Nonlinear Dynamic Finite Element Simulation of Hydroelastic Mounts for Light Weight Vehicles

Talla Jayapal Reddy

Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses

Part of the Mechanical Engineering Commons

Recommended Citation


https://scholarworks.wmich.edu/masters_theses/825

This Masters Thesis-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Master's Theses by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
NONLINEAR DYNAMIC FINITE ELEMENT SIMULATION
OF HYDROELASTIC MOUNTS FOR LIGHT WEIGHT VEHICLES

by

Talla Jayapal Reddy

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Mechanical and
Aeronautical Engineering

Western Michigan University
Kalamazoo, Michigan
June 1993
Nonlinear Dynamic Finite Element Simulation
Of Hydroelastic Mounts for Light
Weight Vehicles

Talla Jayapal Reddy, M.S.
Western Michigan University, 1993

Modern light weight vehicles generate large noise levels, that may need bulky classical rubber mounts to suppress. Hydroelastic mounts can significantly reduce the vibration level of current production automobiles without weight penalty. However, the highly nonlinear behavior of hydroelastic mounts has not been established yet and its use is, therefore, limited to trial and error design methods.

This study discusses the implementation of nonlinear finite element simulation of hydroelastic mounts using the ANSYS finite element code. Fluid elements are limited to linear analysis and therefore are incompatible with the nonlinear hyperelastic elements. A method is proposed to simulate the fluid as an equivalent rubber element by comparing their linear static deflections and small displacement dynamic responses. Thus, the equivalent properties of the hyperelastic elements have been defined for the further nonlinear analysis. A parametric study is done for mounts with different geometric configurations and different durometer hardness of rubber material.
ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Judah Ari-Gur, for his interest and valuable suggestions during the research and preparation of this thesis. I extend my sincere appreciation to Dr. Jerry H. Hamelink and Dr. Dennis J. VandenBrink for their continuous support and constructive comments on this thesis.

I owe a dept of gratitude to all my family who continuously provided support and encouragement.

Talla Jayapal Reddy
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
Nonlinear dynamic finite element simulation of hydroelastic mounts for light weight vehicles

Reddy, Talla Jayapal, M.S.
Western Michigan University, 1993
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ..................................................... ii

LIST OF TABLES ................................................................. v

LIST OF FIGURES ................................................................. vii

CHAPTER

I. INTRODUCTION ................................................................. 1

II. MODELS ............................................................................. 5

III. FINITE ELEMENT MODELING .......................................... 9

  Static Analysis ................................................................. 11
  Modal Analysis ............................................................... 13
  Dynamic Analysis ............................................................ 15
  Iterative Procedures ......................................................... 15

IV. PARAMETRIC STUDY ....................................................... 25

  Static Loading - Effect of Durometer Hardness .................. 25
  Static loading - Effect on Geometries ............................... 25
  Modal Analysis ............................................................... 28
  Effect of Variation in Pressure Loading ............................ 29

V. NONLINEAR TRANSIENT DYNAMIC ANALYSIS ............... 33

  Effect of Concentrated Load ............................................. 34
  Uniform Pressure Loading ................................................ 42

iii
VI. CONCLUSIONS .......................................................... 48

APPENDICES

A. ANSYS Code for Static Analysis for Model MH ..................... 49
B. ANSYS Code for Static Analysis for Model MF ...................... 52
C. ANSYS Code for Modal Analysis
   for Model MH ........................................................... 55
D. ANSYS Code for Modal Analysis
   for Model MF ........................................................... 58
E. ANSYS Code for Dynamic Analysis
   for Model MH ........................................................... 61
F. ANSYS Code for Dynamic Analysis
   for Model MF ........................................................... 64
G. ANSYS Code for Nonlinear Transient
   Dynamic Analysis for Model M1 ..................................... 67
H. ANSYS Code for Nonlinear Transient
   Dynamic Analysis for Model M2 ..................................... 70
I. ANSYS Code for Nonlinear Transient
   Dynamic Analysis for Model M3 ..................................... 73
J. ANSYS Code for Nonlinear Transient
   Dynamic Analysis for Model M4 ..................................... 76

