}^T \Delta \mathbf{p}_i \]  
\[ (3.32) \]

\[ \Delta \mathbf{\dot{P}}_i = \Delta \mathbf{P}_i + \mathbf{a} \mathbf{q}_i + \mathbf{b} \mathbf{\ddot{q}}_i \]  
\[ (3.33) \]

where \( \mathbf{\phi} \) is the mode shape matrix, \( \Delta \mathbf{p}_i \) is the excitation force increment vector between the current step and the previous step, \( \mathbf{\dot{q}}_i \) and \( \mathbf{\ddot{q}}_i \) are the modal coordinate vectors of the velocity and the acceleration, respectively. \( \mathbf{a} \) and \( \mathbf{b} \) are the initial parameters defined in equation 3.38 and 3.39.

Then, the increment in modal coordinate of displacement, \( \Delta \mathbf{q}_i \), is calculated at each time-step, which is expressed as:

\[ \Delta \mathbf{q}_i = (\mathbf{\hat{K}}^{-1}) \Delta \mathbf{\dot{P}}_i \]  
\[ (3.34) \]
where $\hat{K}$ is an initial parameter defined in equation 3.29. $\Delta q_i$ is used to determine the increment in modal coordinate of velocity and acceleration, which are $\Delta \dot{q}_i$ and $\Delta \ddot{q}_i$, respectively. $\Delta q_i$ and $\Delta \dot{q}_i$ are expressed as:

$$
\Delta q_i = \frac{\gamma}{\beta \Delta t} \Delta q_i - \frac{\gamma}{\beta} q_i + \Delta t (1 - \frac{\gamma}{2 \beta}) \dot{q}_i
$$

(3.35)

$$
\Delta \dot{q}_i = \frac{1}{\beta (\Delta t)^2} \Delta q_i - \frac{1}{\beta \Delta t} \dot{q}_i - \frac{1}{2 \beta} \ddot{q}_i
$$

(3.36)

where $\beta$ is the Newmark algorithm constant which was mentioned. Then, the modal coordinates of the displacement, velocity and the acceleration are updated based on the increments, which are shown in equation 3.37~3.39.

$$
q_{i+1} = q_i + \Delta q_i
$$

(3.37)

$$
\dot{q}_{i+1} = \dot{q}_i + \Delta \dot{q}_i
$$

(3.38)

$$
\ddot{q}_{i+1} = \ddot{q}_i + \Delta \ddot{q}_i
$$

(3.39)

where $q_i$, $\dot{q}_i$, and $\ddot{q}_i$ are the modal coordinate vectors of displacement, velocity and acceleration at the previous step, respectively. Lastly, as shown in equation 3.40~3.42, the displacement, velocity and acceleration response vectors are updated at each time-step, which are $u_{i+1}$, $\dot{u}_{i+1}$ and $\ddot{u}_{i+1}$, respectively.

$$
u_{i+1} = \phi^T q_{i+1}
$$

(3.40)

$$
\dot{u}_{i+1} = \phi^T \dot{q}_{i+1}
$$

(3.41)

$$
\ddot{u}_{i+1} = \phi^T \ddot{q}_{i+1}
$$

(3.42)
3.4 Delay Compensation Methods

During dRTHS, time delay due to the communication between two real-time computers (i.e., targets), named the Internet delay, is inevitable in addition to the actuator delay when used to impose loading to experimental substructure. These delays, if not proper compensated, may result in erroneous and even unstable results, as mentioned in section 1.1.2. Fortunately, the adverse effects of time delay may be reduced with the use of delay compensation methods.

Four different delay compensation methods are presented in this section. Two adaptive delay compensation methods are selected to investigate the effects of adaptive parameters which are utilized to compensate varying time delay as expected in dRTHS that involves Internet communication of the command and the responses between computers.

In this section, the displacement quantities associated with the experimental substructure is represented by $d$ instead of $u$, as used in the literatures when introducing delay compensation methods.

Schematic implementation of a delay compensation method is shown in Figure 3-5. In an idealized physical dRTHS experiment, the displacement response of the physical substructure is calculated using an integration algorithm solving an EOM of the whole structural model at each time-step and imposed on the physical using actuators. Meanwhile, restoring force of the physical substructure when subject to the imposed displacement is measured using load cell and feedback to the EOM to calculate the displacement command of the next time step. The displacement responses calculated from the EOM is the desired displacement, $d^d$. The measured displacement, $d^m$ is expected to be identical with the desired displacement $d^d$ if there was no delay. However, this idealized condition is never achieved due to time delay. Delay compensation methods therefore are adopted to predict the command displacement, $d^k$, which will be sent to the actuator with the hope that driven by this command displacement, the measured displacement of the actuator will be identical to the desired one (see Figure 3-6). The compensation methods shall compensate both the Internet delay and the actuator delay in dRTHS, and only the Internet delay in numerical(virtual) dRTHS.
3.4.1 Modified Feedforward Method (MFF)

The modified feedforward (MFF) delay compensation method, has been widely used in the previous RTHS experiments at the LESS laboratories (Sanchez, 2013; Santana, 2014; Shao, et al., 2016). Actuator delay constant, $\alpha$, which is estimated using open-loop test before each RTHS and dRTHS test, is used to determine the command displacement at the time step $i$, as shown in equation 3.43.

$$d_i^c = (1 + \alpha + \frac{\alpha^2}{2})d_i^d - (\alpha + \frac{\alpha^2}{2})d_{i-1}^d + \frac{\alpha^2}{2}d_{i-2}^d$$  \hspace{1cm} (3.43)

$\tau$ is actuator delay and $\alpha = \frac{\tau}{\Delta t}$, and $\Delta t$ is the simulation time step.

3.4.2 Inverse Compensation Method (IC)

Chen (2007) proposed a discrete transfer function model which sends an “inversely delayed” command displacement to an actuator, with the purpose of adjusting the measured displacement
to the desired one. According to Chen and Ricles (2008), the duration for the actuator to compose the desired displacement is $\alpha \Delta t$ and $\alpha$ is greater than 1.0 if there is time delay in the actuator response, shown in Figure 3-7.

Assuming the linear actuator response as shown in Figure 3-7, measured displacement at the $(i+1)^{th}$ time step, $d_{i+1}^m$ is expressed as:

$$d_{i}^m = d_i^m + \frac{1}{\alpha}(d_{i+1}^d - d_i^m)$$  \hspace{1cm} (3.44)

where $d_{i+1}^d$ is desired displacement at the $(i+1)^{th}$ time step. Applying the discrete z-transform to equation 3.44 leads to a discrete transfer function $G_d(z)$ relating the measured actuator displacement $d_{i+1}^m$ to the desired displacement $d_{i+1}^d$:
where $z$ is the complex variable in the discrete $z$-domain; and $X_m(z)$ and $X_d(z)$ are the discrete $z$-transforms of $d_{i+1}^m$ and $d_{i+1}^d$, respectively.

Chen proposed to use inverse of the actuator delay model in equation 3.45 for actuator delay compensation in RTHS, which leads to:

$$G_c(z) = \frac{X^c(z)}{X^d(z)} = \frac{\alpha z - (\alpha - 1)}{z}$$  \hspace{1cm} (3.46)

Applying the inverse discrete $z$-transform (Chen and Ricles, 2008) to Equation 3.46 provides the inverse compensation equation used in the study, which is expressed as:

$$d_{i+1}^c = \alpha d_{i+1}^d - (\alpha - 1)d_i^d$$  \hspace{1cm} (3.47)

Chen and Ricles (2012) applied this method to RTHS of the structure with elastomeric damper and good actuator tracking was observed.

### 3.4.3 Adaptive Inverse Compensation Method (AIC)

The IC method, which is explained in section 3.4.2, assumes constant actuator delay. However, the delay may vary during dRTHS due to mainly the inconsistent data transmission rate between computers through internet. Chen and Ricles (2012) proposed an adaptive control mechanism to minimize the effects of varying time delay.

As an addition to the IC method, an adaptive parameter $\Delta \alpha$ is used in every time step. Equation 3.46 is modified for AIC with the use of $\Delta \alpha$ to consider varying delay, as shown in equation 3.48.

$$G_c(z) = \frac{X^c(z)}{X^d(z)} = \frac{(\alpha + \Delta \alpha)z - (\alpha + \Delta \alpha - 1)}{z}$$  \hspace{1cm} (3.48)
where $\alpha$ is the initial estimation of the actuator delay. Applying the inverse discrete $z$-transform to equation 3.48 leads to the AIC equation (Chen and Ricles, 2008):

$$d_{i+1}^c = (\alpha + \Delta \alpha)d_{i+1}^d - (\alpha + \Delta \alpha - 1)d_i^d$$  \hfill (3.49)

In both equations, $\Delta \alpha$ is initially set to zero. Its value over time $t$ is then determined using the following adaptive control law:

$$\Delta \alpha(t) = k_p * TI(t) + k_i * \int_0^t TI(\tau)d\tau$$  \hfill (3.50)

where $k_p$, and $k_i$ are the proportional and integrative gains of the adaptive control law for an actuator, respectively, and $TI$ is the tracking indicator for the actuator based on the enclosed area of the hysteresis in the synchronized subspace plot, as shown in Figure 3-8, where actuator’s desired displacement $d_{i+1}^d$ is plotted against the actuator’s measured response $d_{i+1}^m$.  

$k_i/k_p$ is chosen as 0.1 in this study as suggested by Chen and Ricles (2012). In any case, selected $k_p$ and $k_i$ values should maintain the stability of the simulation. Calculation of $TI$ at each time step is formulated by Mercan (2007) as:

$$TI_{i+1} = 0.5(A_{i+1} - TA_{i+1})$$

(3.51)

where $A$ and $TA$ are the enclosed and the complementary enclosed areas of the hysteresis, which are calculated as:

$$A_{i+1} = A_i + 0.5(d_i^{m} + d_i^{l})(d_i^{m} - d_i^{m})$$

(3.52)

$$TA_{i+1} = TA_i + 0.5(d_i^{m} + d_i^{l})(d_i^{l} - d_i^{l})$$

(3.53)
Positive rate of change of the TI indicates lagging actuator response compared to the command displacement, whereas negative one corresponds to leading actuator response and additional artificial damping. Perfect actuator control is said to have been achieved if TI remains zero during whole simulation (Mercan, 2007).

The schematic implementation of the adaptive compensation is shown in Figure 3-9.

![Figure 3-9 Schematic Implementation of Adaptive Inverse Compensation (Chen and Ricles, 2012)](image)

### 3.4.4 Adaptive Time Series Compensator (ATS)

The adaptive parameters of the AIC method, $k_p$ and $k_i$, are required to be identified prior to RTHS. However, pre-defined adaptive parameters might be inaccurate at some parts of hybrid simulations due to the nonlinear response of the actuator, so the adaptive parameters need to be optimized at each time-step to yield better results (Chae, et al., 2013).

Adaptive time series compensator (ATS) differs from the AIC as relating the command and the measured displacement to update the adaptive system parameters at each time-step, which is called adaptive coefficients. It reduces the risk of unstable simulations arises from the pre-defined adaptive parameter values. To minimize the error between the desired and the measured displacements, the coefficients are updated at each time step which improves the actuator control adequacy to handle the nonlinearity of the actuator (Chae, et al., 2013).
Unlike the general delay compensation scheme, a compensated command displacement $d_i^c$ is not only the function of the desired displacement but also of the command and the measured one, which enables the computation of the coefficients in accordance with the response of the actuator. As well as other delay compensation methods, $d_i^c$ is sent to the actuator to achieve the measured displacement $d_i^m$ equal to the desired displacement $d_i^d$ or at least to minimize differences between them.

The compensated displacement command in the discrete time domain is expressed as:

$$d_i^c = a_0 d_i^d + a_1 d_i^d + a_2 d_i^d + \ldots + a_n \frac{d^n d_i^d}{dt^n}$$

(3.54)

where $a_j$ is the adaptive coefficient and $j=0,1,2, \ldots, n$, where $n$ is the number of time-derivatives used to calculate the command displacement. The $a_j$ coefficients, represented in $A$ matrix as follows, are computed at each time-step using the equation 3.56.

$$A = \begin{bmatrix} a_{0k} & a_{1k} & a_{2k} & \ldots & a_{jk} \end{bmatrix}$$

(3.55)

$$A = (X_m^T X_m)^{-1} X_m^T U_c$$

(3.56)

$X_m$ matrix includes the measured displacement values and their time derivatives over the previous $q\Delta t$. The measured displacement ($x^m$) and its time derivatives are determined using tapped delay where $q$ represents the tapped delay value.
\[ X_m = \begin{bmatrix} x^m & \dot{x}^m & \ldots & \frac{d^n}{dt^n}(x^m) \end{bmatrix} \]  

\[ x^m = \begin{bmatrix} d_{i-1}^m & d_{i-2}^m & \ldots & d_{i-q}^m \end{bmatrix}^T \]  

\( U_c \) matrix, which includes the command displacement values over the previous \( q \Delta t \), is expressed as:

\[ U_c = \begin{bmatrix} d_{i-1}^c & d_{i-2}^c & \ldots & d_{i-q}^c \end{bmatrix}^T \]  

The effects of high order time derivatives of the desired displacement values were neglected, and a second order formulation was used when calculating the command displacement in the verification test of ATS (Chae, et al., 2013). Equation 3.54, 3.55 and 3.57 are rewritten for second-order formula used in the study, which is shown between equation 3.60~3.62.

\[ d_i^t = a_0 d_i^t + a_1 \dot{d}_i^t + a_2 \ddot{d}_i^t \]  

\[ A = \begin{bmatrix} a_k & a_k & a_2 \end{bmatrix} \]  

\[ X_m = \begin{bmatrix} x^m & \dot{x}^m & \ddot{x}^m \end{bmatrix} \]

Simulink block diagram of the ATS compensator is shown in Figure 3-11. Tapped delay in the diagram, which shall be identified before each experiment to optimize the performance of the ATS, gives chance of extracting measured and command displacement values to be used in equation 3.70.
Inherent noises in actuator response signals may cause erroneous results in measured displacements when they are small. This case may lead to inaccurate results in determination of coefficients \((a_{0k}, a_{1k}, a_{2k})\) since they are calculated based on the desired and the measured displacements, and \(X_m^T X_m\) may be ill conditioned. Therefore, recommended limiting values are adopted for the coefficients as listed in Table 3-1.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Range (Minimum, Maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_{0k})</td>
<td>(0.70, 1.30)</td>
</tr>
<tr>
<td>(a_{1k})</td>
<td>(0, 0.04) sec</td>
</tr>
<tr>
<td>(a_{2k})</td>
<td>(0, 0.0008) sec(^2)</td>
</tr>
</tbody>
</table>
3.5 Summary

This chapter discussed the theoretical background of the study presented in the thesis. First, the EOM of the shear frame building model idealized as a MDOF structure model subject to earthquake induced ground motion is presented. Then, the EOM used to evaluate the dynamic response of a FWT prototype structure is explained where the FWT is idealized as 6 DOF rigid body.

Next, the substructuring and the integration algorithm used in the study are described. The three-story shear building structure was divided into a physical substructure of the first story and a numerical substructure of the upper two story, and their EOMs were derived. Then, integration algorithm methods are discussed. Due to its straightforward format with less calculations within each step when compared to the implicit one, the Newmark’s explicit integration algorithm was selected in the study to solve the EOMs of both the shear-type building structure and the FWT structure.

Lastly, delay compensation methods adopted in the study were discussed in detail. General implementation of compensation methods was introduced first and the functions of the methods in dRTHS were discussed. During dRTHS, the delay compensation methods determine command displacements so that when they are sent to the actuator to act upon, the measured displacements of the actuator will be equal to the desired displacements computed from the numerical simulation of the whole structural model (i.e., EOM). Different approaches are used to determine the command displacements for different delay compensation methods as presented in this chapter. It is worth noting that two of the four methods adopted in this study use adaptive parameters to compensate varying time delay values that might be experienced in both RTHS and dRTHS. The effectiveness of these delay compensation methods is examined numerically in Chapter 4 and experimentally in Chapter 5 of this thesis.
4 NUMERICAL SIMULATION OF THE DELAY COMPENSATION METHODS IMPLEMENTED IN DISTRIBUTED REAL-TIME HYBRID SIMULATION (DRTHS) EXPERIMENTS

4.1 Introduction

Numerical simulations of the delay compensation methods applied in dRTHS tests were carried using the MATLAB/Simulink tools, which are capable of dynamic response simulation of structural models. An idealized three-story shear frame building model was used as the prototype structure. This chapter presents the numerical simulations of dRTHS utilizing the delay compensation methods. The model investigated in the study is introduced first with structural dynamic properties. Then, the numerical simulation procedure and the dynamic responses of the numerical model when subjected to an earthquake excitation is presented.

Next, error indexes, which are used to evaluate the performance of the delay compensation methods, are defined. Numerical simulations of the structural response with a simulated time delay and without any delay compensation method were carried out and the results are presented to compare with the ones obtained with the delay compensation methods to demonstrate the effectiveness of these methods. Then, the optimization of adaptive parameters of the two compensation methods (i.e., Adaptive Inverse Compensation(AIC) and Adaptive Time Series(ATS)) are discussed.

Lastly, numerical simulations of the four delay compensation methods were carried out. For each delay compensation, error indexes and result figures are provided and the performance comparison of the four methods are discussed.

4.2 Numerical Model and Its Dynamic Responses

In the numerical simulations, a three-story shear type building was modeled in the MATLAB/Simulink and virtual RTHS were carried out which is then used to investigate the effectiveness of the delay compensation methods. The structural dynamic properties of the model,
the MATLAB/Simulink model, the earthquake excitation and the numerical simulation procedure are presented in this section.

### 4.2.1 Three-story Model and Its Properties

Figure 4-1 shows the three-story shear frame building model. As previously discussed in chapter 3.3.1, $c_{1,2,3}$, $u_{1,2,3}$ and $m_{1,2,3}$ represent the viscous damping coefficient, displacement and mass at each floor.

![Figure 4-1 Three-Story Model (3-DOF)](image)

The other six terms ($A$, $k$, $\beta$, $\gamma$, $n$ and $\alpha$) shown by the columns are the parameters of the Bouc-Wen hysteresis model that was used to define the identical restoring force of the numerical substructure, i.e., 2\textsuperscript{nd} and 3\textsuperscript{rd} stories. First story was chosen as the physical substructure, as discussed in section 3.3. Constant values were assumed for these Bouc-Wen model parameters as listed in Table 4-1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>k (kips/in)</td>
<td>0.17</td>
</tr>
<tr>
<td>β</td>
<td>0.55</td>
</tr>
<tr>
<td>γ</td>
<td>-0.15</td>
</tr>
<tr>
<td>n</td>
<td>2</td>
</tr>
<tr>
<td>α</td>
<td>0.26</td>
</tr>
</tbody>
</table>

where $k$ is the initial stiffness, $\alpha$ is ratio of post-yield stiffness $k_f$ to initial stiffness $k$. The parameter $n$ controls sharpness of the yield where redundant $A$, $\beta$ and $\gamma$ parameters describe size and shape of hysteretic loop. This redundancy creates the possibility of representing the same hysteretic loop using different combinations of these redundant parameters. Hence, $A$ was set to 1.0 and eliminated from equations in this research.