BIBLIOGRAPHY ............................................................ 80
LIST OF TABLES

1. Convergence Test on Model With Complete Hyperelastic Elements ........................................... 10

2. The Values of Young’s Modulus and Mooney-Rivlin Constants for Different Durometer Hardness of Rubber Material ....................................................................................... 12

3. Static Analysis on Model M1 Subjected to Different Load Intensities for Durometer Hardness 70 and 50 ........................................................................................................ 26

4. Deflections of Node 421 on Models M1, M2, M3 and M4 for Different Static Loading Conditions (Uniform Pressures) Applied on the Surface of the Models ....................................................................................... 27

5. The Natural Frequencies of 1st Four Modes of Models M1, M2, M3 and M4 Resulted from Modal Analysis ........................................................................................................ 29

6. Natural Frequencies for Different Durometer Hardness of the Model M1. The First 5 Modes are Considered ........................................................................................................ 30

7. Deflections of Node 421 for Varying Pressure Load Intensities ........................................................................................................ 31

8. De{\check{s}}ections on Node 421 Due to the Dynamic Loading on Geometry 1 (M1) for Different Durometer Hardness ........................................................................................................ 38

9. Deflection on Node 421 Due to the Dynamic Loading on Model M2 for Different Durometer Hardness ........................................................................................................ 39

10. Deflections on Node 421 Due to the Dynamic Loading on Model M3 and Model M4 for Durometer Hardness of 70 ........................................................................................................ 40

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
List of Tables-Continued

11. Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M1 for Different Durometer Hardness of Rubber Material .................................................... 44

12. Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M2 for Different Durometer Hardness of Rubber Material .......................................................................................................... 45

13. Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M4 for Different Durometer Hardness of Rubber Material .......................................................................................................... 47
LIST OF FIGURES

1. Representation of a Typical Hydroelastic Mount ........................................ 6

2. Geometric Configurations of Axisymmetric Models M1, M2, M3, M4 ......................... 7

3. Convergence of Deflection at Top Center of the Model Using Hyperelastic Elements .......................................................... 10

4. Block Diagram for the Iterative Procedure for Nonlinear Analysis .......................................................... 18

5. Time Dependent Ramp Loading for Dynamic Analysis .......................................................... 18

6. Transient Axial Displacement of Simulated Model MH With 1N/rad Peak Load .......................................................... 20

7. Transient Axial Displacement of Rubber + Fluid Model MF With 1N/rad Peak Load .......................................................... 20

8. Transient Axial Displacement of Simulated Model MH With 5N/rad Peak Load .......................................................... 21

9. Transient Axial Displacement of Rubber + Fluid Model MF With 5N/rad Peak Load .......................................................... 21

10. Displaced Structure of the Meshed Simulated Model M1H Under Dynamic Loading, for a Peak Load of 1N/rad .......................................................... 22

11. Displaced Structure of the Meshed Rubber + Fluid Model MF Under Dynamic Loading, for a Peak Load of 1N/rad .......................................................... 22

12. Displaced Structure of the Meshed Simulated Model MH Under Dynamic Loading, for a Peak Load of 5N/rad .......................................................... 23

13. Displaced Structure of the Meshed Rubber + Fluid Model MF Under Dynamic Loading, for a Peak Load of 5N/rad .......................................................... 23

vii

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
List of Figures-Continued

14. Deflection of Node 421 of Model M1, Subjected to Static Loading for Different Durometer Hardness of Rubber Material ........................................................ 26

15. Deflection Profiles of Node 421 for Models M1, M2, M3 and M4 Subjected to Different Static Loading (Uniform Pressure) Conditions ..................................................... 28

16. Variations of Loading Conditions from Concentrated Load to Uniformly Distributed Load. The Total Force on Model is Kept Constant (10 N/rad) .................................................. 30

17. Deflections of Node for Model M1, Subjected to Different Intensities of Pressure Loading ............................................................... 32

18. A Concentrated Load Acting on the Model M1, and the Time Dependent Triangular Pulse ......................................................... 34

19. Illustration of Impulsive, Resonant and Quasi-Static Loading Conditions Applied on Models ....................................................... 35

20. Deflection Profile of Node 421 for Impulsive Loading Pulse ................................................................................................. 36

21. Deflection Profile of Node 421 for Resonant Loading Pulse ................................................................................................. 36

22. Deflection Profile of Node 421 for Quasi-Static Loading Pulse ................................................................................................. 37

23. Deflection Profiles of the Model M1, M2, M3 and M4 Subjected to Point Loading of 10 N/rad ....................................................... 41

24. Deflection Profiles of Model M1 for Different Durometer Hardness Subjected to Point Loading of 10 N/rad ....................................................... 41

25. Deflection Profiles of Model M2 for Different Durometers Hardness Subjected to Point Loading of 10 N/rad ....................................................... 42
List of Figures-Continued

26. Uniform Pressure Loading of the Model M1, and the Time Dependent Triangular Pulse ........................................ 43

27. Deflection Profiles for Different Models M1, M2 and M4 for Durometer Hardness of 60 ........................................ 43

28. Deflection Profiles of Model M4 With Varying Durometer Hardness of Rubber ..................................................... 46

29. Effect of Incompressibility on the Model M4, in Dynamic Analysis ................................................................. 46
CHAPTER I

INTRODUCTION

Much work has been done and applied on hydroelastic mounts for the automobile industry. For light weight cars and small number of engine cylinders the vibration and noise problem becomes more severe. To counteract this problem, the engines need softer mount systems which produce relatively large deflections. However, the 'soft' mounting system which is required to minimize noise levels is inadequate to maintain engine movement control which requires a 'stiff' mounting system. Hence, an optimal mount should provide low stiffness in the relatively high range of noise frequencies and high stiffness in the low frequency range of engine movement.

A mathematical model was developed by Clark [1], which described the dynamic performance (< 400 Hz) of a hydraulic mount. This model deals with the linear dynamic performance and does not account for the nonlinearity of the mount, encountered with rubber components.

From the work of Clark [1], the mathematical models generated a dynamic performance which increased as the input frequencies increased from a low value to resonance and subsequently there was a drop in the performance for high frequencies thereafter. Particularly with 4 cylinder engines, the increase in dynamic stiffness at
the fluid resonance frequency, can adversely effect the noise levels within a vehicle [1]. However, it is desirable to have a better understanding of the high frequency dynamic characteristics of the hydroelastic mounts, so that their performance can be adjusted to suit a particular application.

To improve the low frequency isolation requires the hydraulic mount stiffness ratio to be as large as possible, but this will be at the detriment of some high frequency isolation. If its low frequency isolation benefits are not compromised, it is important at the initial mount design stage to give adequate consideration to the high frequency performance of the hydraulic mount.

New polymers have been developed that permit specification of the amount of damping. Polymers have also become available that can withstand higher engine compartment temperatures. Rubber compounders have found ways, by formulation and processing techniques, to provide specific dynamic properties and to improve consistency of these properties in respect to the vehicle environment.

Two major development which evolved with packaging technology of the mounts are preloaded rubber to enhance durability and introduce of interlocks to prevent excessive engine motion [2]. The most desirable performance of a hydroelastic mount should have high damping at low frequencies where control is required and low damping at high frequencies where isolation is important. Another desirable characteristic is to have high damping coefficient for large inputs where energy absorption is required and a low damping coefficient for small inputs where isolation is important.
Sugino and Abe [7], in their work on hydroelastic engine mounts, developed a mechanical model which serves to understand the mechanism of the hydroelastic mount, as well as making it possible to incorporate the mount into a vibration model. This mechanical model consists of a mass, springs and a dashpot. The results obtained by the model were compared with experimental values and were in agreement for different orifice cross-sectional areas and lengths.

Generally the fluids used are antifreeze solutions. The mount characteristics are a function of the geometry, porting and the fluid properties. Other fluids, such as silicone oil are also used for some applications.

The majority of work done on hydroelastic mounts so far was on the linear analysis of the systems, and only trial and error methods were available for the nonlinear behavior of mounts. The present research work implements a method of analyzing the nonlinear behavior of the systems which involve fluids and rubber material.