This hysteresis loop model was proposed by Bouc (1967) first and then developed by Wen later (1976), on the purpose of describing nonlinear response of a structure. Restoring force of the 2nd and 3rd stories were obtained using these equations at each-time step as:

$$
\dot{z} = A\dot{u} - \beta|\dot{u}|^{\alpha-1}z - \gamma|\dot{u}|^\gamma
$$

(4.1)

$$
f_s = k\alpha u + (1 - \alpha)kz
$$

(4.2)

where $f_s$ is the restoring force and $z$ is the hysteretic displacement. Equation 4.1 is a differential equation and the initial condition of $z$ is equal to 0 at time zero. All connections of the model were fully restrained from rotation, so the model can be idealized to three degrees of freedom (DOF) where each story moves only in the lateral direction, for the dynamic analysis performed herein. Lumped mass of 0.003 kip-sec$^2$/in was assumed at each story level and a damping ratio, $\zeta$ of 5% was assigned to the first two modes. Structural properties and the numerical simulation parameters are listed in Table 4-2. Newmark explicit integration algorithm parameters were adopted.
To start the time history analysis, model parameters were defined in the initializing MATLAB script and saved in the work space. Natural frequencies and vibration modes, as listed in Table 4-3 were determined based on the mass and the initial stiffness matrices that are shown in equations 4.3 and 4.4. In equation 4.4, $k_{1,2,3}$, equals to 0.17 k/in, which is the stiffness of the physical substructure (1st story) and the initial stiffness of the numerical substructure (2nd and 3rd story).

\[
M = \begin{bmatrix}
m_1 & 0 & 0 \\
0 & m_2 & 0 \\
0 & 0 & m_3 \\
\end{bmatrix} = \begin{bmatrix}
0.003 & 0 & 0 \\
0 & 0.003 & 0 \\
0 & 0 & 0.003 \\
\end{bmatrix} \text{kip.sec}^2/\text{in}
\] (4.3)

\[
K = \begin{bmatrix}
k_1 + k_2 & -k_2 & 0 \\
0 & k_2 + k_3 & -k_3 \\
0 & -k_3 & k_3 \\
\end{bmatrix} = \begin{bmatrix}
0.34 & -0.17 & 0 \\
-0.17 & 0.34 & -0.17 \\
0 & -0.17 & 0.17 \\
\end{bmatrix} \text{k/in}
\] (4.4)
Table 4-3 Dynamic Properties of Model

<table>
<thead>
<tr>
<th>Notation</th>
<th>Circular Natural Frequencies $\omega_n$ (rad/sec)</th>
<th>Natural Periods $T_n$ (sec)</th>
<th>Natural Frequencies $f_n$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Mode</td>
<td>3.35</td>
<td>1.88</td>
<td>0.53</td>
</tr>
<tr>
<td>Second Mode</td>
<td>9.39</td>
<td>0.67</td>
<td>1.49</td>
</tr>
<tr>
<td>Third Mode</td>
<td>13.56</td>
<td>0.46</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Then, the damping matrix was calculated based on the Rayleigh damping whose coefficients were determined first using equations 3.3 and 3.4. Using the Rayleigh damping formula shown in equation 3.2, the damping matrix of the structural model is given in equation 4.5.

$$
\mathbf{C} = \begin{bmatrix}
0.0034 & -0.0013 & 0 \\
-0.0013 & 0.0034 & -0.0013 \\
0 & -0.0013 & 0.0013
\end{bmatrix} \text{ kips.sec/in}
$$

(4.5)

where $\omega_1$ and $\omega_2$ are natural frequency of first and second modes, respectively.

### 4.2.2 Numerical Simulation Procedure

MATLAB/Simulink was used to simulate the dynamic responses of the three-story building model subject to an earthquake excitation. First, MATLAB was utilized to create an initial file containing the model parameters and the parameters used in the integration algorithm and the delay compensation equations.

Figure 4-2 shows the Simulink model where the Newmark explicit integration was utilized to solve the EOM. In the prediction step, displacement and velocity values of the current step are calculated using equations 3.23 and 3.24, then the velocity is updated in the correction step using 3.25.
The restoring force values were calculated for the 2nd and 3rd stories using the Bouc-Wen hysteresis model, which is mentioned in section 4.2.1. Predicted velocity and displacement values are taken as the inputs along with the Bouc-Wen parameters, as shown in Figure 4-3.
Simultaneously, the predicted displacement and velocity values were used in obtaining the restoring force of the 1st story, the physical substructure selected in the dRTHS experiments, as shown in Figure 4-4. Assuming the experimental structure in linear range, the restoring force was calculated at each time-step using the assumed stiffness value (0.17 kips/in).

4.2.3 Earthquake Record and Dynamic Response

The Northridge earthquake record was selected as the input ground motion where it was scaled to 1/5 in this study, as shown in Figure 4-5.
The dynamic response of the three-story model subject to this earthquake input was numerically simulated using the Newmark explicit integration algorithm in the MATLAB/Simulink, where the displacement responses of the three stories are shown in Figure 4-6.
4.3 Optimization of Adaptive Simulation Parameters

AIC and ATS are two delay compensation methods with adapting parameters which affect compensation effectiveness. In this section, adaptive parameters were selected and evaluated for the AIC and ATS methods to optimize their values and improve the accuracy of the methods in the numerical simulations.

4.3.1 Delay Model

Before starting the numerical simulations of the delay compensation methods, estimated delay value in the Simulink model, \( \alpha \) in Figure 4-7, was chosen as 40 time-steps. This value was selected through several open-loop dRTHS tests where the average total delay value was observed as 0.04 second, i.e., 40 time-steps when the time step was 0.001 second. The delay was constant in the numerical simulations so the varying delay effects in the dRTHS were not investigated.

Firstly, a numerical simulation was conducted without delay compensation. Maximum control error, \( CE_{\text{max}} \), which is the largest difference between the desired and the measured displacement, were determined using equation 4.6.

![Figure 4-7 Restoring Force Model with Estimated Delay](image)
\[ CE_{\text{max}} = \max_i \left| d_i^d - d_i^m \right| \]  

(4.6)

where \( d_i^d \) and \( d_i^m \) represents desired and measured displacement values for time step \( i \).

Error norm, based on the difference between desired and measured displacement values, is formulated in equation 4.7. These two indexes are utilized to investigate the effectiveness of the delay compensation methods.

\[
\text{Error Norm} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ d_i^d - d_i^m \right]^2}
\]  

(4.7)

Table 4-4 lists the maximum desired displacement and the error indexes of the numerical simulation without delay compensation.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, ( dd_{\text{max}} ) (in)</th>
<th>Maximum Control Error, ( CE_{\text{max}} ) (in)</th>
<th>( CE_{\text{max}} / dd_{\text{max}} ) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No Compensation</td>
<td>0.7494</td>
<td>0.2462</td>
<td>32.86</td>
<td>34.90</td>
</tr>
</tbody>
</table>

Measured and desired displacement and closed-up views for maximum and minimum values are plotted in Figure 4-8~ 4-10. The results show large errors when delay compensation methods were not utilized in numerical simulations.
Figure 4-8- Desired and Measured Displacements for No Compensation

Figure 4-9 Maximum Desired and Measured Displacements for No Compensation (Close-up View)
The performance and the accuracy of the AIC method was evaluated using different $k_i$ and $k_p$, whose values affect the adaptive parameter $\Delta \alpha$ (see equation 3.50). Thus, optimizing these parameters may lead the best delay compensation results. The ratio of $k_i/k_p$ was set to 0.1, as suggested by Chen and Ricles (2010). The $TI$ and $\Delta \alpha$ values were determined when $k_p=0, 0.2, 0.4, 1, 2, 3, 4, 5, 7, 10, 100, 1000$. The relationship between $TI$ and $\Delta \alpha$ is expressed in equation 3.58. $TI$ for different $k_p$ values are plotted in Figure 4-11 and Figure 4-12, where the latter shows the closed-up view for $k_p$ values up to 10.
Δα for different $k_p$ values are plotted in Figure 4-13 and Figure 4-14, where the latter shows the closed-up view for $k_p$ less than 5.
It was observed that the stability of the simulation was maintained for each $k_p$ values. Hence, the error norm results were used to optimize the $k_p$ value. The error indexes calculated for different $k_p$...
values are listed in Table 4-5. The results show that the least error norm was obtained when $k_p = 2$ (see bold numbers in the table), which was used later in the numerical simulation of AIC.

<table>
<thead>
<tr>
<th>$k_p$</th>
<th>Maximum Desired Displacement, $dd_{max}$ (in)</th>
<th>Maximum Control Error, $CE_{max}$ (in)</th>
<th>$CE_{max}/dd_{max}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.7355</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>0.1</td>
<td>0.7354</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>0.2</td>
<td>0.7354</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>0.4</td>
<td>0.7353</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>1</td>
<td>0.7351</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>2</td>
<td><strong>0.7347</strong></td>
<td><strong>0.0332</strong></td>
<td><strong>4.51</strong></td>
<td><strong>2.92</strong></td>
</tr>
<tr>
<td>3</td>
<td>0.7343</td>
<td>0.0332</td>
<td>4.52</td>
<td>2.92</td>
</tr>
<tr>
<td>4</td>
<td>0.7339</td>
<td>0.0332</td>
<td>4.52</td>
<td>2.92</td>
</tr>
<tr>
<td>5</td>
<td>0.7335</td>
<td>0.0332</td>
<td>4.52</td>
<td>2.92</td>
</tr>
<tr>
<td>7</td>
<td>0.7328</td>
<td>0.0332</td>
<td>4.52</td>
<td>2.92</td>
</tr>
<tr>
<td>10</td>
<td>0.7318</td>
<td>0.0332</td>
<td>4.53</td>
<td>2.93</td>
</tr>
<tr>
<td>100</td>
<td>0.7197</td>
<td>0.0332</td>
<td>4.61</td>
<td>3.05</td>
</tr>
<tr>
<td>1000</td>
<td>0.7247</td>
<td>0.0399</td>
<td>5.50</td>
<td>3.26</td>
</tr>
</tbody>
</table>

### 4.3.3 Adaptive Time Series Compensator (ATS)

Tapped delay value, defined in Section 3.4.4., is used in the ATS method to delay the measured displacement, velocity and acceleration values with the selected sample periods and output all the delay versions. Tapped delay value affect the ATS coefficients which are updated at each time step, as discussed in section 3.4.4.

A series of numerical simulations were conducted with different tapped delay values to find its optimum value. Maximum control error and error norm values were calculated. As can be seen from Table 4-6, minimum error norm was obtained when the tapped -delay is 1250. Hence, a tapped delay of 1250 was utilized in the ATS method in the following numerical simulation.
<table>
<thead>
<tr>
<th>Tapped Delay</th>
<th>Maximum Desired Displacement, (dd_{max}) (in)</th>
<th>Maximum Control Error, (CE_{max}) (in)</th>
<th>(CE_{max}/dd_{max}) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.7646</td>
<td>0.2804</td>
<td>3.67</td>
<td>7.6</td>
</tr>
<tr>
<td>500</td>
<td>0.7043</td>
<td>0.0246</td>
<td>3.50</td>
<td>2.37</td>
</tr>
<tr>
<td>1000</td>
<td>0.7174</td>
<td>0.0206</td>
<td>2.87</td>
<td>2.02</td>
</tr>
<tr>
<td>1100</td>
<td>0.7158</td>
<td>0.0218</td>
<td>3.05</td>
<td>2.10</td>
</tr>
<tr>
<td>1250</td>
<td><strong>0.7157</strong></td>
<td><strong>0.0211</strong></td>
<td><strong>2.95</strong></td>
<td><strong>1.97</strong></td>
</tr>
<tr>
<td>1500</td>
<td>0.7134</td>
<td>0.0216</td>
<td>3.03</td>
<td>2.15</td>
</tr>
<tr>
<td>2000</td>
<td>0.7139</td>
<td>0.0217</td>
<td>3.05</td>
<td>2.21</td>
</tr>
</tbody>
</table>

### 4.4 Validation of Delay Compensation Methods

Four delay compensation methods were implemented in the numerical simulations to reduce the effects of the estimated constant delay, \(\alpha\), which was selected as 40 time-steps. The error indexes were determined, and the effectiveness of the four compensation methods were compared.

#### 4.4.1 Inverse Compensation Method (IC)

Inverse compensation method (IC) was utilized to improve the accuracy of the conducted numerical simulation with introduced time delay, as shown in Figure 4-15. The discrete transfer function, shown in equation 3.46, was implemented into the numerical model and the numerical simulation was carried out.
Maximum control error and error norm are shown in Table 4-7. The error norm was dramatically reduced with the use of IC, when compared to the numerical simulation without any delay compensation method. There is more than 90% decrease in the error norm and the maximum control error.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, $dd_{\text{max}}$ (in)</th>
<th>Maximum Control Error, $CE_{\text{max}}$ (in)</th>
<th>$CE_{\text{max}}/dd_{\text{max}}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IC</td>
<td>0.7355</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Moreover, the maximum and minimum displacements are shown in Table 4-8 together with the time when they were achieved. These results show that there is larger difference between the maximum measured and the desired displacement values (2.43%) when compared to minimum ones (2.29%). Besides, the maximum desired displacement was achieved 0.021 sec before the maximum measured one where the minimum desired one was achieved 0.010 sec before the minimum measured one. These results show the efficiency of using IC delay compensation method where these differences were decreased to these values from 0.04 sec.
Table 4-8 Maximum and Minimum Displacement Values for IC

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7404</td>
<td>11.002</td>
<td>-0.8023</td>
<td>10.046</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and close-up views for maximum and minimum values are provided in Figure 4-16, Figure 4-17 and Figure 4-18. On the other hand, comparison of the delay compensation methods shows that IC yielded the worst delay compensation results, which are discussed in section 4.4.5.
4.4.2 Adaptive Inverse Compensation Method (AIC)

Adaptive inverse compensation (AIC) method, which modifies from IC with adaptive parameters to consider the varying actuator and Internet delay, was implemented into the Simulink model (see Figure 4-19) and the numerical simulation was conducted.
Equation 3.49~3.53 were utilized to obtain compensated command displacement, as shown in Figure 4-20.

The control error and error norm are listed in Table 4-9. The results clearly show that there is almost no change in error indexes when it is compared to IC, which means that the adaptive
parameters do not improve the accuracy when the delay is constant. Using adaptive parameters may be more effective where the delay varies in wide range, like experienced in dRTHS experiments.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, (dd_{\text{max}}) (in)</th>
<th>Maximum Control Error, (CE_{\text{max}}) (in)</th>
<th>(CE_{\text{max}}/dd_{\text{max}}) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AIC</td>
<td>0.7347</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Maximum and minimum displacement values are shown in Table 4-10, where it also shows the time when they were achieved. The differences between the measured and desired displacement values are smaller than the IC method (2.17% in maximum and 2.13% in minimum). On the other hand, the maximum desired displacement was achieved 0.024 sec before the maximum measured where the minimum desired one was achieved 0.011 sec before the minimum measured one, where the difference in delay values are larger than the difference of the IC method. The results show that using the adaptive parameters do not improve the accuracy of delay compensation when the delay is constant.

<table>
<thead>
<tr>
<th>Desired</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Displacement(in)</td>
<td>0.7228</td>
</tr>
<tr>
<td>Time When It Reaches to Maximum (sec)</td>
<td>11.025</td>
</tr>
<tr>
<td>Minimum Displacement(in)</td>
<td>-0.7843</td>
</tr>
<tr>
<td>Time When It Reaches to Minimum (sec)</td>
<td>10.056</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and close-up views for maximum and minimum values are plotted in Figure 4-21, Figure 4-22 and Figure 4-23. The results clearly show the effectiveness of AIC when compared to no compensation case.
Figure 4-21 Desired and Measured Displacements for AIC

Figure 4-22 Maximum Displacement Values of Desired and Measured Displacements (Close-up) for AIC
4.4.3 Modified Feedforward Method (MFF)

Modified feedforward (MFF) compensation method, presented in section 3.4.3., was implemented into the numerical model as shown in Figure 4-24, where $MFF1$, $MFF2$ and $MFF3$ are the coefficients of the three terms in the equation.

Control error and error norm values are shown in Table 4-11. The error norm was greatly reduced around 80% with the use of the MFF, when compared to the IC and AIC. The results show that...
the MFF method provided nearly identical measured displacement values throughout the simulation.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, $d_{d_{\text{max}}}$ (in)</th>
<th>Maximum Control Error, $C_{E_{\text{max}}}$ (in)</th>
<th>$C_{E_{\text{max}}}/d_{d_{\text{max}}}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MFF</td>
<td>0.7205</td>
<td>0.0091</td>
<td>1.27</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Maximum and minimum displacement values are shown in Table 4-12 where the table also shows the time when they were achieved. There are very small differences between the measured and the desired displacement values, as 0.19% errors in the maximum and 0.23% in the minimum values, which are a lot better than the AIC and IC method. Moreover, maximum measured and desired displacement values were achieved almost at almost the same time where the difference is only 0.007 sec.

<table>
<thead>
<tr>
<th>Maximum Displacement(in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement(in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7214</td>
<td>11.024</td>
<td>-0.7825</td>
</tr>
</tbody>
</table>

Figure 4-25, Figure 4-26 and Figure 4-27 shows plots for measured and desired displacement, and close-up views for the maximum and minimum values, respectively. The difference between the desired and measured displacement values was only considerable around the minimum displacement, where it was observed that the MFF method provided almost identical measured displacement values after achieving the minimum point. Moreover, MFF yielded the best delay compensation results when compared to the AIC and IC methods.
Figure 4-25 Desired and Measured Displacements for MFF

Figure 4-26 Maximum Displacement Values of Desired and Measured Displacements (Close-up) for MFF
4.4.4 Adaptive Time Series Compensator (ATS)

Adaptive time series compensator (ATS) method, presented in section 3.4.4, was implemented to the numerical model (see Figure 4-28).
Firstly, the block named subsystem 2, as shown in Figure 4-29, was evaluated to determine the parameters in equations 3.58 and 3.59. Subsystem block was used to determine the measured velocity and acceleration based on the measured displacement and velocity, respectively.

![Figure 4-29 Measurement of Velocity and Acceleration in Subsystem](image)

Then, coefficients \(a_{0k}, a_{1k}, \text{ and } a_{2k}\) were determined and stored as a matrix \(A_{coeff}\), as presented in equation 3.61 and shown in Figure 4-30.

![Figure 4-30 Determination of Coefficients Used in Command Displacement Calculations](image)
Finally, the equation 3.60 was applied in the numerical model as shown in Figure 4-31.

Control error and error norm values are shown in Table 4-13. The error norm was reduced with the use of ATS when compared to the IC and AIC (0.33%). The results show that using the second-order formulation of equation 3.60, may provide accurate results when ATS is utilized to compensate the constant delay.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, $dd_{\text{max}}$ (in)</th>
<th>Maximum Control Error, $CE_{\text{max}}$ (in)</th>
<th>$CE_{\text{max}}/dd_{\text{max}}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ATS</td>
<td>0.7157</td>
<td>0.0211</td>
<td>2.95</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Maximum and minimum displacement values are shown in Table 4-14 where the table also shows the time when they were achieved. When compared to IC and AIC methods, the differences are smaller between the measured and desired displacement values, as there are 1.23% difference in maximum and 1.68% difference in minimum values. The results prove that the ATS yield better delay compensation results than the AIC and IC method. Moreover, minimum measured displacement was achieved 0.006 sec before the desired one where the maximum measured displacement was achieved 0.005 sec before the desired minimum one. Figure 4-32, Figure 4-33 and Figure 4-34 show the measured and desired displacement, and close-up views of the maximum and minimum values, respectively. According to the plots and the table, ATS provided very accurate results at the extremum points, when compared to the AIC, IC and no compensation cases.
### Table 4-14 Maximum and Minimum Displacement Values for ATS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7139</td>
<td>11.020</td>
<td>-0.7711</td>
<td>10.050</td>
</tr>
</tbody>
</table>

**Figure 4-32 Desired and Measured Displacement Values for ATS**
4.4.5 Comparison Between Compensation Methods

The delay compensation methods and their effectiveness are compared where the comparison plot and close-up views are shown in Figure 4-35 and Figure 4-37. The plots show that MFF and ATS
yielded the good compensation results where MFF was the most effective delay compensation method in the numerical simulations when the delay is constant.

MFF computed the command displacement values that led to the measured displacements almost identical to the desired ones. This good performance may be explained by equation 3.43, where the MFF computes command displacements based on the desired displacement values of the previous two steps. Also, the results show that the second order formula used in the ATS method provided accurate responses in numerical simulations, so neglecting higher order time derivatives did not adversely affect the delay compensation performance when the delay is constant.

![Figure 4-35 Comparison of Delay Compensation Methods](image-url)
The results clearly show that there is almost no change in error indexes for the AIC when compared to IC, which demonstrates that the adaptive parameters may not be efficient in improving the accuracy in the constant-delay case. Using adaptive parameters may be more effective where the delay varies in a wide range, like being seen in the dRTHS experiments.
In the numerical simulations with constant delay, AIC yielded the nearly the same compensation results as IC. Moreover, optimizing adaptive parameters of AIC shows that AIC yielded less accurate results for some \( k_p \) values, which shows that using adaptive parameters may provide more accurate results, but the improvement is not assured. To improve the accuracy of the adaptive delay compensation methods, the optimal adaptive parameters shall be identified before conducting numerical simulations and dRTHS experiments.

Table 4-15 lists the maximum control error and error norm results of the numerical simulations out of the four delay compensation methods. According to these error indexes, MFF is the most effective delay compensation method. Moreover, there is more than 90% decrease in error indexes when the delay compensation methods were utilized in the numerical simulations compared to the case of no compensation method.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Desired Displacement, ( dd_{\text{max}} ) (in)</th>
<th>Maximum Control Error, ( CE_{\text{max}} ) (in)</th>
<th>( CE_{\text{max}}/dd_{\text{max}} ) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No Compensation</td>
<td>0.7494</td>
<td>0.2462</td>
<td>32.86</td>
<td>34.90</td>
</tr>
<tr>
<td>IC</td>
<td>0.7355</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.93</td>
</tr>
<tr>
<td>AIC</td>
<td>0.7347</td>
<td>0.0332</td>
<td>4.51</td>
<td>2.92</td>
</tr>
<tr>
<td>MFF</td>
<td><strong>0.7205</strong></td>
<td><strong>0.0091</strong></td>
<td><strong>1.27</strong></td>
<td><strong>0.58</strong></td>
</tr>
<tr>
<td>ATS</td>
<td>0.7157</td>
<td>0.0211</td>
<td>2.95</td>
<td>1.97</td>
</tr>
</tbody>
</table>
4.5 Summary

In this chapter, three-story shear frame building model was used in the numerical investigation of the four delay compensation methods. Idealized structural model parameters are provided including the mass, initial stiffness and damping matrices. Bouc-Wen hysteresis model was used to find the restoring force in the building model.