The fluid elements to be considered for the analysis do not have large displacement capacity and therefore were generally subjected to linear analysis. When they are used for nonlinear analysis they turn out to be incompatible with the associated non-linear hyperplastic elements in the hydroelastic mounts. To overcome this problem, in this research a method is proposed to simulate the linear fluid elements as nonlinear hyperelastic elements and evaluate an equivalent nonlinear hyperelastic elements which resembles exactly the fluid elements. This method compares the linear static deflections at the point of interest and the dynamic behavior.
of the models. Then, the nonlinear dynamic analysis is employed to analyze the response of the simulated model, where the fluid is replaced by its equivalent nonlinear hyperelastic element.

The models that are employed for the analysis are axisymmetric and subjected to two different loading cases for the nonlinear transient dynamic analysis. Case I deals with the dynamic response of the models subjected to a concentrated load pulse. Case II deals with the response to a uniformly distributed pressure pulse on the top surface of the mount. In both cases the axial displacement of the top center point of the mount is considered for comparison between mounts.
CHAPTER II

MODELS

The past work on the hydroelastic mounts resulted in developing different designs. The basic functional elements of all these isolators are essentially the same. The following is a brief review of a particular design of a hydroelastic mount presented in Figure 1.

1. Main spring: This component is the basic spring of the isolator which supports the static loading and provides the device with its base dynamic stiffness.

2. Secondary spring: An additional spring element which functions only when the isolator is subjected to dynamic loading.

3. Damping channel: Its a spiral groove connecting the upper and lower fluid chambers and is the means by which the total dynamic stiffness of the isolator is controlled.

4. Decoupler: Functions to permit low amplitude by-pass of the damping.

5. Inertia Track: It confines and directs the fluid and called so because the oscillating liquid within it offers an inertia or mass like resistance to the upper chamber pumping forces

Different models are considered for the analysis to study the effects of various geometries on the nonlinear dynamic characteristics, involving long and short fluid
Figure 1. Representation of a Typical Hydroelastic Mount.

columns, and hydroelastic mounts with and without an orifice. Also, during the analysis the maximum static and dynamic loads for the considered configurations are investigated.

Figure 2 shows the different models that are considered for the simulation. All the models are axisymmetric. The model base is fixed (fully restrained). Model M1 in Figure 2(a) represents a general and simple model of a hydroelastic mount that serves as a baseline model for this study. Model M2 in Figure 2(b) represents a mount with shorter and wider fluid column with reduced rubber thickness at its side. Model M3 in Figure 2(c) represents a mount with a longer and narrower fluid column.
a. Geometry 1 (M1), with base fixed

volume of the fluid = 0.000392 cum

b. Geometry 2 (M2), with shorter and wider fluid

volume of the fluid = 0.000392 cum

c. Geometry 3 (M3), with longer and narrower fluid

volume of the fluid = 0.000402 cum

d. Geometry 4 (M4), with a diaphragm

Figure 2. Geometric Configurations of Axisymmetric Models M1, M2, M3, M4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Model M4 in Figure 2(d) has a damping element in it, which consists of a diaphragm and an orifice, whose purpose is to move the fluid from upper chamber to the lower chamber when load is applied and the reverse on the release of the load. In all the models the volume of the fluid is kept almost constant (~ 0.000392 m³). In the model M4, the primary rubber element has two functions, first to carry the static and dynamic loads on the mount, and also to act as a piston to pump the liquid through the orifice into the bottom chamber. In the process of pumping the liquid through the orifice, the primary rubber element will bulge slightly such that not all the liquid displaced by the piston action is forced through the orifice. This bulging effect may be expressed as the ratio of chamber volume change to pressure change and is called as the compliance (ΔV/ΔP i.e., mm³/N/mm² = mm⁵/N) of the top chamber. The inverse of this compliance is sometimes called as the volume stiffness (N/mm⁵). The fluid in the upper chamber model, when subjected to a load, enters into bottom chamber through the orifice and accumulates there. When the load is released, the fluid reenters into the upper chamber through the orifice.
CHAPTER III

FINITE ELEMENT MODELING

The base model with nonlinear hyperelastic material is discretized into 4 node, 2-D axisymmetrical quadrilateral elements of equal size along both the axial and radial directions. The model is subjected to a concentrated load applied at the top center of the model and the deflection at the point of loading is considered. Static analysis is carried on these models with different mesh sizes. Table 1 illustrates the deflection values at the point of loading for the different meshes. The element sizes are reduced equally so as to be flexible while designing various interior components such as main spring, secondary spring, fluid column, diaphragm and varying orifice length and cross-sectional areas of the hydroelastic mount.

The mesh with 400 elements provided converged results (Figure 3), and is used throughout this study. Figure 3 presents the convergence of the static deflection at the top center of the base model.

The proposed analysis is done using ANSYS, a finite element commercial code. The hyperelastic element (stiff 84) is used for 2-D axisymmetric modeling of solid hyperelastic round structures. The 2-D element is a 4 node element with radial (X) and axial (Y) translational degrees of freedom. The hyperelastic element formulation being nonlinear requires an iterative solution. The fluid element (stiff 79) is also used for 2D axisymmetrical modeling but is restricted to linear analysis.
Table 1
Convergence Test on Model with Complete Hyperelastic Elements

<table>
<thead>
<tr>
<th>Number of elements in the model</th>
<th>Deflection at the top center of the model (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 elements</td>
<td>8.412</td>
</tr>
<tr>
<td>64 elements</td>
<td>10.103</td>
</tr>
<tr>
<td>144 elements</td>
<td>13.074</td>
</tr>
<tr>
<td>256 elements</td>
<td>15.610</td>
</tr>
<tr>
<td>400 elements</td>
<td>16.203</td>
</tr>
</tbody>
</table>

Figure 3. Convergence of Deflection at Top Center of the Model Using Hyperelastic Elements.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
only, without the capability of large deflections.

Due to the incompatibility of the fluid elements when associated with hyperelastic elements in a model for non-linear analysis, it is interesting to find equivalent hyperelastic material properties which simulate the fluid elements in the static and dynamic analysis. The baseline model (M1) was selected for this simulation. One model with contained fluid elements inside and the other model with hyperelastic element replacing the fluid elements are compared. The outer element remains the same, hyperelastic elements.

Different properties of rubber were used representing the range of durometer hardness between 80 to 50. The rubber is softer and more nonlinear for lower durometer hardness number. The values of Young's modulus calculated from the rigidity modulus are tabulated in Table 2. The Table also illustrates the two non-linear parameters A and B values calculated from the assumptions made in the Mooney-Rivlin plot [6].

Static Analysis

The base model with the fluid elements inside (designated as MF hereafter) and the one with the hyperelastic elements substituting the fluid elements (hereafter designated as MH) were subjected to linear static loading. The concentrated load is applied on the top of the mount along the axis of symmetry (node 421, of the converged finite element model). The outer rubber material properties are unchanged throughout the analysis. As cited before, the fluid can be any antifreeze liquid
Table 2

The Values of Young’s Modulus and Mooney-Rivlin Constants for Different Durometer Hardness of Rubber Material

<table>
<thead>
<tr>
<th>Durometer Hardness</th>
<th>Bulk Modulus (G in Psi)</th>
<th>Young’s Modulus (E in Psi)</th>
<th>Young’s Modulus (E in Psi)</th>
<th>Mooney-Rivlin Constant A (MPa)</th>
<th>Mooney-Rivlin Constant B (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duro 80</td>
<td>216.0</td>
<td>648.0</td>
<td>4.4809</td>
<td>0.5975</td>
<td>0.1494</td>
</tr>
<tr>
<td>Duro 70</td>
<td>172.5</td>
<td>517.5</td>
<td>3.5782</td>
<td>0.4771</td>
<td>0.1193</td>
</tr>
<tr>
<td>Duro 60</td>
<td>123.0</td>
<td>369.0</td>
<td>2.5516</td>
<td>0.3402</td>
<td>0.0851</td>
</tr>
<tr>
<td>Duro 50</td>
<td>90.0</td>
<td>270.0</td>
<td>1.8670</td>
<td>0.2489</td>
<td>0.0622</td>
</tr>
<tr>
<td>Duro 40</td>
<td>63.0</td>
<td>189.0</td>
<td>1.3069</td>
<td>0.1743</td>
<td>0.0436</td>
</tr>
<tr>
<td>Duro 30</td>
<td>45.0</td>
<td>135.0</td>
<td>0.9335</td>
<td>0.1245</td>
<td>0.0311</td>
</tr>
</tbody>
</table>