Numerical simulation was first conducted without delay compensation. Inaccurate responses were obtained due to the accumulated error since the delay was not compensated. The results show the necessity of implementing a system that considers delay and performs to compensate this. Then, the adaptive parameters of the AIC and ATS methods were examined to find the optimum values to be used in the numerical simulations. It was observed that the AIC method yielded worse results than IC for some selected adaptive parameters revealing that the delay compensation method may improve dRTHS results, but it is not guaranteed. The adaptive parameters shall be identified before numerical simulations to optimize the performance of these adaptive delay compensation methods.

Finally, four different delay compensation methods were implemented, and the numerical simulations were carried out. The error norm results proved the efficiency of the delay compensation methods in this constant delay case, where more than 90% decrease in the error was obtained for each method when compared to errors from the no compensation case. Moreover, MFF method yielded the best compensation results, where the method computed the command displacement values that made the measured displacement values almost identical to the desired ones. It was observed that MFF took the advantage of computing the command displacement not only regarding the previous the time-step but also the two steps before the current step. Moreover, ATS yielded the second-best results in numerical simulation, which validates that neglecting the high order time derivatives does not affect the performance of ATS adversely when there is constant delay.
5 EXPERIMENTAL INVESTIGATION OF DELAY COMPENSATION METHODS FOR DISTRIBUTED REAL-TIME HYBRID SIMULATION (DRTHS)

5.1 Introduction

To implement the four delay compensation methods in DRTHS and investigate their effectiveness on improving accuracy of DRTHS results, a series of experiments were carried out at the Laboratory of Earthquake and Structural Simulation (LESS) at Western Michigan University (WMU). This chapter presents the DRTHS experiments with delay compensation methods. An overview of the experimental system is introduced first with the description of each component such as hydraulic loading equipment, test specimen, data acquisition, DRTHS platform controllers’ hardware and software.

To prepare for the physical DRTHS tests on the physical substructure (i.e., the test specimen), virtual distributed real-time hybrid simulations (vdRTHS) were carried out first to verify the feasibility of the LESS DRTHS platform, which consists of two real-time targets simultaneously performing numerical simulations of the two numerical substructures and transferring response data in-between them through the Internet communication protocol. The delay compensation methods were implemented in vdRTHS to compensate the Internet delay. Open-loop vdRTHS tests were conducted to estimate the Internet delay which is used to optimize the parameters in the delay compensation methods. Right after each open-loop test, vdRTHS tests were carried out with the delay compensation method. Results of each compensation method are presented and discussed.

DRTHS involving the hydraulic loading equipment and the test specimen were conducted using the delay compensation methods. Similar to vdRTHS, open-loop DRTHS tests were carried out to estimate the total delay (i.e., the actuator delay and the Internet delay). Then, DRTHS tests were performed and the results are analyzed and presented.
5.2 Experimental System

The dRTHS testing platform, which was recently developed at the LESS, includes the integrated software and the hardware that allow distributed numerical simulation and physical experiment equipment to perform a coordinated dRTHS experiment. The schematic diagram of the dRTHS system used in the study is presented in Figure 5-1.

In the dRTHS experiments, the testing models (including both numerical simulation and control algorithms prepared in MATLAB/Simulink and compiled to VeriStand (VS) project files) are deployed from the hybrid testing controller (HTC) to the two real-time targets, namely the PXI-RT and the PC-RT. At each time-step, the command displacement is sent from the PC-RT to the PXI-RT, which is then sent to the hydraulic controller as an external input. This data transferring path is called as the external hybrid testing connection that connects the numerical simulation to the controller of physical loading equipment. The hydraulic power supply (HPS), the hydraulic controller and the actuators, which are connected using various cables, form the hydraulic control connection that are used in open-loop type experiments such as cyclic loading tests and shaking table tests. The data acquisition (DAQ) cards embedded in the PXI-RT, on one hand, transfer commands and responses of the loading equipment (i.e., actuators) in-between the PXI-RT and the hydraulic controller. On the other hand, displacement and acceleration responses measured by the instruments installed on the testing specimen are fed back to the PXI-RT through these DAQ cards and then further sent to the PC-RT to calculate the command for the next time setup using the testing models deployed onto it.
Figure 5-1 Schematic Diagram of dRTHS System
5.2.1 dRTHS Platform Controllers

5.2.1.1 Overview of dRTHS Platform Controllers

Table 5-1 shows the dRTHS platform controllers at LESS, including their operating systems and tasks, which are discussed in the following subsections.

<table>
<thead>
<tr>
<th>Computer Name</th>
<th>Operating System</th>
<th>Software</th>
<th>Tasks</th>
</tr>
</thead>
</table>
| Host (Desktop PC)           | Windows 7        | National Instrument (NI) Veristand (VS) | 1. Configure & install Real-Time OS  
2. Configure and deploy VS Project and run its interface  
3. Post-processing measured responses  
4. Troubleshooting                                   |
| PXI-RT (PXI Chassis Controller) | PharLap          | VS Engine                          | 1. Simulate numerical sub-model  
2. Relay data  
3. Data acquisition through embedded DAQ cards  
4. Send command to hydraulic controller                      |
| PC-RT (Desktop PC)          | PharLap          | VS Engine                          | 1. Simulate numerical sub-model  
2. Relay data                                   |
| Hydraulic Controller        | Windows 7        | Shore Western SC6000               | 1. Control and calibrate the actuators based on external inputs (i.e., commands sent from the PXI-RT)  
2. Monitor the actuators’ positions and the forces                    |

5.2.1.2 Host PC and dRTHS software

The testing models used in dRTHS experiments are prepared in the host PC, which is a regular PC running Windows operating system, (see Figure 5-2), utilizing the MATLAB/Simulink programming tools and the NI tool sets, such as the VS, the Reflective Ethernet and the Measurement and Automation Explorer (NI-MAX).

To prepare a dRTHS experiment, the PXI-RT and the PC-RT needs to be configured in the host PC. The NI Veristand software, and the related hardware drivers are installed on these real-time targets using the NI-MAX. Prior to each vD RTHS and dRTHS experiment, the host PC builds the Simulink models and creates the VS project. To provide the connections between the real-time targets, Reflective Ethernet custom device is utilized to create channels for sending and receiving
data between the targets. Then, the VS projects are deployed to the PC-RT and the PXI-RT to be executed during dRTHS. In addition to preparing a dRTHS as described above, the host PC is also utilized during the experiments to trigger the simulation and control its process, as discussed in section 5.2.1.6.

![Figure 5-2 Host PC](image)

### 5.2.1.3 PXI-RT with Embedded Data Acquisition (DAQ) Card

The PXI-RT, the real-time target configured through NI MAX using the host PC, is shown in Figure 5-3. Real-time processing required for vdRTHS and the dRTHS tests are provided using the NI PXI-1050 chassis system in the PXI-RT.
The NI PXI-1050 chassis system, including a 2.53 GHz Dual Core real-time processor (NI PXI-8108) and two DAQ cards (NI PXI-6229 Multifunctional M Serie), enables real-time processing and data transferring defined in the VS projects. Each DAQ card consists of 16-bit 32 analogue inputs, 3 analogue outputs, and 48 digital input/output channels to transfer command signals and instruments/measurements between the physical test setup and the numerical simulation. Specifically, the commands and responses of the hydraulic loading equipment are transferred between the DAQ and the SC6000 using the NI shielded connector block (SBC-68).

5.2.1.4 Hydraulic Controller (SC6000)

The Shore Western Control System employed in the dRTHS platform as the hydraulic controller, consists of both controlling hardware (i.e., Servo control chassis) and software (i.e., SC6000) to perform basic control of the hydraulic loading system. During dRTHS, the hydraulic controller receives the command from the PXI-RT as an external input and drives the actuator to the command displacement. Meanwhile, it receives the responses of the actuators measured by their embedded load cells and the linear variable differential transducers (LVDT).
5.2.1.5 PC-RT

To enable dRTHS experimental capabilities at LESS, a regular PC, as shown in Figure 5-5, is converted as the other real-time target (i.e., PC-RT) through the installation of the NI PharLap operating system and the VS with the related drivers using the NI MAX.

During vdRTHS and the dRTHS experiments, the PC-RT simulates the responses of the numerical substructure and performs delay compensation methods to determine the command displacement that are then sent to the PXI-RT through the TCP/IP connection, as discussed in the introduction of section 5.2. Meanwhile, the PC-RT receives the responses of the physical substructure fed back from the PXI-RT to compute the command of the next time-step.
5.2.1.6 Communication Between the Controllers

The TCP/IP connection is used in the dRTHS experiments to transmit data between the real-time targets and the host PC. The data transfer is enabled using the MAC addresses of the targets and the host PC which are connected to same Local Area Network (LAN). Moreover, the TCP/IP connection is used to transfer data over the provided network. dRTHS communication between the controllers are shown in Figure 5-6.

Prior to each vdRTHS and dRTHS experiment, a VS project is created in the host PC where the simulation model and mapping of the channels among the two targets and the hydraulic controller...
are defined. To provide the connections between the two targets in the VS project, the Reflective Ethernet custom device is utilized as a VS add-on feature. Reflective Ethernet contains configurable channels that send and receive data from the two targets as input or output. Then, the VS project is deployed to the PC-RT and the PXI-RT.

During the dRTHS experiments, the PC-RT target is selected as a remote target to simulate the numerical substructure, while the PXI-RT receives command displacement from the PC-RT through TCP/IP connection, sends it to the hydraulic controller. The hydraulic controller drives the actuator to the command displacement and receives the measured displacement and the restoring force responses from the physical substructure. Then, the responses are sent from the hydraulic controller to the PCI-RT through the PXI-RT and the command displacement of the next-step is computed. The host PC runs and controls the simulation. After dRTHS, the logged data files are sent to the host PC, which enables the evaluation of the results.

5.2.2 Testing Setup

In addition to the dRTHS platform controllers, testing setup such as the hydraulic loading equipment and test specimen (i.e, physical substructure) are necessary to perform dRTHS, as shown in Figure 5-7.
5.2.2.1 Table and Structural Actuators

The LESS has two identical actuators, namely the structural actuator and the table actuator. These actuators are embedded with the LVDT and LC which measure the actuator’s position and reaction force, respectively. Properties of the actuators are listed in Table 5-2.
The table actuator is used to drive the uniaxial shake table during a shaking table test. In the dRTHS experiments performed herein, the table actuator was under high pressure and controlled by a constant displacement command to enable the shaking table serving as a strong floor for the test specimen.

The structure actuator is attached to a steel reaction frame. On this frame, the vertical position of the structural actuator can be adjusted, via a hole pattern on the frame and a pulley, to the position where the displacement commands are intended to impose. During the dRTHS experiments, the structural actuator imposes the command displacement through the hydraulic system and the channel named EXT2, and the displacement and the restoring force responses are measured by means of LC and LVDT. Prior to each dRTHS experiment, the positions of the LVDT and the LC2 are set to zero to match the readings with the measured responses.

### 5.2.2.2 Hydraulic Power Supply (HPS)

The hydraulic power supply (HPS) with a model name of Servo Quality 10 gpm Model No. 110.11S, is used in the dRTHS experiments to send hydraulic fluid to the actuators. The HPS is shown in Figure 5-8. The HPS has a 20-horsepower(hp) electric motor, which provides an opportunity for pumping up to 10 gpm at 3000 psi (LESS, 2015). To prevent the laboratory facilities from the possible accidents, the HPS system has an emergency stop button on the
hydraulic controller chassis, which shuts down the pump immediately and keeps the pump unavailable when fixing the problem (LESS, 2015).

Figure 5-8 Hydraulic Power Supply

5.2.2.3 Test Specimen

The test specimen used as the physical substructure, shown in Figure 5-9, is a cantilever column with a height of 3 ft. The column section is HSS 3”x1.5” x 1/8 and the yield strength is 36 ksi. The column is welded to a 5”x12” steel plate with a ½” thickness. The bottom plate is installed on the shaking table with four bolts located at each corner.
Connections of the specimen are shown in Figure 5-10. Hinge is used as a connection where it is welded to the bottom plate. Two A307 steel bolts, with a 4.5” length and a ¼” diameter, are used as coupons. Movement of the bolts are restricted by fastening two nuts of each bolt. The distance between the bolts is 8”. 

Figure 5-9 Physical Specimen used in dRTHS

Figure 5-10 Physical Connections of the Specimen
Proper installation of the specimen, which is the one of the essential steps of conducting dRTHS experiments, is completed prior to each dRTHS experiment. Firstly, the specimen is fastened to the structural actuator when the actuator is at zero position. Then, the coupons are fastened to the bottom plate with the bolts and the force shall be kept at 0 when they are fastened. Finally, nuts are tightened when providing the force reading at 0.

5.3 Virtual Distributed Real-Time Hybrid Simulation (vdRTHS)

vdRTHS was carried out before the physical dRTHS involving loading equipment and test specimen to examine the numerical simulation executed in the RT target and the network communication between the computers (Mohammadi, et al., 2016). In vdRTHS, the physical substructure of the whole structural model is numerically simulated in the PXI-RT, and the remaining part of the structure (the numerical substructure) is modelled and simulated in the PCI. Data transferring between the two RT targets is realized through Internet communication. In brief, the physical substructure tested in dRTHS experiment is transformed into another virtual (numerical) substructure in vdRTHS. The vdRTHS was utilized to investigate the efficiency of the delay compensation methods in compensating the Internet delay, which varies all the time that may cause inaccurate or even unstable results.

In both vdRTHS and dRTHS experiments, the three-story shear frame building model presented in Chapter 3 was used, where the first story was selected as the physical substructure and the upper stories were the numerical substructure. Time-step of the simulation, ground motion, structural model parameters including the hysteresis restoring force model, were the same as discussed in Chapter 4. Apart from the numerical simulations, the duration of vdRTHS and dRTHS tests was set to 35 secs, to see how the responses are damped out when the ground motion stops at 30 secs. Moreover, the ground motion was scaled to 1/10 in dRTHS (compared to 1/5 in numerical simulation discussed in Chapter 4) due to the strength capacity limitation of the bolts of the specimen, which would fail when the imposed displacement values are greater than 0.6 in.

In the vdRTHS study, the PXI-RT target was utilized to receive the command displacement and send the measured displacement back. The two RT targets, the PC-RT and the PXI-RT were used
to simulate the dynamic responses of the numerical and the virtual physical substructures, respectively when the whole structural model subject to the earthquake excitation. Different from the numerical model (see Figure 4-4) used in the numerical simulations, the simulation of the virtual physical substructure (1st story) was conducted at PXI-RT. The mapping between the PC-RT and the PXI-RT is shown in Figure 5-11. The command displacement at the first story level, $D_1$, was determined at the PC-RT based on the desired displacement using delay compensation methods. Then, $D_1$ was sent from the PC-RT to the PXI-RT as the input and the measured displacement, $D_1-Mea$, was received back from the PXI-RT. In this section, received $D_1-Mea$ values are compared with the desired displacement to evaluate the performance of each method in compensating the varying Internet delay in vdRTHS. Moreover, the restoring force $F_1$ was calculated for the virtual substructure based on the assumed stiffness of the physical substructure (0.17 k/in) and sent from the PXI-RT to the PC-RT. At PC-RT, $F_1$ was utilized to compute the acceleration and the velocity response of the model at each-time step using integration algorithm, as discussed in Chapter 3.

![Figure 5-11 Mapping Between the Targets in vdRTHS](image)

Figure 5-11 Mapping Between the Targets in vdRTHS

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5.3.1 Open-Loop Virtual Distributed Real-Time Hybrid Simulation (Open-Loop vdRTHS)

Open-loop vdRTHS were conducted prior to each vdRTHS to estimate the Internet delay. As well as the vdRTHS, $D1$ was sent from the PC-RT to the PXI-RT and $D1-Mea$ was received back from the PXI-RT. In open-loop vdRTHS tests, $D1-Mea$ was compared with $D1$ to estimate the delay. On the other hand, the restoring force was determined in PC-RT based on the assumed stiffness (0.17 k/in) of the physical substructure. Since any response received from PXI-RT does not affect the simulation in PC-RT, these vdRTHS tests are called as open-loop vdRTHS test.

It was observed from these open-loop tests that the Internet delay varied so much (see Table 5-1), which was dependent on several factors, e.g. the crowd of the used server, data speed, etc. Hence, conducting consecutive tests right after each open-loop test is recommended to reduce the risk of using the obsolete delay value for the parameters of the compensation method resulting in inaccurate results. 3 vdRTHS experiments were conducted consecutively right after each open-loop vdRTHS, using the estimated Internet delay at time to optimize the performance of delay compensation. Best result of each delay compensation method was selected as discussed next.

Table 5-3 lists the estimated Internet delay values from the open-loop vdRTHS with the dates. After each open-loop test, including open-loop dRTHS tests as discussed in section 5.4.1, the command displacement and the measured displacement were plotted in the same figure, and an average delay was then estimated. Last two columns show the compensation methods and the number of tests that were carried out right after the open-loop test. The test numbers are given chronologically.
<table>
<thead>
<tr>
<th>Test No</th>
<th>Date</th>
<th>Delay (sec)</th>
<th>Conducted for</th>
<th>No of Test Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05/28/18</td>
<td>0.036</td>
<td>AIC ($k_p=0.2$)</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>05/28/18</td>
<td>0.035</td>
<td>AIC ($k_p=0.4$)</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>05/28/18</td>
<td>0.045</td>
<td>AIC ($k_p=1$)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>05/28/18</td>
<td>0.036</td>
<td>AIC ($k_p=5$)</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>05/28/18</td>
<td>0.047</td>
<td>AIC ($k_p=10$)</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>05/28/18</td>
<td>0.039</td>
<td>AIC ($k_p=100$)</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>05/28/18</td>
<td>0.036</td>
<td>AIC ($k_p=1000$)</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>05/28/18</td>
<td>0.034</td>
<td>AIC ($k_p=2000$)</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>05/28/18</td>
<td>0.06</td>
<td>IC</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>05/28/18</td>
<td>0.038</td>
<td>MFF</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>05/31/18</td>
<td>0.034</td>
<td>ATS(Delay=200)</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>05/31/18</td>
<td>0.039</td>
<td>ATS(Delay=500)</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>05/31/18</td>
<td>0.033</td>
<td>ATS(Delay=1000)</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>05/31/18</td>
<td>0.032</td>
<td>ATS(Delay=1500)</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>05/31/18</td>
<td>0.032</td>
<td>ATS(Delay=2000)</td>
<td>3</td>
</tr>
</tbody>
</table>

### 5.3.2 Best Results of Each Delay Compensation Method

In this subsection, four existing delay compensation methods developed for RTHS were investigated when they were implemented in vdRTHS tests. Best result of each delay compensation method was presented, and their performances were evaluated using the error indexes introduced in Chapter 4.

#### 5.3.2.1 Inverse Compensation Method (IC)

The IC method was implemented into the numerical Simulink model and three vdRTHS tests were carried out. The implementation of the method was discussed in section 4.4.1, where the mapping between the targets was discussed at the introduction this section.
The maximum control error $C_{E_{\text{max}}}$, and the error norm values of the three vdRTHS using the IC compensation method are shown in Table 5-4. The formulation of the maximum control error and the error norm were discussed in Section 4.3.1. The table also shows the delay used in the vdRTHS tests, which was estimated in the open-loop test (Test 9, see Table 5-3) and used as the parameter in the compensation method. According to the error indexes, variability and inconsistency of the Internet connection caused less accurate results in the 1st test, and the 3rd test was selected to be presented in this section and compared with the other compensation methods in this chapter in section 5.5.1.

Table 5-4 Maximum Control Error and Error Norm for IC vdRTHS

<table>
<thead>
<tr>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, $d_{\text{d_{max}}}$(in)</th>
<th>Maximum Control Error, $C_{E_{\text{max}}}$ (in)</th>
<th>$C_{E_{\text{max}}}/d_{\text{d_{max}}}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.7534</td>
<td>0.0403</td>
<td>5.35</td>
<td>3.14</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.7571</td>
<td>0.0376</td>
<td>4.96</td>
<td>2.99</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>0.7571</td>
<td>0.0376</td>
<td>4.96</td>
<td>2.99</td>
</tr>
</tbody>
</table>

Table 5-5 shows the maximum and minimum measured displacements from the vdRTHS and the desired displacements, where it also shows the time when they were achieved. According to the table, there is a difference of 5.32% between the maximum measured and the desired displacement and 4.28% for minimum ones. Besides, the maximum measured displacement was achieved 0.013 sec before the maximum desired one and the minimum measured displacement was achieved 0.005 sec before the minimum desired one.