exceptional cases silicone oils, can be used. To be simple with fluid elements, water properties are considered for the analysis. The results that are obtained are good for the models with rubber (with different durometer hardness) and water interfaces inside the mount.

The criterion that is evaluated for the static loading is the equivalent Young’s modulus of the non-linear hyperelastic elements which provides results identical to those of the linear fluid elements. The modulus of elasticity for the inside hyperelastic elements (MH) is varied and the total deflection at node 421 (top center of mount) is compared to the corresponding displacement of the same node for MF.
model. Trial and error method is employed to evaluate the corresponding Young's modulus. For Young's modulus of $E = 6600$ Pa and Mooney-Rivlin non-linear Coefficients $A = 880$ and $B = 220$ of the inside hyperelastic element, the model gave results that had less than 5% difference compared to MF model. The Poisson's ratio for both the hyperelastic elements and fluid elements is chosen as 0.4999, assuming they are incompressible. The only other term that has to be matched is the equivalent density of hyperelastic element to that of fluid elements.

Modal Analysis

The modal analysis in ANSYS produces natural frequencies and mode shapes (both reduced and expanded). To do the modal analysis, the model structure must be linear elastic. Damping even if present is ignored in modal analysis. Non-linear elements such as hyperelastic elements (stiff 84) are also treated as linear with their stiffness determined by their initial status.

Natural frequencies and mode shapes are obtained from the equation given below:

\[
(K - \omega_i^2 M) \{ \phi \}_i = 0 \quad \ldots(1)
\]

where

- $[K] =$ Stiffness Matrix of the Structure.
- $[M] =$ Mass Matrix of the Structure (For the reduced model solution, both the stiffness and mass are reduced matrices)
- $\omega_i =$ The eigenvalue for mode i (circular natural
frequency of mode $i$)

$$\{\phi\}_i = \text{The eigenvector for mode } i \text{ (the mode shape of mode } i)$$

$\{\phi\}_i$ is normalized such that

$$\{\phi\}_i^T [M] \{\phi\}_i = [I] \quad \text{..(2)}$$

The mass and stiffness matrices may be full or they may be reduced by the Guyan reduction scheme to contain only selected master degrees of freedom. The master degrees of freedom may be selected manually or by default. For the modal analysis carried out on MF and MH models the master degrees of freedom chosen are 200 (assumption). The modal analysis (KAN=2) does not require any loading details.

After executing the static analysis and comparing the Young's modulus, it is needed to evaluate the equivalent density of hyperelastic element to that of the fluid element. Similar to the static analysis, water is considered also for the modal analysis (density = 1000 Kg/m$^3$). The model MH exhibited a natural frequency (1st natural mode) of 126.5 Hz, whereas the model MF resulted in 0.05022 Hz (for the first mode). This same wide discrepancy is observed in the case of 2nd, 3rd, and 4th modes. It was then decided to use dynamic analysis of both MF and MH models to compare and simulate the dynamic properties of hyperelastic model (MH) and the model with fluid elements (MF).
Dynamic Analysis

The nonlinear transient dynamic analysis (KAN=4) is an extension of the static analysis that solves for the dynamic response of a structure under the action of applied time dependent loads.

Iterative Procedures

The iterative procedure is a sequence of calculations in which the structure is fully loaded in each iteration. Due to some approximate, constant value of the stiffness in each step, equilibrium is not necessarily satisfied. After each iteration, the portion of the total loading that is not balanced is calculated and used in the next step to compute an additional increment of the displacements. This process is repeated until equilibrium is approximated to some acceptable degree. Essentially, the iterative procedure consists of successive corrections to a solution until equilibrium under the total load \( \{P\} \) is satisfied.

Let \( \{P_o\} \) and \( \{p_o\} \) be the initial loads and displacements in our nonlinear problem. \( \{P_o\} \) and \( \{p_o\} \) are not necessarily null in the general case. For the cycle \( i \) of the iteration procedure, the necessary load is determined by

\[
\{P_i\} = \{P\} - \{P_{e,i+1}\}
\]  

...(3)

where \( \{P\} \) is the total load to be applied and \( \{P_{e,i+1}\} \) is the load equilibrated after the previous step. An increment to the displacement is computed during the step \( i \) by using the relation
Where the superscript \( i \) denotes a cycle of iteration. The total displacement after the iteration \( i \) is computed from

\[
[p_i] = [p_0] + \sum [p_j]
\]  

Finally, \( \{P_{eq}\} \) is calculated as the load necessary to maintain the displacements \( \{p_i\} \).

The procedure is repeated until the increments of displacements or the unbalanced forces become zero, that is \( \{ p_i \} \) or \( \{ P_i \} \) becomes null or sufficiently close to null according to some preselected convergence criterion.

In the above iterative procedure we need to select a method for the computation of the stiffness matrix \([k^{(0)}]\) in equation (4). One common choice is the tangent stiffness at the end of the previous iterative step, this is the slope of the \( \{P\}-\{p\} \) curve at the point \( \{p_{i-1}\},\{P_{i-1}\} \)

\[
[k^{(0)}] = [k_{i-1}]
\]  

where \([k_{i}]\) is the tangent stiffness at \( \{p_{i}\}, \{P_{i}\} \). Instead of calculating different stiffnesses, different modified iterative techniques can be used, but this involves using the initial stiffness matrix and a greater number of iterations. The main advantage with these modified iterative techniques is that there is substantial saving of computation because it is not necessary to invert a new stiffness at each cycle. Figure 4 presents a block diagram for the iterative procedures discussed. The Newton-Raphson method is very much analogous to this method and is employed for the nonlinear dynamic analysis in this study. The new adaptive method in mixed procedures yield higher accuracy at the cost of more computational effort.
The basic equation of motion being solved in the KAN=4 analysis for the Newton-Raphson solution procedure is:

\[
[M]\{u_a\} + [C]\{u_v\} + [K]\{u\} = \{F_{app}\} + \{F_{th}\} + \{F_{pr}\} + \{F_{el}\} = \{F(t)\} \quad \text{(7)}
\]

where

\[
[M] = \text{total mass matrix} \\
[C] = \text{structure damping matrix} \\
[K] = \text{total stiffness matrix (sum of element stiffness matrix)} \\
\{u_a\} = \text{nodal acceleration vector} \\
\{u_v\} = \text{nodal velocity vector} \\
\{u\} = \text{nodal displacement vector} \\
\{F_{app}\} = \text{applied nodal force load vector} \\
\{F_{th}\} = \text{applied element thermal load vector} \\
\{F_{pr}\} = \text{applied element pressure load vector} \\
\{F_{el}\} = \text{element elastic load vector}
\]

The equation is solved by the Newmark implicit direct integration scheme.

The density of the inner hyperelastic element was assumed to be the same as that of the considered fluid (in this case, water) and dynamic analysis was carried out for low magnitude load cases, to check if the models MF and MH behave the same under forced dynamic loads, for the equivalent calculated Young’s modulus and the densities assumed thereafter.

A triangular time dependent load as shown in Figure 5 is applied to both models MF and MH. The dynamic load was applied at the same location as for the...
Figure 4. Block Diagram for the Iterative Procedure for Nonlinear Analysis.

Figure 5. Time Dependent Ramp Loading for Dynamic Analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
static loading case. At time \( t=0 : F_0 = 0 \), at \( t=T : F_0 = F_{\text{max}} \) and at \( t = T + \delta T \), the load returns to zero and is then kept zero. The time \( T \) corresponds to half the fundamental natural period of model MH, obtained from the modal analysis.