Table 5-5 Maximum and Minimum Displacement Values for IC vdRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement(in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement(in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7613</td>
<td>11.012</td>
<td>-0.8179</td>
<td>10.051</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and the closed-up views of the maximum and minimum values are shown in Figure 5-12, Figure 5-13 and Figure 5-14. The method generally compensated delay properly except the extremum points, where the relatively larger differences might be explained using equation 3.47. As discussed in Chapter 3, the command displacement value is sent to the virtual physical substructure and the value is measured after n time-step, where n is the delay.
value. In the equation, the command displacement is computed based on the difference between the desired displacement values of the actual last step and one step before that. However, the method is not able to predict when the sign of the difference changes, which might cause inaccuracy at the extremum points.

Figure 5-12 Desired and Measured Displacements for IC vdRTHS
5.3.2.2 Adaptive Inverse Compensation Method (AIC)

The AIC method, proposed based on the IC method to compensate varying delay with adaptive parameters, was implemented in the Simulink for the vdRTHS tests. Compared to the IC method,
the measured displacement value, $D1-Mea$, was fed back to the numerical simulation in the PC-RT at each time-step since AIC uses the measured displacement to determine the adaptive delay parameter $\Delta \alpha$ during the test. The implementation of the method was discussed in section 4.4.2.

Three consecutive vdRTHS tests were conducted for the selected $k_p$ values, as shown in Table 5-6. The error indexes and the estimated delay used in the vdRTHS tests are also listed in the table. To estimate the delay, open-loop tests were conducted prior to vdRTHS tests, which are shown in Table 5-3. According to the error index results, the best performance of the AIC was achieved when $k_p = 5$. Thus, the test was selected to be presented in this section and compared with the other compensation methods in section 5.5.1.
Table 5-6 vDRTHS Tests Conducted for AIC vDRTHS

<table>
<thead>
<tr>
<th>k_p</th>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, dd_{max} (in)</th>
<th>Maximum Control Error, CE_{max} (in)</th>
<th>CE_{max}/dd_{max} (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1</td>
<td>0.036</td>
<td>0.6786</td>
<td>0.0477</td>
<td>7.03</td>
<td>4.67</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.036</td>
<td>0.736</td>
<td>0.0498</td>
<td>6.77</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.036</td>
<td>0.8161</td>
<td>0.0665</td>
<td>8.14</td>
<td>6.02</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>0.035</td>
<td>0.8243</td>
<td>0.0698</td>
<td>8.47</td>
<td>6.36</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.035</td>
<td>0.8243</td>
<td>0.0698</td>
<td>8.47</td>
<td>6.36</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.035</td>
<td>0.8242</td>
<td>0.0698</td>
<td>8.47</td>
<td>6.36</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.045</td>
<td>0.7472</td>
<td>0.0527</td>
<td>7.05</td>
<td>4.03</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.045</td>
<td>0.7472</td>
<td>0.0528</td>
<td>7.06</td>
<td>4.03</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.045</td>
<td>0.6863</td>
<td>0.0474</td>
<td>6.90</td>
<td>4.81</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.036</td>
<td>0.7351</td>
<td>0.034</td>
<td>4.62</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.036</td>
<td>0.7348</td>
<td>0.034</td>
<td>4.63</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.036</td>
<td>0.8027</td>
<td>0.066</td>
<td>8.22</td>
<td>5.53</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.047</td>
<td>0.7481</td>
<td>0.0373</td>
<td>4.98</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.047</td>
<td>0.8098</td>
<td>0.0737</td>
<td>9.10</td>
<td>5.98</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.047</td>
<td>0.7481</td>
<td>0.0732</td>
<td>4.97</td>
<td>2.8</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>0.039</td>
<td>0.7137</td>
<td>0.0344</td>
<td>4.82</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.039</td>
<td>0.713</td>
<td>0.0551</td>
<td>7.73</td>
<td>4.65</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.039</td>
<td>0.7137</td>
<td>0.0344</td>
<td>4.82</td>
<td>3.13</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>0.036</td>
<td>0.7179</td>
<td>0.0383</td>
<td>5.34</td>
<td>3.08</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.036</td>
<td>0.7179</td>
<td>0.0383</td>
<td>5.34</td>
<td>3.08</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.036</td>
<td>0.7198</td>
<td>0.0689</td>
<td>9.57</td>
<td>4.81</td>
</tr>
<tr>
<td>2000</td>
<td>1</td>
<td>0.034</td>
<td>0.7165</td>
<td>0.0381</td>
<td>5.32</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.034</td>
<td>0.7165</td>
<td>0.0382</td>
<td>5.33</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.034</td>
<td>0.7141</td>
<td>0.0773</td>
<td>10.82</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Maximum and minimum values of the measured displacement achieved at the vDRTHS test and the desired displacement determined by the numerical simulation are listed in Table 5-7, where it also shows the time when they were achieved. The differences between the measured and the desired displacement values are 2.24% in maximum and 2.13% in minimum. The maximum measured displacement was achieved 0.021 sec before the maximum desired one where the minimum measured one was achieved 0.003 sec before the minimum desired one.
Table 5-7 Maximum and Minimum Displacement Values for AIC vdRTHS

<table>
<thead>
<tr>
<th>Desired</th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7390</td>
<td>11.004</td>
<td>-0.8010</td>
<td>10.053</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and the close-up views for maximum and minimum values are plotted in Figure 5-15, Figure 5-16 and Figure 5-17. It was observed that the method generally compensated the delay properly except when the responses reached to the extremum points, which was discussed in section 5.3.2.2.
Figure 5-16 Maximum Desired and Measured Displacements (Close-up) for AIC vdRTHS

Figure 5-17 Minimum Desired and Measured Displacements (Close-up) for AIC vdRTHS
5.3.2.3 Modified Feedforward Method (MFF)

The MFF was utilized in vdRTHS experiments to compensate the delay. The method was implemented into the Simulink model as discussed in section 4.4.3. The mapping between the targets was presented at the introduction of this section.

Three tests were conducted repeatedly for the MFF, as shown in Table 5-8. The Internet delay value, which was estimated at the open-loop test (Test 10, see Table 5-3), was selected as the actual constant delay in the vdRTHS tests. According to the error indexes shown in Table 5-8, the best performance of the MFF was achieved at the 1\textsuperscript{st} and the 3\textsuperscript{rd} tests. Moreover, inconsistent Internet delay causes worse results in Test 2, when the actual delay determined at open-loop test was not same as the one during the vdRTHS. Test 1 was selected for presentation and comparison in this chapter.
Table 5-8 vdRTHS Tests Conducted for MFF vdRTHS

<table>
<thead>
<tr>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, $\text{dd}_{\text{max}}$ (in)</th>
<th>Maximum Control Error, $\text{CE}_{\text{max}}$ (in)</th>
<th>$\text{CE}<em>{\text{max}}/\text{dd}</em>{\text{max}}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.038</td>
<td>0.7776</td>
<td>0.0448</td>
<td>5.76</td>
<td>3.43</td>
</tr>
<tr>
<td>2</td>
<td>0.038</td>
<td>0.7792</td>
<td>0.0485</td>
<td>6.22</td>
<td>3.54</td>
</tr>
<tr>
<td>3</td>
<td>0.038</td>
<td>0.7776</td>
<td>0.0448</td>
<td>5.76</td>
<td>3.43</td>
</tr>
</tbody>
</table>

Table 5-9 shows the maximum and minimum values of the measured displacement and the desired displacement, where it also shows the time when they were achieved. The maximum displacement values were achieved with 0.007 sec difference where there is 0.004 sec difference between the minimum ones. However, the differences between measured and desired displacement values, as 7.71% for maximum and 5.72% for minimum ones.

Table 5-9 Maximum and Minimum Displacement Values for MFF vdRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>0.7786</td>
<td>11.032</td>
<td>-0.8292</td>
<td>10.052</td>
</tr>
</tbody>
</table>

Figure 5-18, Figure 5-19 and Figure 5-20 show the plots for measured and desired displacement, and the closed-up views of maximum and minimum values, respectively. When the whole simulation plot was investigated, it was observed that the method yielded worse compensation results when the responses reached to the extremum points, which might be explained with equation 3.43. The MFF coefficients include the square of the actuator delay constant ($\alpha^2$), which may provide inaccurate results when the delay varies in very wide range, like the Internet delay in the vdRTHS tests.
Figure 5-18 Desired and Measured Displacements for MFF vdRTHS

Figure 5-19 Maximum Desired and Measured Displacements (Close-up) for MFF vdRTHS
5.3.2.4 Adaptive Time Series Compensator (ATS)

The ATS method was implemented into the Simulink model for vdRTHS tests. The implementation of the method was discussed in section 4.4.4. As well as the AIC method, the adaptive parameters are utilized to compensate the varying delay. In addition to the mapping of vdRTHS discussed at the introduction of this section, $D1_{-Mea}$ and $D1$ were fed back to the numerical simulation in the ATS method to compute the adaptive parameters at each time-step.

Three consecutive tests were conducted for each selected tapped delay values, as shown in Table 5-10. Open-loop tests were conducted prior to the vdRTHS tests and Internet delay values were estimated, which are also listed in the table. According to the results, the optimal performance of ATS was achieved when the tapped delay was 500. Results of the consecutive three tests are almost identical for this tapped delay value. 1$^{st}$ test, which has less maximum control error than the others, was selected to be presented and compared with the other compensation methods.
Table 5-10 ATS vdRTHS Test Results for Selected Tapped Delay Values

<table>
<thead>
<tr>
<th>Tapped Delay</th>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, ( dd_{\text{max}} ) (in)</th>
<th>Maximum Control Error, ( CE_{\text{max}} ) (in)</th>
<th>( CE_{\text{max}}/dd_{\text{max}} ) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1</td>
<td>0.034</td>
<td>0.9812</td>
<td>0.8117</td>
<td>82.73</td>
<td>82.30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.034</td>
<td>0.9807</td>
<td>0.8114</td>
<td>82.74</td>
<td>82.28</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>0.039</td>
<td>0.9733</td>
<td>0.1931</td>
<td>19.84</td>
<td>17.93</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.039</td>
<td>0.9733</td>
<td>0.1933</td>
<td>19.86</td>
<td>17.93</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.039</td>
<td>0.9733</td>
<td>0.1933</td>
<td>19.86</td>
<td>17.93</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>0.033</td>
<td>1.0187</td>
<td>0.1896</td>
<td>18.61</td>
<td>17.98</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.033</td>
<td>1.0187</td>
<td>0.1896</td>
<td>18.61</td>
<td>17.98</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.033</td>
<td>1.0187</td>
<td>0.1895</td>
<td>18.60</td>
<td>17.98</td>
</tr>
<tr>
<td>1500</td>
<td>1</td>
<td>0.032</td>
<td>1.1566</td>
<td>0.2953</td>
<td>25.53</td>
<td>28.63</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.033</td>
<td>1.1494</td>
<td>0.2914</td>
<td>25.35</td>
<td>27.31</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.033</td>
<td>1.1499</td>
<td>0.2918</td>
<td>25.37</td>
<td>28.28</td>
</tr>
<tr>
<td>2000</td>
<td>1</td>
<td>0.032</td>
<td>1.0219</td>
<td>0.1889</td>
<td>18.49</td>
<td>18.12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.032</td>
<td>1.0219</td>
<td>0.189</td>
<td>18.49</td>
<td>18.12</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.032</td>
<td>1.0219</td>
<td>0.1889</td>
<td>18.49</td>
<td>18.11</td>
</tr>
</tbody>
</table>

Table 5-11 shows the maximum and the minimum values of the measured displacement and the desired displacement, and the time when they were achieved. It was observed that there are significant differences between the measured and the desired displacement values, which are 52.14% in the maximum and 51.53% in the minimum values. Moreover, the maximum of the measured and the desired displacement values were achieved with 0.096 sec difference where there is 0.056 sec difference between the minimum values, which are totally erroneous.

Table 5-11 Maximum and Minimum Displacement Values for ATS vdRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>Measured</td>
<td>1.0997</td>
<td>10.929</td>
<td>-1.1885</td>
<td>10.00</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and the close-up views for maximum and minimum values are plotted in Figure 5-21, Figure 5-22 and Figure 5-23. The ATS achieved erroneous results at the extremum points. Regarding the performance of ATS in numerical simulations, it may be concluded that the second order formula used in vdRTHS experiments is not able to predict accurate command displacement values when the delay varies in wide range.
Figure 5-21 Desired and Measured Displacements for ATS vdRTHS

Figure 5-22 Maximum Desired and Measured Displacements (Close-up) for ATS vdRTHS
5.4 Distributed Real-Time Hybrid Simulation (dRTHS)

In this section, effects of the delay compensation methods when they are implemented in dRTHS experiments are investigated. The mapping between the targets and the physical substructure is shown in Figure 5-24. Differently from vdRTHS, the command displacement $D1$ was sent from the PC-RT to the PXI-RT, where the PXI-RT further sent the command displacement to the hydraulic controller SC6000 via the channel $EXT2$. The hydraulic controller then controls the actuator to impose displacement onto the physical substructure, i.e., the test specimen. Meanwhile, the measured displacement, $D1-Mea$, and the restoring force measured from the test specimen were fed back via the inverse path back to the PC-RT. At PXI-RT, the measured restoring force was scaled down to account for the assumed stiffness of the physical substructure, then sent to the PC-RT as $F1$. The restoring force and $D1-Mea$ were measured through $LC2$ and $LVDT2$, respectively. Moreover, the displacement measured at the PXI-RT, $D1-Mea1$, was also sent to the PC-RT to check the Internet delay if needed. Finally, $F1$ was utilized in the PC-RT to compute the velocity and the acceleration response of the model at each-time step through the integration algorithm.
5.4.1 Open-Loop Distributed Real-Time Hybrid Simulation (Open-Loop dRTHS)

Before conducting dRTHS experiments, open-loop distributed tests were conducted. The same procedure of dRTHS was followed to conduct open-loop dRTHS except that the restoring force was not fed back from the test specimen to the model as inputs. Rather it was computed numerically based on the assumed stiffness value, as done in the open-loop vdRTHS experiments.

The open-loop dRTHS experiments were conducted to estimate the total delay including both the Internet and the actuator delay. The estimation procedure of the delay was discussed in section 5.3.1, where $D1-Mea$ is the displacement measured from the physical substructure in dRTHS. To estimate the Internet delay if needed, $D1-Mea1$ is compared with the desired displacement.

As well as the Internet delay, the actuator delay may also vary which increases the possible varying range of the total delay, so dRTHS has more uncertainties in this aspect when compared with vdRTHS. After each open-loop test, three dRTHS experiments were conducted consecutively. However, most ATS tests were stopped due to the unstable results. Best results of each compensation method were selected to be presented and compared in the study.
Table 5-12 lists the estimated total delay values from the open-loop dRTHS. Estimated delay values include the delay sourced from both actuator delay and the Internet delay. The procedure used to estimate the delay was discussed in section 5.3.1. Last two column shows the compensation methods and the number of tests which were carried out right after each open-loop test. The test numbers are given chronologically.
<table>
<thead>
<tr>
<th>Test No</th>
<th>Date</th>
<th>Delay (sec)</th>
<th>Conducted for</th>
<th>No of Test Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05/29/18</td>
<td>0.043</td>
<td>IC</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>05/29/18</td>
<td>0.043</td>
<td>MFF</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>06/01/18</td>
<td>0.045</td>
<td>AIC (k_p=0.2)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>06/01/18</td>
<td>0.046</td>
<td>AIC (k_p=0.4)</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>06/01/18</td>
<td>0.048</td>
<td>AIC (k_p=1)</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>06/01/18</td>
<td>0.055</td>
<td>AIC (k_p=5)</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>06/01/18</td>
<td>0.047</td>
<td>AIC (k_p=10)</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>06/01/18</td>
<td>0.048</td>
<td>AIC (k_p=100)</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>06/01/18</td>
<td>0.053</td>
<td>AIC (k_p=1000)</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>06/01/18</td>
<td>0.045</td>
<td>AIC (k_p=2000)</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>06/01/18</td>
<td>0.043</td>
<td>ATS(Delay=200)</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>06/01/18</td>
<td>0.045</td>
<td>ATS(Delay=500)</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>06/01/18</td>
<td>0.055</td>
<td>ATS(Delay=1000)</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>06/01/18</td>
<td>0.042</td>
<td>ATS(Delay=1500)</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>06/01/18</td>
<td>0.060</td>
<td>ATS(Delay=2000)</td>
<td>3</td>
</tr>
</tbody>
</table>

### 5.4.2 Best Results of Each Delay Compensation Method

Similar to vdRTHS, best result of each delay compensation method was selected, and their performances are presented and evaluated in this section.

#### 5.4.2.1 Inverse Compensation Method (IC)

The IC method was implemented into the Simulink model in dRTHS experiments, as discussed in section 4.4.1. The mapping between the targets and the substructure was discussed at the introduction of this chapter.

Three tests were conducted consecutively right after the first open-loop dRTHS test. The maximum control error and the error norm values for these tests are shown in Table 5-13. The table also lists the estimated delay used in the tests. The 2\textsuperscript{nd} and the 3\textsuperscript{rd} tests yielded worse
compensation results when compared to the first one. The 1st test was selected to be presented in this section and compared with the other compensation methods in section 5.5.2.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, ( \dd_{\text{max}} ) (in)</th>
<th>Maximum Control Error, ( \text{CE}_{\text{max}} ) (in)</th>
<th>CE_{\text{max}}/\dd_{\text{max}} (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.043</td>
<td>0.3656</td>
<td>0.0304</td>
<td>8.32</td>
<td>4.71</td>
</tr>
<tr>
<td>2</td>
<td>0.043</td>
<td>0.367</td>
<td>0.0288</td>
<td>7.84</td>
<td>4.81</td>
</tr>
<tr>
<td>3</td>
<td>0.043</td>
<td>0.3647</td>
<td>0.0285</td>
<td>7.82</td>
<td>4.74</td>
</tr>
</tbody>
</table>

Table 5-14 shows the maximum and minimum values of the measured and the desired displacement. Moreover, the table also shows when these values were achieved. The difference between the minimum measured and desired displacement values is 1.99% where it is 3.32% for the maximum ones. Besides, the maximum measured displacement was achieved 0.103 sec before the maximum desired one which is 0.02 sec for the minimum ones.

<table>
<thead>
<tr>
<th>Desired</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Displacement (in)</td>
<td>0.3614</td>
</tr>
<tr>
<td>Time When It Reaches to Maximum (sec)</td>
<td>11.024</td>
</tr>
<tr>
<td>Minimum Displacement (in)</td>
<td>-0.3922</td>
</tr>
<tr>
<td>Time When It Reaches to Minimum (sec)</td>
<td>10.055</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and the close-up views for their maximum and minimum values are plotted in Figure 5-25, Figure 5-26 and Figure 5-27. According to the plots and the results, the IC method overcompensated the delay at the extremum points which might be related to inconsistent delay. Moreover, it was observed that the method achieved more inaccurate results at extremum points and it may be explained with equation 3.47 as discussed in section 5.3.2, as the IC method is not able to predict when the extremum points were achieved.
Figure 5-25 Desired and Measured Displacements for IC dRTHS

Figure 5-26 Maximum Desired and Measured Displacements (Close-up) for IC dRTHS
5.4.2.2 Adaptive Inverse Compensation Method (AIC)

dRTHS experiments were conducted utilizing AIC method for 8 different $k_p$ values. In addition to the mapping of the dRTHS tests discussed at the beginning of this section, $D1-Mea$ was used in dRTHS tests to compute the adaptive parameter of the AIC method at each-time step. 3 consecutive tests for each $k_p$ values were carried out after 8 open-loop dRTHS tests, as shown in Table 5-15. The minimum error norm was obtained when $k_p=0.4$ (Test 3), which is bolded on the table. The test was selected to be presented in this section and compared with the other methods in section 5.5.2.
Table 5-15 dRTHS Tests Conducted for AIC

<table>
<thead>
<tr>
<th>kp</th>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, ddmax (in)</th>
<th>Maximum Control Error, CEmax (in)</th>
<th>CEmax/ddmax (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1</td>
<td>0.045</td>
<td>0.3533</td>
<td>0.027</td>
<td>7.66</td>
<td>4.29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.045</td>
<td>0.3926</td>
<td>0.0413</td>
<td>10.51</td>
<td>7.67</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.045</td>
<td>0.3531</td>
<td>0.0267</td>
<td>7.56</td>
<td>4.39</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>0.046</td>
<td>0.3477</td>
<td>0.0257</td>
<td>7.38</td>
<td>4.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.046</td>
<td>0.3835</td>
<td>0.042</td>
<td>10.94</td>
<td>7.52</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><strong>0.046</strong></td>
<td><strong>0.343</strong></td>
<td><strong>0.0259</strong></td>
<td><strong>7.55</strong></td>
<td><strong>4.16</strong></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.048</td>
<td>0.341</td>
<td>0.026</td>
<td>7.61</td>
<td>4.32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.048</td>
<td>0.3751</td>
<td>0.0419</td>
<td>11.16</td>
<td>6.97</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.048</td>
<td>0.3376</td>
<td>0.028</td>
<td>8.30</td>
<td>4.30</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.055</td>
<td>0.3118</td>
<td>0.0378</td>
<td>12.12</td>
<td>7.37</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.055</td>
<td>0.3218</td>
<td>0.0281</td>
<td>8.72</td>
<td>5.72</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.055</td>
<td>0.3467</td>
<td>0.0384</td>
<td>11.08</td>
<td>6.08</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.047</td>
<td>0.3179</td>
<td>0.026</td>
<td>8.19</td>
<td>5.23</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.047</td>
<td>0.3764</td>
<td>0.0423</td>
<td>11.23</td>
<td>7.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.047</td>
<td>0.3403</td>
<td>0.0252</td>
<td>7.40</td>
<td>4.23</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>0.048</td>
<td>0.3351</td>
<td>0.03</td>
<td>8.94</td>
<td>4.55</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.048</td>
<td>0.3353</td>
<td>0.0261</td>
<td>7.77</td>
<td>4.42</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.048</td>
<td>0.3342</td>
<td>0.0257</td>
<td>7.70</td>
<td>4.39</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>0.053</td>
<td>0.3339</td>
<td>0.0341</td>
<td>10.20</td>
<td>5.07</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.053</td>
<td>0.3322</td>
<td>0.0282</td>
<td>8.50</td>
<td>4.91</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.053</td>
<td>0.3298</td>
<td>0.0379</td>
<td>11.49</td>
<td>7.05</td>
</tr>
<tr>
<td>2000</td>
<td>1</td>
<td>0.045</td>
<td>0.3334</td>
<td>0.0417</td>
<td>12.51</td>
<td>7.18</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.045</td>
<td>0.3318</td>
<td>0.04</td>
<td>12.06</td>
<td>7.19</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.045</td>
<td>0.3325</td>
<td>0.0264</td>
<td>7.95</td>
<td>4.68</td>
</tr>
</tbody>
</table>

Table 5-16 shows the maximum and minimum displacements from the dRTHS and the desired displacements, where the table also shows when they were achieved. The results show that difference between the measured and desired displacement value is 3.57% in maximum and 0.28% in minimum, where the minimum measured displacement value is almost identical to the desired one. On the other hand, the maximum measured displacement was achieved 0.097 sec before the maximum desired one where the minimum measured displacement was achieved 0.018 sec before the minimum desired one.
Table 5-16 Maximum and Minimum Displacement Values for AIC dRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.3614</td>
<td>11.024</td>
<td>-0.3922</td>
<td>10.055</td>
</tr>
<tr>
<td>Measured</td>
<td>0.3485</td>
<td>10.927</td>
<td>-0.3911</td>
<td>10.037</td>
</tr>
</tbody>
</table>

Measured and desired displacement, and the close-up views for maximum and minimum values are plotted in Figure 5-28, Figure 5-29 and Figure 5-30. As well as vRTHS tests, AIC method did not perform proper delay compensation at the extremum points, which might be explained with equation 3.49 as discussed in section 5.3.2.

Figure 5-28 Desired and Measured Displacements for AIC dRTHS
5.4.2.3 Modified Feedforward Method (MFF)

The MFF method was implemented in dRTHS experiments to compensate the total delay including the Internet delay and the actuator delay. The implementation of the method was discussed in
section 4.4.3, where the mapping between the targets and the substructure was discussed at the introduction of this chapter.

Three MFF experiments were conducted consecutively right after the second open-loop dRTHS test. The estimated delay value used in the dRTHS tests is shown in Table 5-17, where the table also lists the error indexes for each experiment. The second test, which yielded the best compensation results along the simulation, was selected to be presented in this section and compared with the other methods in section 5.5.2.
Table 5-17 Error Norm Values for MFF dRTHS

<table>
<thead>
<tr>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, $dd_{max}$ (in)</th>
<th>Maximum Control Error, $CE_{max}$ (in)</th>
<th>$CE_{max}/dd_{max}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.043</td>
<td>0.3921</td>
<td>0.0328</td>
<td>8.36</td>
<td>6.27</td>
</tr>
<tr>
<td>2</td>
<td>0.043</td>
<td>0.3868</td>
<td>0.0316</td>
<td>8.17</td>
<td>6.02</td>
</tr>
<tr>
<td>3</td>
<td>0.043</td>
<td>0.3867</td>
<td>0.0323</td>
<td>8.35</td>
<td>6.10</td>
</tr>
</tbody>
</table>

Table 5-18 shows the maximum and minimum values of the measured and the desired displacement, where it also shows the time when they were achieved. According to the results, the maximum measured displacement value was achieved 0.042 sec before the desired one where the measured minimum displacement was achieved 0.025 sec before the desired one. Besides, the differences between the measured and the desired displacement values are 7.39% in the maximum and 7.50% in the minimum.

Table 5-18 Maximum and Minimum Displacement Values for MFF dRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.3614</td>
<td>11.024</td>
<td>-0.3922</td>
<td>10.055</td>
</tr>
<tr>
<td>Measured</td>
<td>0.3881</td>
<td>10.983</td>
<td>-0.4216</td>
<td>10.030</td>
</tr>
</tbody>
</table>

Figure 5-31, Figure 5-32 and Figure 5-33 shows the plots for measured and desired displacement, and the close-up views of maximum and minimum values, respectively. The MFF achieved more inaccurate measured values at the extremum points, which might be explained with equation 3.43 as discussed in section 5.3.2. The varying actuator delay, which is also considered in dRTHS, might cause worse compensation results since the delay might increase the possible varying range of the total delay.
Figure 5-31 Desired and Measured Displacements for MFF dRTHS

Figure 5-32 Maximum Desired and Measured Displacements (Close-up) for MFF dRTHS
The ATS method was implemented into dRTHS and experiments were carried out. Like AIC, measured displacement $D1$-$Mea$ was fed back into the model as input since ATS uses the measured displacement to find the adaptive coefficients at each time step. Moreover, the command displacement $D1$ was also used to compute the adaptive coefficients. The implementation of the ATS method was discussed in section 4.4.4.

dRTHS tests were conducted for different selected tapped delay values, however only 3 stable tests were achieved where the others were stopped due to the unstable results. The error indexes of these 3 tests are shown in Table 5-19. The table also shows the delay values used in dRTHS tests, which were estimated through open-loop test (see Table 5-12). According to the results, the optimal performance of ATS was achieved when tapped delay was 1500. The test was selected to be presented in this section and compared with the other compensation methods in section 5.5.2.
Table 5-19 Successful ATS dRTHS Test Results for Selected Tapped Delay Values

<table>
<thead>
<tr>
<th>Delay</th>
<th>Test No</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, $d_{max}$ (in)</th>
<th>Maximum Control Error, $C_{E_{max}}$ (in)</th>
<th>$C_{E_{max}}/d_{max}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1</td>
<td>0.055</td>
<td>0.5037</td>
<td>0.0821</td>
<td>16.31</td>
<td>14.96</td>
</tr>
<tr>
<td>1500</td>
<td>2</td>
<td>0.042</td>
<td>0.5057</td>
<td>0.0801</td>
<td>15.83</td>
<td>14.96</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>0.060</td>
<td>0.4899</td>
<td>0.083</td>
<td>16.93</td>
<td>15.14</td>
</tr>
</tbody>
</table>

Table 5-20 shows the maximum and minimum values of desired and measured displacement, where it also shows when they were achieved. There are significant differences between the measured and desired displacement values, which are 38.68% in the maximum and 27.58% in the minimum. On the other hand, maximum measured and desired displacement values were achieved with 0.025 sec difference where there is 0.013 sec difference between the minimum values.

Table 5-20 Maximum and Minimum Displacement Values for ATS dRTHS

<table>
<thead>
<tr>
<th></th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.3614</td>
<td>11.024</td>
<td>-0.3922</td>
<td>10.055</td>
</tr>
<tr>
<td>Measured</td>
<td>0.5012</td>
<td>11.049</td>
<td>-0.5004</td>
<td>10.068</td>
</tr>
</tbody>
</table>

The measured and the desired displacement, and close-up views for the maximum and the minimum values are plotted in Figure 5-34, Figure 5-35 and Figure 5-36. The plots show that ATS achieved erroneous results especially at the extremum points. Using higher order time derivatives in the ATS may yield better compensation results providing more accurate adaptive coefficients.
Figure 5-34 Desired and Measured Displacements for ATS dRTHS

Figure 5-35 Maximum Desired and Measured Displacements (Close-up) for ATS dRTHS
5.5 Comparison of Delay Compensation Methods

Comparison of the four delay compensation methods implemented in vdRTHS and dRTHS experiments are discussed based on the observation of combined displacement responses plots and the summarized tables of error index.

5.5.1 vdRTHS

The measured displacement of each vdRTHS test and the desired displacement from the pure numerical simulation are plotted together as shown in Figure 5-37–5-39. According to the plots, the AIC method yielded the best compensation results followed by IC, which demonstrates the advantage of the adaptive delay parameters to compensate varying delay. The MFF method, which showed the best delay compensation performance in numerical simulations with constant delay, yielded worse compensation results than the IC and the AIC methods in vdRTHS. Moreover, the ATS method, which was the second-best in the numerical simulations, showed the worst performance in vdRTHS.
Figure 5-37 Comparison of Delay Compensation Methods in vdRTHS

Figure 5-38 Comparison of Delay Compensation Methods (Close-up Maximum) in vdRTHS
Table 5-21 shows the maximum and minimum of measured displacements at the vdRTHS tests and the desired displacement of the numerical simulation together with the time when they were achieved.

Table 5-21 Maximum and Minimum Displacement Values for vdRTHS Tests

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.7228</td>
<td>11.025</td>
<td>-0.7843</td>
<td>10.056</td>
</tr>
<tr>
<td>IC</td>
<td>0.7613</td>
<td>11.012</td>
<td>-0.8179</td>
<td>10.051</td>
</tr>
<tr>
<td>AIC</td>
<td>0.739</td>
<td>11.004</td>
<td>-0.801</td>
<td>10.053</td>
</tr>
<tr>
<td>MFF</td>
<td>0.7786</td>
<td><strong>11.032</strong></td>
<td>-0.8292</td>
<td>10.052</td>
</tr>
<tr>
<td>ATS</td>
<td>1.0997</td>
<td>10.929</td>
<td>-1.1885</td>
<td>10</td>
</tr>
</tbody>
</table>

According to the table, the AIC method achieved the most accurate maximum and minimum displacement values when compared to the other methods, where the IC method was the second-best. The results show the improvement in yielding accurate measured displacement values by means of adaptive delay parameter. Moreover, the difference between the measured displacement values of the ATS test and the desired displacement are 52.14% in the maximum and 51.53% in
the minimum, which are approximately ten times larger when compared with the other compensation methods.

Moreover, the MFF method performed better than the other compensation methods in predicting where the maximum desired value was achieved. AIC was the best in predicting the maximum point (0.003 sec before), where the MFF (0.004 sec before) and the IC method (0.005 sec before) also predicted very accurate results. On the other hand, according to the points where the IC and the AIC predicted the minimum desired displacement values, using adaptive parameters does not improve the prediction of the extremum points.

Although the MFF method showed the best performance in predicting where the maximum desired displacement was achieved, it performed worse than AIC and IC in achieving the maximum and minimum measured displacement values, which may be explained with equation 3.43. \( \alpha^2 \), the square of the delay constant which is used equation 3.43., may cause inaccurate results with varying delay values in vdRTHS and dRTHS.

Table 5-22 lists the estimated delay used in the vdRTHS tests and compares the error index results. According to the results, which show the performance of the delay compensation methods along the whole simulation, AIC yielded the best compensation results when there is varying Internet delay. The results indicate the importance of using adaptive parameters when compensating the varying delay. Moreover, the error norm values show that IC method yielded better compensation results than MFF.
<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, ( dd_{\text{max}} ) (in)</th>
<th>Maximum Control Error, ( CE_{\text{max}} ) (in)</th>
<th>( CE_{\text{max}}/dd_{\text{max}} ) (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>-</td>
<td>0.7228</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IC</td>
<td>0.06</td>
<td>0.7571</td>
<td>0.0376</td>
<td>4.96</td>
<td>2.99</td>
</tr>
<tr>
<td>AIC</td>
<td>0.036</td>
<td>0.7348</td>
<td>0.034</td>
<td>4.63</td>
<td>2.65</td>
</tr>
<tr>
<td>MFF</td>
<td>0.038</td>
<td>0.7776</td>
<td>0.0448</td>
<td>5.76</td>
<td>3.43</td>
</tr>
<tr>
<td>ATS</td>
<td>0.039</td>
<td>0.9733</td>
<td>0.1931</td>
<td>19.84</td>
<td>17.93</td>
</tr>
</tbody>
</table>

When compared to the other methods, ATS yielded the worst compensation results. Regarding the performance of ATS in numerical simulations with constant delay, it may be concluded that the second order formula used in vdRTHS experiments is not able to predict accurate command displacement values when the delay is varying in wide range. Considering higher order time derivatives in the ATS may provide more accurate results where the delay varies in wide range, like the Internet delay in vdRTHS.
5.5.2 dRTHS

The measured displacement values of each dRTHS test and the desired displacement values from the pure numerical simulation are plotted together as shown in Figure 5-40~5-42. According to the plots, the ATS method yielded the worst compensation results in dRTHS experiments as well as in vdRTHS. The AIC and the IC method achieved accurate minimum and maximum measured displacement values. On the other hand, the MFF and the ATS performed better in predicting where the minimum and maximum desired responses were achieved, respectively.

![Figure 5-40 Comparison of Delay Compensation Methods in dRTHS](image)
Figure 5-41 Comparison of Delay Compensation Methods (Close-up Maximum) in dRTHS

Figure 5-42 Comparison of Delay Compensation Methods (Close-up Minimum) in dRTHS
The maximum and the minimum measured displacements at the dRTHS tests and the desired displacement of the numerical simulation are shown in Table 5-23 together with the time when they were achieved.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Maximum Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>0.3614</td>
<td>11.024</td>
<td>-0.3922</td>
<td>10.055</td>
</tr>
<tr>
<td>IC</td>
<td>0.3734</td>
<td>10.921</td>
<td>-0.4</td>
<td>10.035</td>
</tr>
<tr>
<td>AIC</td>
<td>0.3485</td>
<td>10.927</td>
<td>-0.3911</td>
<td>10.037</td>
</tr>
<tr>
<td>MFF</td>
<td>0.3881</td>
<td><strong>10.983</strong></td>
<td>-0.4216</td>
<td>10.03</td>
</tr>
<tr>
<td>ATS</td>
<td>0.5012</td>
<td>11.049</td>
<td>-0.5004</td>
<td><strong>10.068</strong></td>
</tr>
</tbody>
</table>

According to the table, the AIC method achieved the minimum measured displacement almost identical to the desired one. In maximum displacement values, the IC method achieved the most accurate minimum displacement value (3.32% difference) when compared to the other methods, where AIC was the second-best (3.57% difference). The MFF method, which achieved the most accurate responses in the numerical simulation, achieved worse measured displacement values at minimum and maximum when compared to the IC and the AIC. It may be explained with the equation 3.43, as discussed in section 5.5.1. Moreover, the ATS method achieved the worse maximum and minimum measured displacement values by far.

On the other hand, the MFF method performed better than the other compensation methods in predicting where the minimum desired value was achieved, where the ATS method was the best in predicting where the maximum one was achieved. The MFF method considered the previous two steps to compute the command displacement of the current step, where the ATS considered the previous 1500 time-steps. Selected tapped delay value represents the number of previous steps which are considered to find the adaptive coefficients of the current step, as discussed in Chapter 3. According to the results, considering the previous steps might provide the accurate predictions of the points where the maximum and minimum desired responses are achieved.

The error indexes and the estimated delay values used in the dRTHS tests are listed in Table 5-24. Similar to the observation in the vdRTHS tests, the AIC method showed the best delay
compensation performance and followed by the IC method demonstrating the necessity of using adaptive delay compensation methods in dRTHS. The error norm difference between the AIC and the IC method was 0.33% in vdRTHS and 0.55% in dRTHS. When compared with numerical simulations, the adaptive delay parameter shows its effectiveness in vdRTHS and dRTHS experiments, where the delay is varying in wide range.

Moreover, the error norm results prove that IC and AIC yielded better results than MFF. Besides, the difference of error norms between the MFF and the IC was 1.31% in dRTHS and 0.44 % in vdRTHS, which shows that the increase in the range of the delay, which is possible in dRTHS since the actuator delay is also considered, may adversely affect the performance of the MFF method. Therefore, it is recommended that further development of adaptive MFF compensation method is needed in future studies.

ATS method yielded the worst performance in dRTHS experiments as well as in vdRTHS. The results indicate the need of using higher order time derivatives when implementing the ATS method in vdRTHS and dRTHS experiments. The effects of using higher order time derivatives may be investigated in the further studies. On the other hand, ATS had the closest prediction about when the extremum desired values were achieved. Using optimum tapped delay values may provide accurate predictions of the extremum points.

<table>
<thead>
<tr>
<th>Compensation Method</th>
<th>Estimated Delay (sec)</th>
<th>Maximum Desired Displacement, $dd_{max}$ (in)</th>
<th>Maximum Control Error, $CE_{max}$ (in)</th>
<th>$CE_{max}/dd_{max}$ (%)</th>
<th>Error Norm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>-</td>
<td>0.3614</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IC</td>
<td>0.043</td>
<td>0.3656</td>
<td>0.0304</td>
<td>8.32</td>
<td>4.71</td>
</tr>
<tr>
<td>AIC</td>
<td><strong>0.046</strong></td>
<td><strong>0.343</strong></td>
<td><strong>0.0259</strong></td>
<td><strong>7.55</strong></td>
<td><strong>4.16</strong></td>
</tr>
<tr>
<td>MFF</td>
<td>0.043</td>
<td>0.3868</td>
<td>0.0316</td>
<td>8.17</td>
<td>6.02</td>
</tr>
<tr>
<td>ATS</td>
<td>0.042</td>
<td>0.5057</td>
<td>0.0801</td>
<td>15.83</td>
<td>14.96</td>
</tr>
</tbody>
</table>

Table 5-24 Comparison of Delay Compensation Methods in dRTHS
5.6 Summary

This chapter started with the discussion of the dRTHS platform recently developed at the LESS, which contains hardware and software components and the test specimen utilized in this experimental study. Proper installation of the test specimen, which is an important step in dRTHS experiments, was explained. Configuration of dRTHS projects using NI Veristand software and the custom device toolbox were discussed. The real-time target computers, which were used to carry out the numerical simulation and transferring data in between using the TCP/IP connections, were introduced with their functions in a dRTHS.

dRTHS tests with delay compensation methods were conducted next. Three-story shear-frame building model was used in the experiments where the first story of the model was the physical substructure and numerically simulated in dRTHS and the upper two stories were the numerical substructure. Best result of each compensation method was identified and presented. The AIC method yielded the best compensation results in dRTHS with varying Internet delay, which was followed by the IC. When compared to the numerical simulation, the dRTHS results indicated the importance of using adaptive delay parameters when compensating the varying delay. Moreover, the results implied that the MFF method, which yielded the best compensation results when the delay was constant, is more sensitive to the varying delay when compared to the IC and the AIC. The ATS method yielded the worst compensation results, where the use of high order time derivatives shall be considered to improve the performance of the ATS when the delay varies in wide range.

Lastly, the delay compensation methods were utilized in dRTHS and the experiments were carried out. It was observed that the dominance of the AIC method was strengthened in dRTHS, since the varying actuator delay increase the possible varying range of the delay. Moreover, the MFF yielded worse compensation results when compared to the dRTHS, it shows the need for developing adaptive MFF method in future studies. On the other hand, the MFF and the ATS performed better than the other methods in predicting where the extremum desired responses were reached, which might be due to the methods consider more than one previous step to predict the extremum points. ATS yielded the worst compensation results where only 3 tests were achieved out of 15 tests,
which clearly shows the need of using higher order time derivatives when utilizing the ATS in dRTHS.
6 DISTRIBUTED REAL-TIME HYBRID SIMULATION (DRTHS) SYSTEM FOR A PROTOTYPE FLOATING WIND TURBINE (FWT) STRUCTURE

6.1 Introduction

To expand the application of dRTHS and validate its applicability on capturing accurate responses on FWT system, virtual distributed real-time hybrid simulation (vdRTHS) tests were carried out at the Laboratory of Earthquake and Structural Simulation (LESS) at Western Michigan University (WMU). An introduction on the FWT model, numerical simulation procedure, and the loading protocols are presented first with the explanation of the model properties, numerical simulation parameters and the determination of wave and wind load time histories.

Next, numerical simulation of the FWT model response when subject to wind and wave loadings are presented. The section starts with the discussion on the accuracy and the stability of the model. Then, the responses of the model when subject to separate wave and wind load followed by the responses when subject to both loads are discussed including error analysis. A substructure simulation was performed to prepare for the vdRTHS, during which two FWT models were used and their responses under wind and wave loads are superimposed to obtain the whole structural responses. The results are discussed to indicate the possible numerical simulation errors. Next, the responses of the FWT model subject to both loads are provided as the reference data.

Lastly, vdRTHS test procedure and results are discussed. Substructuring of the model and the communication between the two real-time computers are explained first. New error norm formula, adapted from the one used for the valuation of delay compensation methods, and its application to analyze the vdRTHS results are presented. The comparison of the vdRTHS and numerical simulation results reveals the applicability of dRTHS method into FWT dynamic response evaluation.
6.2 FWT Prototype and Numerical Simulation

In this section, FWT prototype model, which was created through modification of a reference FWT model, is presented. Assumptions and calculations carried out to create the prototype model are provided in Appendix B. Along with the FWT prototype model, the numerical simulation procedure and the wind and wave loading protocols are explained.

6.2.1 FWT Prototype

A 1.5-megawatt (MW) FWT, shown in Figure 6-1 (Lee, 2005), was adopted as the prototype FWT structure in this study to investigate the applicability of dRTHS on FWT system. The FWT model has a cylindrical floating platform (buoy), which is indicated with blue in the figure, and a tower and mooring lines, which are explained in Chapter 2.

![Figure 6-1 1.5 MW FWT (Lee, 2005)](image)
As can be seen from Figure 6-1, the reference FWT has 8 mooring lines where 4 of them are connected to the bottom of platform and the others are connected to the top of the platform. The properties of the mooring lines and the reference FWT are given in Table 6-1.

However, most properties of the FWT necessary for establishing the equation of motion as discussed in section 3.2 were not given in the reference. Moreover, the geometric properties of the tower and platform sections were not given. Therefore, some assumptions were made on the reference FWT to create a reasonable model. Appendix B provides the details on the assumptions and the calculations of the FWT model parameters including the mass, the damping and the restoring force matrices used in the dynamic equation of motion. In addition to the properties of the mooring lines and the reference FWT, assumed properties of the FWT prototype are also listed in Table 6-1. The FWT prototype used in the study preserved the listed properties of the reference FWT. As well as reference FWT, the entire FWT prototype was modeled as a rigid body. Moreover, the blade and rotor components of the reference FWT were not included in the prototype. Figure 6-2 shows the front view of the prototype used in the study. The prototype comprises of the tower, ballast, floating platform and the mooring lines, which are anchored to the sea floor.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position</strong></td>
<td>Top</td>
<td>Bottom</td>
<td></td>
</tr>
<tr>
<td>Tension (N)</td>
<td>6.17E+05</td>
<td>5.50E+05</td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>128.1</td>
<td>141.5</td>
<td></td>
</tr>
<tr>
<td>Distance (m)</td>
<td>20</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>EA (N)</td>
<td>1.50E+09</td>
<td>1.50E+09</td>
<td></td>
</tr>
<tr>
<td><strong>Platform/Tower Height</strong></td>
<td></td>
<td>20/84</td>
<td></td>
</tr>
<tr>
<td><strong>Platform Radius</strong> (m)</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Outer/Inner Radius of</strong></td>
<td></td>
<td>4/3.988</td>
<td></td>
</tr>
<tr>
<td><strong>Total Mass (kg)</strong></td>
<td></td>
<td>198000</td>
<td></td>
</tr>
<tr>
<td><strong>Mass of Platform (kg)</strong></td>
<td></td>
<td>213000</td>
<td></td>
</tr>
<tr>
<td><strong>Mass of Ballast (kg)</strong></td>
<td></td>
<td>1569000</td>
<td></td>
</tr>
<tr>
<td><strong>Inner Radius of</strong></td>
<td></td>
<td>5.965</td>
<td></td>
</tr>
<tr>
<td>**COM, ( z_g ) (m)</td>
<td></td>
<td>-5.74</td>
<td></td>
</tr>
<tr>
<td><strong>COM of Ballast (m)</strong></td>
<td></td>
<td>-4.67</td>
<td></td>
</tr>
</tbody>
</table>
The natural frequency values of the created FWT prototype and the reference FWT for six modes of motion are listed in Table 6-2. Assumptions made to create the FWT prototype, such as mass of the tower, the position of the ballast, selected materials and geometrical properties of the platform and the tower, may be the reason of the differences. Moreover, nacelle, rotor and the blades were not included in the created FWT prototype, which may also result in difference natural frequency values between the reference FWT and the FWT prototype.

<table>
<thead>
<tr>
<th>Modes of Motion</th>
<th>Natural Frequency of FWT Prototype (rad/sec)</th>
<th>Natural Frequency of Reference FWT (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.18</td>
<td>1.16</td>
</tr>
<tr>
<td>Sway</td>
<td>0.18</td>
<td>1.16</td>
</tr>
<tr>
<td>Heave</td>
<td>11.08</td>
<td>2.09</td>
</tr>
<tr>
<td>Roll</td>
<td>3.79</td>
<td>0.91</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.79</td>
<td>0.91</td>
</tr>
<tr>
<td>Yaw</td>
<td>0.11</td>
<td>0.79</td>
</tr>
</tbody>
</table>

6.2.2 Numerical Simulation Procedure

MATLAB/Simulink was utilized to simulate the dynamic responses histories of FWT model subject to wave and wind excitations. The Simulink file contains the properties of the FWT model and the integration parameters are initialized in a MATLAB script. Duration of the simulation was selected as 60 sec and the time step is 0.001 sec.

Figure 6-3 shows the numerical FWT model in Simulink, where the simulation was carried out using the incremental Newmark integration algorithm for multi-degrees of freedom (MDOF) systems, which was discussed in Chapter 3. Predefined wind and wave loading protocols were called by the Simulink model and the response of the FWT structure was simulated at each time-step.
Figure 6-3- Numerical FWT Model in Simulink
6.2.3 Wind and Wave Loadings

Wind force data, shown in Figure 6-5, was calculated using MATLAB script. The data was taken from the measured wind speed of the 1959 Patricia hurricane with a one-hour duration (NOAA, n.d.). A half scale was applied to the original data and time histories of 60 sec was prepared as shown in Figure 6-4. The wind load was applied along the positive surge direction of the FWT model.

![Figure 6-4 Wind Speed (mph)](image_url)
Wind force was calculated based on the formula (Woude, 2010):

\[ F_w = \frac{q \cdot A \cdot C_d}{2} \]  

(6.1)

where \( q \) is the wind pressure, \( A \) is the projected area subject to wind force and \( C_d \) is the drag coefficient, which is taken as 1.2 for long cylinders as the tower of the FWT prototype. Linear wind pressure was assumed to act on the tower, where the total wind load, \( F_w \), was applied at the 2/3 height point of the tower, which is 56 m from the reference point of the FWT, shown in Figure 6-6. The figure also shows the applied wave load, \( F_{wa} \), which was applied at the center height of the platform, which is -10 m from the reference point of the FWT prototype.
Figure 6-6 Wind and Wave Load Applied to the FWT Prototype

$q$ can be calculated as (Barros, et al., 2013):

$$q = 0.613 |V|V (N/m^2)$$ (6.2)

where $V$ is the wind speed. Along with wind force, wave force was also applied to the FWT model and predetermined using the MATLAB script.

Similar to wind load calculation, wave force was determined based on the wave speed data which was generated using the period limits recommended in the literature (DNV, 2007), as shown in Figure 6-7.
The wave drag force, $F_{wa}$, applied to the platform was then calculated as:

$$F_{wa} = \frac{C_d A |u| u}{2}$$  \hfill (6.3)

where $C_d$ is the drag coefficient, which is set to 1.2 for the cylindrical platform, $u$ is the wave velocity and $A$ is the area subjected to wave loading. Wave load time history is shown in Figure 6-8. Rectangular wave block was assumed to apply on the FWT platform in the surge direction, where the total wave force was applied at the half height point of the draft, which is -10 m from the water level (reference point), as shown in Figure 6-6.
6.3 Numerical Simulation of the FWT Model

In this section, numerical simulation was conducted on the FWT model subjected to the wave and wind loadings in surge direction.

Prior to the numerical simulation, the FWT model was exposed to a steady wind speed of 32 mph as recommended by Lee (2005), and it was observed that the peak surge displacement of the FWT model was 26 in compared to the 22 in in the reference FWT model. The different peak displacement responses may be due to the modification to the damping ratio in the FWT model and different algorithms used for the simulations. Nevertheless, stable responses were obtained when the FWT model was subjected to the 6000 secs (6 million time-steps with a 0.001 sec time step) wind loading time histories.

6.3.1 Wind and Wave Analysis of the Model

Following the preliminary simulation mentioned above, two numerical simulations were carried out on the dynamic response of the FWT model subject to separate wave and wind load, which are called as “wind only” and “wave only” cases, respectively. Then, the
numerical simulation was carried out for the FWT model subject to simultaneous wind and wave loads which are defined in 6.2.3 as is the usual case for a real FWT structure, where the “total” responses of the FWT were obtained.

The results show that the responses of the FWT in sway, heave, roll and yaw motions are very small that can be neglected when the loads were applied only in the surge direction. Heave motion were mainly restrained by mooring lines.

Figure 6-9, Figure 6-10 and Figure 6-11 show the displacement, the velocity and the acceleration responses of these three cases in surge direction, respectively. The surge displacement responses were governed by wave loading, where wave load responses are larger than the wind load responses with a peak displacement of 29.4 in. The total peak surge displacement (26.5 in) is smaller than that of the wave only case (29.4 in) since the surge displacement response amplitude due to the wind load was positive (2.9 in) when the negative peak response was reached.

The surge velocity responses were again governed by wave loading. However, the instantaneous change in the surge velocity due to the wind load is higher when compared to the wave load, which might imply the dominancy of the wind loading in the surge acceleration when the instantaneous change in wind load is high.

The surge acceleration results proved the observation from the surge velocity responses, where the maximum surge acceleration in wind only case is larger than that in the wave only case. Moreover, the instantaneous changes in surge acceleration amplitudes of wind only case are high when the instantaneous changes in wind load frequency is high.
Figure 6-9 Surge Displacement Response of FWT for Wind and Wave Only Case

Figure 6-10 Surge Velocity of FWT for Wind and Wave Only Case
The displacement, the velocity and the acceleration responses of the three cases in pitch direction are demonstrated in Figure 6-12, Figure 6-13 and Figure 6-14, respectively. Despite its effect on surge displacement and velocity responses is smaller when compared to the wave loading, the wind load governs the pitch motions since it was applied to 2/3 height of the tower (56 m) and the moment arm is greater than moment arm (-10 m) of the wave load. Moreover, it was observed that the pitch response amplitudes of the wave only case were negative when the maximum wave force value was achieved since the applied wave load produced pitch moment in the negative direction.

The total pitch displacement responses followed the track of those in the wind only case when the instantaneous change in wind load responses are high. Moreover, the wind loading governs the pitch velocity responses. It was observed that the peak velocity amplitude of the numerical simulation was reached at the same time as that of the wind only case.

As well as it was observed in the pitch velocity responses, wind load also governs the pitch acceleration responses. Especially when the maximum and minimum wind load values were reached, the instantaneous change in pitch acceleration response amplitudes are very high.
for the wind load when compared to the wave load. It was observed that the peak acceleration amplitude of the numerical simulation was reached at the same time as that of the wind only case. This large change in the responses might result in inaccurate superimposed results in vdRTHS tests if there are varying delay values.

Figure 6-12 Pitch Displacement Response of FWT for Wind and Wave Only Case
Figure 6-13 Pitch Velocity Response of FWT for Wind and Wave Only Case

Figure 6-14 Pitch Acceleration Response of FWT for Wind and Wave Only Case
6.3.2 Substructured Numerical Simulation

Before conducting the vdRTHS experiments, the numerical simulation was divided into two parts. Each part contained the same FWT model but subject to wind and wave loads separately. The FWT responses under these two loads were then simulated in the same Simulink model (see Figure 6-15) and were combined to obtain the whole structural response. When compared the combined response to the total response when the model subject to the combined load, identical results were observed in both the pitch and surge motions, which verified the applicability of the superposition that would be adopted in the vdRTHS experiments that are discussed next.
6.4 Virtual Distributed Real-Time Hybrid Simulation (vdRTHS)

dRTHS not only facilitates large-scale experiments on physical substructures utilizing geographically distributed testing equipment, it may also be utilized to improve the accuracy of complex numerical simulations through substructuring method so that two or more numerical parts can be simulated synchronically in real-time. FWT system may be considered as one of the complex structural systems due to the challenges to obtain its dynamic responses as discussed in Chapter 2. Applicability of dRTHS on FWT models was
investigated in this research. An FWT prototype was created based on a reference FWT structure and the vdRTHS tests were conducted.

In these vdRTHS tests, numerical simulation of the FWT prototype was divided into two parts, and the responses of the FWT model subject to wind and wave loads were simulated separately and synchronically using two real-time computers (also called targets), namely the PC-RT and the PXI-RT. The total response was obtained through superposition of the responses from the two separate simulations, which was validated in section 6.3.2. Five vdRTHS tests were carried out without delay compensation as these vdRTHS was open-loop simulation, meaning that the results from one simulation (response due to one load) would not affect the other simulation (response due to the other load).

Figure 6-16 and Figure 6-17 shows the numerical models in the PC-RT and PXI-RT, respectively. The PC-RT target simulated responses of the FWT model subject the wind load, and then sent the displacement, velocity and acceleration responses of each motion to the PXI-RT target at each time-step through Internet communication. These responses are named as $u_w$, $udw$ and $uddw$. The PXI-RT received these responses and superimposed them onto the responses of the FWT model subject to the wave load of the same time step (named as $u_{wa}$, $udwa$ and $uddwa$). Then, the total responses, $u_t$, $udt$ and $uddt$, were obtained in the PXI-RT.

Since the wind responses were delayed when they reached the PXI-RT due to the Internet communication between the two targets, wave load responses were artificially delayed using a constant delay block to ensure the superposition of the responses at the same time step yielding correct results. The one-way internet time delay was 20 time-step delays, which was estimated based on previous dRTHS experiments at LESS.
Figure 6-16 Numerical Simulation of FWT Model Subject to Wind Load (PC-RT)
To provide accurate comparison between the responses of the numerical simulation and the vdRTHS, numerical simulation responses were also artificially delayed for 20 time-steps. Error norm formula, which was defined in equation 4.7, was adapted to the FWT study to investigate the accuracy of the vdRTHS results.

$$\text{Error Norm} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [r_i^n - r_i^e]^2}$$

(6.4)

where $r_i^n$ and $r_i^e$ represents the numerical simulation and vdRTHS response values at time step $i$, respectively. Table 6-1 lists the error norm values of five tests for the surge and pitch responses. Comparing the error norms calculated from five tests, Test 1 has the smallest error.
norm values for each response and was selected to be further investigated. The error norm results also demonstrate that the Internet delay in vdRTHS, which was not constant, may lead to different test results.

<table>
<thead>
<tr>
<th>Table 6-3 Error Norm (%) of FWT vdRTHS Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error Norm</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Surge Displacement</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Surge Velocity</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Surge Acceleration</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Pitch Displacement</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Pitch Velocity</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Pitch Acceleration</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
</tbody>
</table>

Figure 6-18 shows the displacement responses of the numerical simulation and the vdRTHS in surge direction. The surge displacement responses of the numerical simulation were accurately tracked in the vdRTHS. The error norm results also demonstrate the accuracy of the responses from the vdRTHS test, despite the varying delay between the two targets used for the separate simulations.
Moreover, the maximum and minimum surge displacement responses are shown in Table 6-4 together with the time when they were achieved. The difference between the maximum surge displacement values is 0.045% and 0.038% for the minimum ones. The results show that vdRTHS provided nearly identical surge displacement responses. Besides, the maximum surge displacement of the numerical simulation was achieved 0.004 sec before that of the vdRTHS where the minimum surge displacement of the numerical simulation was achieved 0.003 sec before that of the vdRTHS.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Surge Displacement (in)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Surge Displacement (in)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Simulation</td>
<td>17.458</td>
<td>43.818</td>
<td>-26.545</td>
<td>57.039</td>
</tr>
<tr>
<td>vdRTHS</td>
<td>17.466</td>
<td>43.822</td>
<td>-26.555</td>
<td>57.042</td>
</tr>
</tbody>
</table>

Figure 6-19 shows the velocity responses of the numerical simulation and the vdRTHS in surge direction. vdRTHS test yielded the surge velocity responses that followed the track of those in the numerical simulation.
Table 6-5 lists the maximum and minimum surge velocity responses together with the time when they were achieved. The difference between the maximum surge velocity values is 0.07% where it is 0.04% for the minimum ones, which shows that vdRTHS yielded nearly identical surge velocity results. Besides, the minimum surge velocity of the numerical simulation was achieved 0.005 sec after that of the vdRTHS, but the maximum surge velocity of the numerical simulation was achieved 0.012 sec after that of the vdRTHS. As discussed in Chapter 5, the Internet delay is not constant in vdRTHS, which may lead to superposition of the responses at different time-steps. Nevertheless, the improper superposition did not affect the response amplitudes notably since the instantaneous change in surge velocity responses are not high.
<table>
<thead>
<tr>
<th></th>
<th>Maximum Surge Velocity (in/sec)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Surge Velocity (in/sec)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical Simulation</strong></td>
<td>4.231</td>
<td>40.703</td>
<td>-4.986</td>
<td>47.987</td>
</tr>
<tr>
<td><strong>vdRTHS</strong></td>
<td>4.234</td>
<td>40.691</td>
<td>-4.988</td>
<td>47.982</td>
</tr>
</tbody>
</table>

Figure 6-20 shows the acceleration responses of the simulation and the test in surge direction. The surge acceleration responses of the vdRTHS test followed track of those in the numerical simulation. However, as shown in Figure 6-20, there are small discrepancies at the points of high instantaneous change in wind acceleration responses, which was discussed in the section 6.3.1. The superposition of the responses at different time-steps may lead to discrepancies when the instantaneous change in response amplitudes are high, which is possible in vdRTHS due to the varying delay. Rather than using constant delay (20 steps) shown in Figure 6-17, adapting delay values identified during vdRTHS may provide more accurate results to accommodate the varying delay values.
The maximum and minimum surge acceleration responses are shown in Table 6-6 together with the time when they were achieved. The difference between the maximum values is 0.39% and the difference is 0.17% for the minimum ones, which shows that vdRTHS provided accurate superimposed results in surge acceleration responses where the instantaneous change in responses are not high. The discrepancies were observed at the points with high instantaneous change in responses.

Moreover, the maximum surge acceleration response of the numerical simulation was reached 0.009 sec after that of the vdRTHS, where the minimum response of the numerical simulation was reached 0.01 sec after that of vdRTHS. As discussed for the surge velocity responses, superposition of the different time-steps may result in these differences but vdRTHS results may follow the track of the numerical simulation responses when the instantaneous change in response amplitudes are not high. As shown in Figure 6-20, the improper superposition at the points of high instantaneous change in responses may lead to the discrepancies. Utilizing an adaptive delay compensation method may improve the accuracy and enable superimposing the responses at the same-time and yielding accurate results since the method may compensate the varying delay between the targets.
Table 6-6 Maximum and Minimum Surge Acceleration

<table>
<thead>
<tr>
<th></th>
<th>Maximum Surge Acceleration (in/sec²)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Surge Acceleration (in/sec²)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Simulation</td>
<td>2.304</td>
<td>38.910</td>
<td>-3.428</td>
<td>42.871</td>
</tr>
<tr>
<td>vdRTHS</td>
<td>2.313</td>
<td>38.901</td>
<td>-3.422</td>
<td>42.861</td>
</tr>
</tbody>
</table>

Figure 6-21 shows the displacement responses of the vdRTHS and the numerical simulation in pitch direction. The vdRTHS responses followed the track of the pitch response of numerical simulation and no significant discrepancies between the two responses are seen.

Figure 6-21 Pitch Displacement Comparison

Table 6-7 lists the maximum and minimum pitch displacement responses together with the time when they were reached. The difference between the minimum values is zero where it is 0.93% for the minimum ones. However, the maximum pitch displacement value of vdRTHS was reached 0.024 sec before that of numerical simulation where the minimum pitch displacement response of the vdRTHS was reached 0.033 sec before that of the numerical simulation. The results also show that superposition of the responses at different
time-steps did not cause the discrepancies since the instantaneous change in pitch displacement responses are not high.

<table>
<thead>
<tr>
<th>Table 6-7 Maximum and Minimum Pitch Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical Simulation</strong></td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Numerical Simulation</td>
</tr>
<tr>
<td>vdRTHS</td>
</tr>
</tbody>
</table>

Figure 6-22 shows the velocity responses of the vdRTHS and the numerical simulation in pitch direction. The pitch velocity responses of vdRTHS test followed the track of those captured in numerical simulation.

![Figure 6-22 Pitch Velocity Comparison](image)

Maximum and minimum pitch velocity responses are shown in Table 6-8 together with the time when they were achieved. The difference between the maximum and minimum values are negligible. On the other hand, the maximum response of the numerical simulation was
reached 0.003 sec after that of the vdRTHS, where minimum response of the numerical simulation was reached 0.01 sec after the vdRTHS.

Table 6-8 Maximum and Minimum Pitch Velocity

<table>
<thead>
<tr>
<th></th>
<th>Maximum Pitch Velocity (rad/sec)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Pitch Velocity (rad/sec)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Simulation</td>
<td>0.0037</td>
<td>41.653</td>
<td>-0.0036</td>
<td>42.483</td>
</tr>
<tr>
<td>vdRTHS</td>
<td>0.0037</td>
<td>41.650</td>
<td>-0.0036</td>
<td>42.473</td>
</tr>
</tbody>
</table>

Figure 6-23 shows the pitch acceleration responses of the vdRTHS and the numerical simulation. There are noticeable discrepancies observed between the responses of the numerical simulation and the vdRTHS, where the most noticeable is observed when the minimum peak response was obtained. Inaccurate superposition, which is due to the varying delay in vdRTHS, yielded inaccurate results at the points of high instantaneous change in pitch acceleration responses. To improve the robustness of the dRTHS tests of FWT structures, delay compensation methods shall be considered where the adaptive ones may also consider the varying delay to compensate and yield more accurate results.
Table 6-9 lists the maximum and minimum pitch acceleration responses together with the time when they were reached. The difference between the maximum values is 4.22% whereas the it is 6.68% for the minimum ones. Moreover, the maximum pitch acceleration response of the vdRTHS was reached 0.011 sec before the numerical simulation where the minimum response of the vdRTHS was reached 0.021 sec before the numerical simulation.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Pitch Acceleration (rad/sec²)</th>
<th>Time When It Reaches to Maximum (sec)</th>
<th>Minimum Pitch Acceleration (rad/sec²)</th>
<th>Time When It Reaches to Minimum (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Simulation</td>
<td>0.0237</td>
<td>44.822</td>
<td>-0.0389</td>
<td>41.722</td>
</tr>
<tr>
<td>vdRTHS</td>
<td>0.0227</td>
<td>44.811</td>
<td>-0.0363</td>
<td>41.701</td>
</tr>
</tbody>
</table>
6.5 Summary

This chapter started with the discussion of the properties and assumptions of the FWT prototype model. This FWT model was then validated through the numerical simulation of its responses subject to steady wind load that yielded reasonable responses when compared to those in the literature.

Then, the numerical simulation procedure and the simulation properties were presented. The duration of the loading histories was 60 secs, and the time step is 0.001 sec. Realistic wind speed and wave speed were obtained through adaption of the field data and their loading effects on the FWT model was determined based on the drag coefficient of the FWT and the pressure acting on the FWT body.

Next, numerical simulations of the FWT model subject to separate and simultaneous wave and wind loads were carried out and their responses were presented and discussed. It was observed that the sway, heave, roll and yaw responses of the model are negligible when the loads were applied only in surge direction. Particularly, the mooring lines restrained the heave motion. It was observed that the pitch and surge acceleration responses were governed by the wind load with higher frequency than the wave load. To demonstrate the applicability of superposition, the numerical simulation was divided as two parts in a Simulink model where the responses due to wind and wave loads were first simulated separately and then combined to obtain the total responses. Identical pitch and surge responses were achieved when compared to the responses obtained from the model subject to simultaneous loads which validated superposition of the responses to be adopted in vdRTHS.

Lastly, vdRTHS was conducted to simulate the FWT model. The two numerical parts were executed in two targets and the total responses was obtained by superposing responses from the two parts. Due to the Internet delay between the targets, artificially delayed (20 time-steps) wave load responses were used to enable the superposition of the responses at the same time-step and yield accurate results. Numerical simulation responses were also delayed for 20 time-steps to enable the accurate comparison of vdRTHS tests. According to the error
norm values, the best experiment was selected for evaluation. The responses verified the feasibility of dRTHS on capturing FWT responses when subject to wave and wind loading. The test yielded very accurate results in surge displacement and surge velocity responses despite the varying Internet delay in vRTHS. The acceleration responses in surge and pitch direction show that the varying delay leads to the superposition of the different time-steps in vRTHS, which may lead to discrepancies between the numerical simulation and the vRTHS when the instantaneous change in response amplitudes are high. The delay compensation methods using adaptive parameters may provide more accurate results at that point and improve the robustness of the dRTHS on capturing dynamic responses of FWT systems. To conclude, dRTHS is an applicable and a promising test method for FWT systems since it provides accurate results and its challenges are possible to be avoided by means of adaptive delay compensation methods.
7 CONCLUSION AND FUTURE WORKS

The goal of this thesis work is to improve the robustness of the distributed real-time hybrid simulation dRTHS environment and to expand its application from seismic evaluation of civil structural systems to other disciplines. To achieve this goal, a literature review on distributed hybrid simulation (dHS) and dRTHS was conducted first. It was found out that the combined time delay due to the network communication and the actuator dynamics may lead to inaccurate testing results in dHS and dRTHS experiments. In addition, only one delay compensation method originally developed for RTHS experiments has been investigated in the dRTHS environment. Hence, one objective of this study is to implement four selected delay compensation methods in dRTHS. Moreover, it was discovered from the literature review that no researcher yet investigated the applicability of dRTHS in evaluation of dynamic responses of FWT structural systems when subject to hazardous loadings. It was expected that dRTHS may overcome the limitations of the current experimental studies on FWT structures, such as complex coupled dynamics between the aerodynamic and hydrodynamic loads and the improper scaling of FWT prototypes due to this complexity. Hence, the second objective of this thesis is to investigate the feasibility of dRTHS application in capturing the dynamic behavior of FWT structural systems.

Chapter 2 reviewed the literatures on the developments in dHS and dRTHS experimental methods and the experimental methods for FWT structural systems. The literature on dHS and dRTHS indicated the importance of robust communication between the geographically distributed experimental/simulation facilities and proper compensation of time delay necessary for stable and reliable dRTHS experiments. On the other hand, literature review on the experimental testing methods in FWT systems revealed computational limitations in capturing the accurate responses of FWT structures. In addition, challenges of proper scaling of FWT systems was also mentioned. These limitations and challenges may be addressed when adopting dRTHS in FWT experimentation.
Chapter 3 discussed the theoretical background for this study. Equation of motion (EOM) for shear-type building model and the prototype FWT structure were presented, including the rigid-body dynamics of the FWT models adopted herein. Substructuring method in dRTHS was presented with their applications to the building and the FWT models. Newmark’s explicit integration algorithm was selected to solve the EOM of both models. Theoretical explanations of the selected four delay compensation in RTHS were provided. Terms such as desired, command and measured displacements were defined, where command displacement was predicted using a delay compensation method to ensure measured displacement match desired displacement. Adaptive parameters of two delay compensation methods, which compensate varying time delay values during a dRTHS test, were also introduced together with the four compensation methods.

Chapter 4 presented numerical simulations of the three-story shear-type building model and the implementation of the four delay compensation methods. For the delay compensation methods using adaptive parameters, a series of numerical simulations were carried out first to optimize the adaptive parameters. Then, the best adaptive parameters were selected, and numerical simulations were conducted for each compensation method. The accuracy of the compensation methods was compared and investigated by examine the differences between the measured displacements and the desired displacements. The findings from this numerical simulation study were utilized in dRTHS experiments in the next chapter and are summarized in Section 7.1.1.

The experimental investigation of the delay compensation methods for dRTHS was carried out at the Laboratory of Earthquake and Structural Simulation (LESS) and was presented in Chapter 5. Firstly, virtual dRTHS (vdRTHS) were carried out to verify the feasibility of the substructural modeling, the network communication and overall dRTHS test platform at LESS. Then, a series of dRTHS experiments were carried out for each delay compensation method immediately following an open-loop test from which the total time delay was estimated to optimize parameters used by the delay compensation methods. The performance of each method in the dRTHS experiments was compared against the results from numerical simulations and vdRTHS tests, to understand their effectiveness in compensating long and
varying delay values. The findings from the vdRTHS and physical dRTHS experiments are summarized in Section 7.1.2.

Chapter 6 presented an investigation on the potential of applying dRTHS to a FWT structure to capture its dynamic responses when subject to wind and wave loadings. FWT prototype, which was created based on several references, was subjected to the generated wind and wave loads and numerically simulated to obtain its dynamic response. Then, uncoupled numerical simulations were carried out to verify the substructuring method for the vdRTHS tests, during which the prototype FWT models was subjected to separate wave and wind loadings that were numerically simulated in two real-time computers and the responses were combined and compared with the coupled and uncoupled numerical simulation results. The findings of this pilot study on dRTHS application in FWT structure is discussed in Section 7.1.3.

7.1 Summary of Findings

7.1.1 Numerical Simulations of Delay Compensation Methods

To prepare dRTHS experiments on physical substructures, the selected four delay compensation methods were first implemented numerically in MATLAB/Simulink and their effectiveness were compared through numerical simulations.

Firstly, optimal adaptive parameters used in adaptive delay compensation methods were identified for the assumed time delay value of the dRTHS platform. For the adaptive inverse compensation (AIC) method, different $k_p$ and $k_i$ values were tested. The AIC method, which is modified based on the inverse compensation (IC) method using adaptive parameters, yielded less accurate results than IC for some $k_p$ values. The results showed that using adaptive parameters may improve delay compensation performance but was not assured. $\Delta \alpha$, the parameter which predicts the varying delay at each time-step, accounts for the accumulated varying delay till the current step, resulting in sometimes erroneous delay estimations that may jeopardize the accuracy and stability of dRTHS. Therefore, adaptive
parameters require careful tuning before adaptive delay compensation methods are adopted in dRTHS experiments.

After the optimization of the adaptive parameters for AIC and the adaptive time compensator (ATS) method, numerical simulations were carried out. A constant delay of 40 secs was assumed to be the total delay of the LESS dRTHS platform including both internet and actuator delay. The error norm results, which calculates the total error between the measured and desired displacements during the whole-time histories, proved the efficiency of the delay compensation methods in this constant, yet large, time delay case since there was more than 90% decrease in the error for all delay compensation methods.

Modified Feedforward (MFF) method and ATS yielded the best compensation results, where MFF predicted the command displacement values that almost made measured displacements identical to the desired ones. This superior performance of MFF may be due to its command displacements computed based on the measurements from the previous two steps. Also, it was found out that neglecting high order time derivatives does not adversely affect the performance of ATS in constant delay case.

### 7.1.2 Experimental Investigations of Delay Compensation Methods

After the numerical simulations, a series of vdRTHS and dRTHS tests were carried out. In vdRTHS tests, it was observed that IC did not properly predict the command displacements at the extremum points. It might be explained with equation 3.55, which shows that the command displacements are calculated based on the difference between the desired displacements of the last step and a step before that. Therefore, this method may predict the delay to be compensated but cannot predict when the sign of the difference changes, which might cause inaccuracy at the extremum points. Moreover, the same challenge was observed in vdRTHS tests using the AIC method, where effect of the adaptive parameters was also manifested by the results. AIC actually showed the best delay compensation performance in vdRTHS test, where the Internet delay varied in wide range.
MFF, which yielded the best results in numerical simulations with constant delay to be compensated, performed worse than the IC and AIC methods, especially for the extremum points. \( \alpha^2 \), the square of the delay constant which is used when calculating the displacement values, may cause inaccurate results with varying delay values in real cases since the square of the difference between the actual delay and the estimated delay is larger than the difference itself.

ATS, which showed the second-best performance in numerical simulations, predicted the most inaccurate results in vdRTHS experiments. The results showed that the high order time derivatives might improve the ATS method in vdRTHS through improved accuracy of the coefficients used to optimize the adaptive delay parameters at each time-step.

Lastly, dRTHS experiments were carried on a physical substructure of a steel column and the results proved the predominance of the AIC method over the other methods with very large and greatly varying time delays experienced in dRTHS. In the study, AIC was determined to be the best delay compensation method for vdRTHS and dRTHS experiments, especially in the dRTHS since the actuator delay is added onto the Internet delay which increase the uncertainty in the varying range of the delay. Moreover, dRTHS experiments totally revealed the sensitivity of the MFF method to the varying delay since MFF yielded worse results in dRTHS experiment when compared to its results in vdRTHS tests.

Only 3 stable ATS experiments were achieved which proved the necessity of using high order time derivatives in ATS in the dRTHS experiments that are expected to have large and varying delay values.

7.1.3 vdRTHS Tests on a FWT Prototype

To investigate the applicability of dRTHS in FWT systems, the numerical simulations and vdRTHS tests were carried out on the FWT prototype. Firstly, FWT prototype was subjected to wave and wind loading separately, and the numerical simulations were carried out. Then, the numerical simulation was carried out for the FWT model subject to simultaneous wind
and wave loads as is the usual case for a real FWT structure, and the total responses of the FWT were obtained.

It was observed that the responses in sway, heave, pitch and yaw directions were negligible when the loading was applied in the surge direction. Besides, the mooring line system particularly restrained the heave motion of the system. According to the numerical simulation results, the wind loading was observed to govern the acceleration responses due to its high frequency changes when compared to wave loading. Hence, the numerical simulation also indicated the possibility of the inaccurate responses in vdRTHS tests at the points of high instantaneous change in responses. Next, the FWT prototype was subjected to wind and wave load separately in a Simulink model, and the responses were combined using superposition. The identical results with the numerical simulation proved the applicability of superposition of FWT responses in real-time.

After proving the applicability of superposition, the FWT prototype was divided into two numerical parts and the vdRTHS tests were carried out. Evaluated error norm result of the best test showed that vdRTHS provided accurate results, especially in surge displacement and surge velocity responses despite the delay was not properly compensated. In the vdRTHS tests, the wave responses were also delayed in order to provide more accurate superposition of the responses. However, the delay was constant, and it might cause the superposition of the responses at different time-steps due to the varying delay in vdRTHS.

Even they were not erroneous, the discrepancies were observed between the surge acceleration amplitudes of the numerical simulation and the vdRTHS test when the instantaneous change in the responses amplitudes are high. On the other hand, there was no discrepancy observed at the pitch displacement responses, which shows that the superposition of the responses at different time-steps does not yield inaccurate results when the instantaneous change in responses are not high.

The results showed that the varying delay in dRTHS may yield inaccurate results when the high frequency loading, such as wind loading, governs the response amplitudes. The pitch
acceleration responses, which were governed by wind loading especially when the frequency change in wind loading was high, also supported this finding as the significant discrepancies were observed when the frequency of the wind load changes. The results indicated that the delay compensation methods using adaptive delay parameters shall be utilized in dRTHS tests on FWT systems to improve the robustness of dRTHS experiments.

To conclude, dRTHS is an applicable and feasible test method for FWT systems since it yields accurate responses. Moreover, dRTHS is a promising test method where delay compensation methods may overcome the challenges due to the varying delay and the sudden changes in loading frequency.

7.2 Future Work

Robustness of dRTHS and the applicability of dRTHS in FWT systems can be further benefited from the researches outlined below:

- **Using High Order Time Derivates in ATS:**

  Both vdRTHS and dRTHS experiments showed that the ATS method did not provide proper delay compensation when second order formulation was used to predict the command displacement. The ATS method uses the least squares method to find adaptive coefficients at each time-step and the results presented in the study indicated that high order time derivates shall be used to optimize the objective function used to find the adaptive coefficients, which were discussed in section 3.4.4. dRTHS performance of the ATS method can be improved with the studies investigating the effects of the high order time derivatives.

- **Using Adaptive Parameters in MFF:**

  On the contrary of the performance in constant delay values, MFF was observed to predict erroneous command displacements in both vdRTHS and dRTHS experiments.
Further studies can be carried out to add adaptive parameters in the MFF method to accommodate varying delay values in dRTHS.

- **Utilizing Adaptive Delay Compensation Methods in dRTHS Applications on FWT Systems:**

Comparison of the numerical simulations and the vdRTHS tests showed that the varying Internet delay caused inaccurate simulation of the dynamic responses of the FWT model. These inaccurate results were seen especially when there were high instantaneous changes in the responses, which were induced by the higher loading frequencies of the wind force. The adaptive delay compensation methods may be utilized to overcome this varying delay effects on the response simulation by using adaptive parameters to compensate the varying delay and improving the applicability of dRTHS to FWT systems.

- **Developing more realistic FWT Prototypes:**

In this study, which focused on demonstrating the possibility of applying dRTHS to FWT systems, a simplified FWT prototype model was created. However, the rotor and blades, which are important parts of a FWT system to capture wind energy, shall be modeled properly to yield more realistic wind turbine models that can be used to investigate the coupled dynamics of FWT systems. Moreover, installation of the ballast to the platform and the effects of the water on concrete and steel materials were not investigated in the study. In terms of improving the applicability of dRTHS in FWT systems, further studies shall be carried out to develop more realistic FWT prototypes to be tested using distributed testing facilities.
REFERENCES

Ahmed, M., I., (2016). Distributed Real-Time Hybrid Simulation at LESS. Master Project. Western Michigan University, Kalamazoo, MI, USA.


Laboratory of Earthquake and Structural Simulation, LESS. (2015) *Lab Manual*. Western Michigan University, Kalamazoo, MI, USA.


A. MATLAB AND SIMULINK FILES FOR THE INVESTIGATION OF DELAY COMPENSATION METHODS

Initial File for 3-Story Building Frame

```matlab
clc; clear all; close all;
%% Begin - Input Variables

g = 386.089;
%% Seismic mass and damping
%M Inertial properties are modeled analytically in PSD simulation.
M = zeros(3);
for i=1:3
    M(i,i)=0.003; % Mass matrix
end
Pcoeff = -M*ones(3,1);
zeta = 0.05; % Damping ratio of first two modes
%% Ground Motion
ga_scale = 0.2; % Scale for 'NORTH279' ground motion
load 'NORTH279.mat'
pga = max(abs(ga))*g*ga_scale; % Peak ground acceleration
%% Bouc-Wen parameters of experimental substructure
A = 1;
k = 0.17;
beta = 0.55;
gamma = -0.15;
n = 2;
alpha = 0.26;
%% Stiffness matrix
K = [2*k,-k,0;-k,2*k,-k;0,-k,k];
%% Natural frequency and period
[v,D]=eig(K,M); % Evaluate natural frequencies and natural modes
Wn=zeros(1,3);
Tn=zeros(1,3);
for i=1:3
    Wn(i)=sqrt(D(i,i)); % Extract natural frequencies
    Tn(i)=2*pi/Wn(i); % Extract natural periods
end
%% Damping matrix
a0=zeta*2*Wn(1)*Wn(2)/(Wn(1)+Wn(2));
a1=zeta*2/(Wn(1)+Wn(2));
C=a0*M+a1*K; % Damping matrix
```
%% Explicit Newmark parameters
dt = 0.001;                  % Time step
gammaN = 0.5;                % Scaling ground motion
Meff = M+dt*gammaN*C;
num = length(ga);

% Interpolate ground acceleration and calculate new time step, dt
t1 = linspace(0,(num-1)*dtga,num);
ni = floor((num-1)*dtga/dt + 1);
t = linspace(0,(ni-1)*dt,ni);
ga = interp1(t1,ga,t);
t = t(:);
Ag = ga(:);
tga = [t,ga];

%% Feedforward compensation
Tau=0.04;
EnTa=Tau/dt;

%% Modified Feedforward compensation (paper ID216)

Simulink Model

Prediction (Explicit Newmark Part 1)

function [Dp,Vp] = Prediction(D,V,A,dt,gammaN)
Dp = D+dt*V+dt^2/2*A;
Vp = V+dt*(1-gammaN)*A;

**Correction Step (Explicit Newmark Part 2)**

function [V,A] = Correction(P,F,C,Vp,Meff,dt,gammaN)

A=Meff*(P-F-C*Vp);
V=Vp+dt*gammaN*A;

**Bouc-Wen Model**

![Bouc-Wen Model Diagram]

**Bouc-Wen Part 1**

function z_dot=z_dot(A,z,beta,gamma,n,V)

z_dot=A*V-beta*abs(V)*abs(z)^(n-1)*z-gamma*V*abs(z)^n;

**Bouc-Wen Part 2**

function F=F(alpha,k,D,z)

F=alpha*k*D+(1-alpha)*k*z;
**IC Simulink Block**

![IC Simulink Block Diagram]

**MFF Simulink Block**

![MFF Simulink Block Diagram]

**MFF Coefficients**

MFF1 = 1 + Enta + Enta^2/2;

MFF2 = -(Enta + Enta^2);
MFF3=\text{Enta}^2/2;

**AIC Simulink Model**

![Simulink Diagram]

**AIC (Command Displacement and \( \Delta \alpha \))**

function \([\text{Area} \_\text{out}, \text{TA} \_\text{out}, \text{dc} \_\text{out}, \text{TI}, \Delta \alpha, \text{dif}, \text{dc} \_\text{out2}] = \text{solve}\_\text{dc}(\text{MEA}, \text{dm}, \text{DES}, \text{dd}, \text{Area}, \text{TA}, \text{TTTotal}, \text{kp}, \text{ki}, \text{Alpha})\)

%#codegen

\[
\begin{align*}
\text{Area} \_\text{out} &= \text{Area} + (0.5 \times (2 \times \text{dd}) - \text{DES}) \times \text{MEA}; \\
\text{TA} \_\text{out} &= \text{TA} + (0.5 \times (2 \times \text{dm}) - \text{MEA}) \times \text{DES}; \\
\text{TI} &= 0.5 \times (\text{Area} \_\text{out} - \text{TA} \_\text{out}); \\
\Delta \alpha &= (\text{kp} \times \text{TI}) + (\text{ki} \times \text{TTTotal}); \\
\text{Alpha1} &= \text{Alpha} + \Delta \alpha; \\
\text{dc} \_\text{out} &= \text{dd} + (\text{Alpha1} - 1) \times \text{DES}; \\
\text{dif} &= \text{dm} - \text{dd}; \\
\text{dc} \_\text{out2} &= \text{dc} \_\text{out}^2;
\end{align*}
\]

**ATS Simulink Model**
ATS (Parameter Determination for ATS)

function [Acoef,Acoef1,Acoef2] = ATS2(dm,dmt,dmtt,dc)

%#codegen ATS paper Equation (6)
Dmea=[dm,dmt,dmtt];
Acoef1=(Dmea'*Dmea)^-1;
Acoef2=Dmea'*dc;
Acoef=Acoef1*Acoef2;

ATS (Command Displacement Simulink Model)

ATS (Command Displacement)
function dcom = ATS(A,dd,ddt,ddtt)

%#codegen ATS paper Equation (9)
dstate=[dd,ddt,ddtt];
dcom=dstate*A;

vdRTHS and dRTHS Simulink Models in PC-RT

MFF

IC
Mapping in vdRTHS (PC-RT)

For IC and MFF

For AIC and ATS
Mapping in vdRTHS (PXI-RT)

Mapping in dRTHS (PC-RT)

For IC and MFF
For AIC and ATS

Mapping in dRTHS (PXI-RT)
B. FWT MODEL PARAMETERS

Tower and platform masses were not given in the selected FWT. Regarding the literature, total tower mass (including rotor, nacelle, hub) were assumed to be 10% of the total mass. This assumption also proves that the COM of system is under water line. Moreover, radius of tower was also assumed as 2/3 of the platform, which is 4m (Karimirad and Moan, 2011).

Moreover, even it was not stated, floating platform and tower were assumed as hollow cylinder since the mass of the platform would be bigger than the entire mass of the FWT if it was solid cylinder, where it is also same for tower. Along with the assumptions, the following calculation were made to match the properties of the selected FWT. Platform and tower material was selected as steel with a density of 8050 kg/m³.

\[ m_{\text{plat}} = m_{\text{system}} - m_{\text{ballast}} - m_{\text{tower}} = 213000 \text{ kg} = 1211 \text{ lbf}.\text{sec}^2/\text{in} \]  \hspace{1cm} (A.1)

\[ \rho_{\text{steel}} = 8050 \text{ kg/m}^3 \]  \hspace{1cm} (A.2)

\[ V_{\text{plat}} = 26.45 \text{ m}^3 = \pi (r_{\text{out}}^2 - r_{\text{in}}^2)T = \pi (36 - r_{\text{in}}^2)20 \]  \hspace{1cm} (A.3)

\[ r_{\text{in}} = 5.965 \text{ m} = 236.22 \text{ in} \]  \hspace{1cm} (A.4)

\[ t_{\text{plat}} = 35 \text{ mm} = 0.035 \text{ m} = 1.378 \text{ in} \]  \hspace{1cm} (A.5)

where \( V_{\text{plat}} \) is the volume of the floating platform and \( m_{\text{plat}} \), \( m_{\text{ballast}} \) and \( m_{\text{tower}} \) are the mass of platform, ballast and tower, respectively. According to the calculation, thickness of the platform, \( t_{\text{plat}} \), and inner radius of the platform, \( r_{\text{in}} \), were chosen as 0.035 m and 5.965 m, respectively.
The following calculation procedure was conducted to find the thickness of the tower. It should be noted that rotor and nacelle masses were neglected in the study to simplify the calculations.

\[ m_{\text{tower}} = 198000 \text{ kg} = 1130 \text{ lbf} \cdot \text{sec}^2 / \text{in} \]  
(A.6)

\[ V_{\text{tower}} = 24.59 \text{ m}^3 = \pi (r_{\text{out}}^2 - r_{\text{in}}^2)T = \pi (16 - r_{\text{in}}^2)84 \]  
(A.7)

\[ r_{\text{in}} = 3.988 \text{ m} = 157.00 \text{ in} \]  
(A.8)

\[ t_{\text{tower}} = 12 \text{ mm} = 0.012 \text{ m} = 0.472 \text{ in} \]  
(A.9)

\[ V_{\text{tower}} \] is the volume of the tower. According to the calculation, thickness and inner radius of the tower, \( t_{\text{plat}} \), and \( r_{\text{in}} \), were chosen as 0.012 m and 3.988 m, respectively.

In FWT structures, the ballast is used to bring the COM of FWT down to provide its stability and increase the hydrostatic restoring force of FWT structure (Karimirad and Moan, 2011). Since the properties of the ballast were not given, the position of ballast was determined to provide the same COM with the referenced turbine.

The ballast was assumed to be inside of the platform since it is physically impossible to provide the referenced COM (of the ballasted structure) if the ballast was used at the bottom of the platform. Moreover, the radius of ballast was assumed as the inner radius of the platform to avoid new challenges sourced from the difference in dimensions. In brief, the ballast was assumed as fixed mass block inside of the cylindrical FWT platform. The position of the center of ballast was calculated as follows:

\[ \frac{m_{\text{ballast}}(z_{\text{ballast}}) + m_{\text{tower}}(z_{\text{tower}}) + m_{\text{plat}}(z_{\text{plat}})}{m} = -5.74 \text{ m} \]  
(A.10)

\[ z_{\text{tower}} = 42 \text{ m}, \ z_{\text{plat}} = -10 \text{ m} \]  
(A.11)

\[ z_{\text{ballast}} = -4.67 \text{ m} = -183.858 \text{ in} \]  
(A.12)
\(z_{ballast}, z_{tower}, z_{plat}\) is the COM of the ballast, the tower and the platform, respectively.

The results proved the assumption that the ballast is not at the bottom of the spar.

Moreover, thickness of the ballast was not given. Concrete ballast (concrete block) was assumed to and the thickness of ballast was calculated, as shown in equation A.13 and A.14. As well as steel platform, the structural damages of water on concrete was not investigated.

\[
m_{ballast} = 1569000 \text{ kg} = \rho \cdot A_{b} \cdot t_{ballast} = (2400 \text{ kg} / \text{ m}^3)(\pi \cdot (5.965 \text{ m})^2)(t) \quad \text{(A.13)}
\]

\[
t_{ballast} = 5.84 \text{ m} = 229.921 \text{ in} \quad \text{(A.14)}
\]

Thickness of the ballast, \(t_{ballast}\), was assumed as 5.84 m.

Mass moment of inertia of system for roll, pitch and yaw motion, which are \(I_{11}, I_{22}\) and \(I_{33}\), respectively, regarding the following equations (Singh, 2011). Shapes of the tower and the platform are hollow cylinder where the ballast is solid cylinder.

\[
I_{11} = I_{22} = \frac{M}{12}(3(r_{out}^2 + r_{in}^2) + I^2) \text{ (Hollow Cylinder)} \quad \text{(A.15)}
\]

\[
I_{33} = M \cdot (r_{out})^2 \text{ (Hollow Cylinder)} \quad \text{(A.16)}
\]

\[
I_{33} = \frac{M \cdot r^2}{2} \text{ (Solid Cylinder)} \quad \text{(A.17)}
\]

The mass moment of inertia of the FWT in roll, pitch and moment were determined as follows:

\[
I_{11} = I_{22} = 1.43 \times 10^8 \text{ kg.m}^2 \quad \text{(A.18)}
\]

\[
I_{33} = 4.216 \times 10^8 \text{ kg.m}^2 \quad \text{(A.19)}
\]

Then, mass matrix and added mass matrix of the FWT were obtained, which are:
So, the total mass matrix of the FWT system is:

\[
M_{\text{tot}} = 
\begin{bmatrix}
  4.299e6 \text{kg} & 0 & 0 & 0 & 1.182e7 \text{kg.m} & 0 \\
  0 & 4.299e6 \text{kg} & 0 & -1.182e7 \text{kg.m} & 0 & 0 \\
  0 & 0 & 2.907e6 \text{kg} & 0 & 0 & 0 \\
  0 & -1.182e7 \text{kg.m} & 0 & 4.522e8 \text{kg.m} \cdot \text{m} & 0 & 0 \\
  1.182e7 \text{kg.m} & 0 & 0 & 0 & 4.522e8 \text{kg.m} \cdot \text{m} & 0 \\
  0 & 0 & 0 & 0 & 0 & 4.216e8 \text{kg.m} \cdot \text{m}^2 \\
\end{bmatrix}
\]  

(A.22)

The hydrostatic restoring matrix of the platform and the mooring lines are shown below:

\[
K_{\text{hyd}} = 
\begin{bmatrix}
  0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1.137e6 \text{N/m} & 0 & 0 & 0 \\
  0 & 0 & 0 & 5.041e7 \text{N.m} & 0 & 0 \\
  0 & 0 & 0 & 0 & 5.041e7 \text{N.m} & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]  

(A.23)
Natural period and frequency values are shown as follows:

\[ T = \begin{bmatrix} 34.903 & 34.903 & 0.567 & 1.658 & 1.658 & 57.602 \end{bmatrix} \text{sec} \quad \text{(A.26)} \]

\[ \omega = \begin{bmatrix} 0.18 & 0.18 & 11.082 & 3.789 & 3.789 & 0.109 \end{bmatrix} \text{rad/sec} \quad \text{(A.27)} \]

Damping ratio of the FWT structure was taken as 0.02 in the study (Karimirad, 2014). Damping matrix is presented below:

\[ C = \begin{bmatrix} 1.6e+4 \text{N/m/s} & 0 & 0 & 0 & -6.4e+4 \text{N/s} & 0 \\ 0 & 1.6e+4 \text{N/m/s} & 0 & 6.4e+4 \text{N/s} & 0 & 0 \\ 0 & 0 & 2e+7 \text{N/m/s} & 0 & 0 & 0 \\ 0 & 6.4e+4 \text{N/s} & 0 & 3.6e+8 \text{N/m/ rad/s} & 0 & 0 \\ -6.4e+4 \text{N/s} & 0 & 0 & 0 & 3.6e+8 \text{N/m/ rad/s} & 0 \\ 0 & 0 & 0 & 0 & 1.2e+6 \text{N/m/ rad/s} & 0 \end{bmatrix} \quad \text{(A.28)} \]
C. MATLAB AND SIMULINK FILES USED FOR THE EVALUATION OF THE FWT PROTOTYPE

Initial File for FWT Prototype

```matlab
% Multiple Degree of Freedom Systems

% The response of a FWT structure is analyzed using the Newmark-Linear Acceleration method when the structure is exposed to the wave and wind loading.

clear;

g=386.4; % gravity, in/s^2
H_t=3308; %height of tower, in
rt=157.48; %radius of tower, in, equal to 4m, taken as 2/3 of platform diameter

m_system=11300; %mass of system, lbf.sec^2/in
m_ballast=8959; %mass of ballast, lbf.sec^2/in
m_tow=m_system/10; %mass of tower, lbf.sec^2/in
m_plat=m_system-m_ballast-m_tow; %mass of platform, lbf.sec^2/in
mass=m_system; %mass, lbf.sec^2/in
T=787.4; %Draft, in
t_ballast=229.921; %thickness of ballast, in
r=236.22; %Platform radius, in
rt=157.48; %radius of tower, in, equal to 4m, taken as 2/3 of platform diameter
r_in=234.842; %platform inner radius, in
r_int=157; %tower inner radius, in
zg=-225.984; %Center of Mass system, z direction, in
zb=-78.74; %center of buoyancy, in
yg=0; %Center of Mass, y direction, in
xg=0; %Center of Mass, x direction, in

I11=[m_tow*[3*(r^2)+r_int^2]+(H_t^2)/12]+[m_plat*[3*(r^2)+r_in^2]+T^2]/12]+[m_ballast*r^2]/4;
I22=I11;
z_bal=-183.858; %distance of com of ballast to water level, in
z_plat=-393.7; %distance of com of plat to water level, in
z_tow=1653.543; %distance of com of tower to water level, in
```

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I33\_out=[(m\_ballast*r^2)/4]+[(m\_plat*r^2)/4]+[(m\_tow*rt^2)/4]+[m\_ballast*(z\_bal^2)]+[m\_plat*(z\_plat^2)]+[m\_tow*(z\_tow^2)];

I33=I33\_out;

r\_wl=236.22; %radius at water level, in
rho=0.0000959; %density of water, lbf sec^2/in4

W=(m\_ballast+m\_plat)*g; %weight of system under waterline, lbf
F\_b=W; %buoyancy force, lbf
V=F\_b/(rho*g); %submerged volume, in^3

A\_0=pi()\*r\_wl^2; %water-plane area, in^2

M\_sys=[mass 0 0 (mass*zg) (-mass*yg);0 mass 0 (mass*zg) 0 (mass*xg);0 0 mass (mass*yg) (-mass*xg) 0 (mass*yg);111 0 0;0 (mass*zg) 0 I\_xx]; % Mass matrix

I\_xx=pi*(r^4-r\_in^4)/4; %moment of inertia of platform at -x direction, in^4
I\_yy=pi*(r^4-r\_in^4)/4; %moment of inertia of platform at -y direction, in^4

A\_mass=zeros(6,6); %added mass matrix
A\_mass(1,1)=pi*rho*((r^2)^3)/3; %lbf.sec^2/in
A\_mass(2,2)=A\_mass(1,1); %lbf.sec^2/in
A\_mass(3,3)=4*pi*rho*((r^3))/3; %lbf.sec^2/in
A\_mass(4,4)=pi*rho*((r^3)^3)/3; %lbf.sec^2/in
A\_mass(5,5)=A\_mass(4,4);
A\_mass(5,1)=pi*rho*((r^2)*((T^2)/2);
A\_mass(1,5)=A\_mass(5,1);
A\_mass(4,2)=-pi*rho*((r^2)*((T^2)/2);
A\_mass(2,4)=A\_mass(4,2);

%Establish Structural Properties
df=6; %Number of Degrees of Freedom
m=(M\_sys+A\_mass); %mass matrix % in lbf-s^2/in

K\_hydro=zeros(6,6); %hydrostatic restoring matrix, N/m and Nm/rad,
K\_hydro(3,3)=rho*g*A\_0; %lbf/in=0.001 kips/in
K\_hydro(4,4)=[(-W*zg)+(F\_b*zb)+(rho\_g*A\_xx)+(rho\_g*A\_yy^2)]; %lbf.in=0.001 k.in
K\_hydro(5,5)=[(-W*zg)+(F\_b*zb)+(rho\_g*A\_xx)+(rho\_g*A\_yy^2)]; %lbf.in=0.001 k.in

EA\_lines=337213415; %structural stiffness of lines, lbf

T\_bottom=138707.118; %Fairlead Tension of bottom Mooring Lines,lbf,
L_bottom=5043.307; %Length of bottom lines, in
D_bottom=787.401; %distance of bottom lines to water line, in
T_top=123644.919; %Fairlead Tension of Top Mooring Lines, lbf
L_top=5570.866; %Length of Top lines, in

K_linear=zeros(6,6); %linearized restoring matrix of mooring lines
K_linear(1,1)=4*[4*T_bottom/L_bottom]+(4*T_top/L_top);%Fairlead Tension of Top Mooring Lines, lbf
K_linear(2,2)=K_linear(1,1);
K_linear(3,3)=4*[4*EA_lines/L_top]+(4*EA_lines/L_bottom);%Fairlead Tension of Top Mooring Lines, lbf
K_linear(4,4)=4*[4*pi*D_bottom^2/L_bottom]+4*[2*(EA_lines/L_bottom)*r^2]+4*[4*pi*D_bottom]+4*[2*(EA_lines/L_top)*r^2];%Fairlead Tension of Top Mooring Lines, lbf
K_linear(5,5)=K_linear(4,4);
K_linear(6,6)=4*[4*T_bottom*r^2/L_bottom]+(4*T_top*r^2/L_top);%Fairlead Tension of Top Mooring Lines, lbf
K_linear(2,4)=4*[4*pi*D_bottom/L_bottom];%Fairlead Tension of Top Mooring Lines, lbf
K_linear(4,2)=K_linear(2,4);
K_linear(1,5)=-K_linear(2,4);
K_linear(5,1)=K_linear(1,5);

k=(K_hydro+K_linear); %stiffness matrix % in lbf/in

Wn(1,1)=sqrt(k(1,1)/m(1,1));
Wn(1,2)=sqrt(k(2,2)/m(2,2));
Wn(1,3)=sqrt((K_linear(3,3))/(m(3,3)));%Fairlead Tension of Top Mooring Lines, lbf
Wn(1,4)=sqrt((k(4,4))/(m(4,4)));%Fairlead Tension of Top Mooring Lines, lbf
Wn(1,5)=sqrt((k(5,5))/(I22+A_mass(5,5)));%Fairlead Tension of Top Mooring Lines, lbf
Wn(1,6)=sqrt((k(6,6))/(m(6,6)));%Fairlead Tension of Top Mooring Lines, lbf

Tn=(Wn.^-1)*2*pi; % natural period
zeta=0.02;
a0=zeta*2*Wn(1)*Wn(2)/(Wn(1)+Wn(2));
a1=zeta*2/(Wn(1)+Wn(2));
C_sys=a0*m+a1*k; % Damping matrix

c=C_sys; % Damping matrix % in lbf-s/in

%Newmark Parameters
gamma = 1/2;
beta = 1/6;
dt=0.001;

% load Manzanillo_dt1.mat
% Natural frequency and period
[v,D]=eig(k,m);  % Evaluate natural modes and natural frequencies

% Normalize the Structural Properties
M=v'*m*v;
C=v'*c*v;
K=v'*k*v;

Simulink Model of FWT Prototype

FWT Response
function [u,q,ud,qd,udd,qdd] = MDOFMyFunction(dWave,dWind,M,C,K,v,gamma,beta,dt,qi,qdi,qddi)
%Initial Calculations

\[
p = \text{zeros}(6,1);
p(1,1) = \text{dWave} + \text{dWind}; \quad \% \text{Total Difference of Surge Force}\n\]
\[
p(5,1) = [\text{dWind} \times 3308 \times 2/3] - [787.4 \times \text{dWave}/2]; \quad \% \text{Different of Pitch Moment at the Platform (Induced by Wind), } 3308 \text{ in=Height of Tower}\n\]
\[
P = (v' \times p);\n\]
\[
dP = P;\n\]
\[
k_{c1} = (\gamma/(\beta \times dt)) \times C + (1/(\beta \times (dt^2))) \times M;\n\]
\[
Khat = K + k_{c1};\n\]
\[
dc_{2} = (1/\beta) \times M + (\gamma/\beta) \times C;\n\]
\[
dc_{3} = (1/(2 \beta)) \times M + dt \times ((\gamma/(2 \beta)) - 1) \times C;\n\]
\[
v_{c1} = \gamma/(\beta \times dt);\n\]
\[
v_{c2} = ((\gamma/\beta));\n\]
\[
v_{c3} = dt \times (1 - 0.5 \times \gamma/\beta);\n\]
\[
ac_{1} = 1/(\beta \times dt^2);\n\]
\[
ac_{2} = 1/(\beta \times dt);\n\]
\[
ac_{3} = (0.5/\beta);\n\]

%Looping Calculations

\[
dPhat = dP + dc_{2} \times qdi + dc_{3} \times qddi;\n\]
\[
dqi = (Khat^{-1}) \times dPhat;\n\]
\[
dqdi = vc_{1} \times dqi - vc_{2} \times qdi + vc_{3} \times qddi;\n\]
\[
dqddi = ac_{1} \times dqi - ac_{2} \times qdi - ac_{3} \times qddi;\n\]
\[
q = dqi + qi;\n\]
\[
qd = dqdi + qdi;\n\]
\[
qdd = dqddi + qddi;\n\]
\[
u = v \times q;\n\]
\[
u_d = v \times qd;\n\]
\[
u_{dd} = v \times qdd;\n\]