Figure 6 and Figure 7 present the transient displacement of node 421 for both the models MH and MF under dynamic load and \( F_{\text{max}} = 1\text{N}/\text{rad} \) (total force equals to \( 2\pi \) times \( F_{\text{max}} \)). The free vibration frequencies obtained from these plots immediately after the release of the loads is same for both models MF and MH. The plots in Figures 8 and 9 display very similar dynamic behaviors of both models during the loading and long after its release.

The displaced configurations as seen in Figures 10 and 11 of the meshed model are very similar. They only show some differences at the fluid-rubber interface, on the center line. These are recorded at the time of the releasing of the dynamic loads. The top surface of both structures behave the same irrespective of inside media. There are slight deformation changes in the fluid elements compared to the rubber elements. As the loading is applied longitudinally, the fluid media inside, being incompressible, expanded laterally due to the load, keeping the sides of the mount in tension and the rubber-fluid interface under compression. Also, when the load intensities are increased by small magnitudes (from 1N to 5N), both models MF and MH behave the same on their surface but there is little variation in the deformation of the hyperelastic elements as seen in Figures 12 and 13.

The fluid elements which are stressed more at the interface as seen in Figure 13 are not rectangular in shape any more but one of their corners becoming convex.
Figure 6. Transient Axial Displacement of Simulated Model MH With 1N/rad Peak Load.

Figure 7. Transient Axial Displacement of Rubber + Fluid Model MF With 1N/rad Peak Load.
Figure 8. Transient Axial Displacement of Simulated Model MH With 5N/rad Peak Load.

Figure 9. Transient Axial Displacement of Rubber + Fluid Model MF With 5N/rad Peak Load.
Figure 10. Displaced Structure of the Meshed Simulated Model MH Under Dynamic Loading, for a Peak Load of 1N/rad.

Figure 11. Displaced Structure of the Meshed Rubber + Fluid Model MF Under Dynamic Loading, for a Peak Load of 1N/rad.
Figure 12. Displaced Structure of the Meshed Simulated Model MH Under Dynamic Loading, for a Peak Load of 5N/rad.

Figure 13. Displaced Structure of the Meshed Rubber + Fluid Model MF, Under Dynamic Loading, for a Peak Load of 5N/rad.
As the load intensities are increased say to 10N, and above, the fluid elements produce more convexity thus making the shape of the fluid elements more complicated and more incompatible for the analysis to proceed, thus resulting in the abrupt stop in the further analysis. Comparatively, the rubber elements just follow the same trend for loads such as 5N, 10N and higher thereafter. Figures 12 and 13 show deformation of model for the load step 4 and iteration 11 which corresponds to the release of the load. Similarly Figures 10 and 11 show the deformations in models MH and MF for load step 4 and iteration 2, which corresponds immediately after the release of the load on the mounts. However this implies the model MH can be subjected to higher loads such as dynamic and static ones whereas the MF model does not sustain the higher dynamic loads for nonlinear analysis. The maximum load range for a model of 0.1m X 0.1m size is around 200N for concentrated static load for durometer hardness 70 of rubber and about 350 KPa for uniform pressure on the surface of model. These ranges also depend on the durometer hardness number of the rubber. As the durometer hardness number is reduced the maximum load range is also lowered.
CHAPTER IV

PARAMETRIC STUDY

Static Loading - Effect on Durometer Hardness

The base model M1 consisting of the hyperelastic elements that have properties equivalent fluid elements is subjected to a concentrated point loading. The deflections of the node 421 are evaluated for durometer hardness 70 of the outer rubber material of model M1. The intensities of the static loading are increased until the failure of the model occurred. Similarly the durometer hardness 70 is replaced by more softer material of durometer hardness of 50 and its effect is studied with respect to its load bearing capacities. The values of this static analysis are recorded in Table 3. Figure 14 represents the material behavior for the static loads applied on the model. For durometer hardness of 50, the deflection were linear until a load intensity of 75N/rad, and deviated from its linearity until it failed due to the structural instability. Similarly if the hardness is increased to 70 then the deflections are linear and can be used for extended intensities of the loads as seen in Figure 14.

Static Loading - Effect on Geometries

Models defined in Chapter II with different geometric configurations are subjected to static loading. Unlike the previous case these models are subjected to
Table 3

Static Analysis on Model M1 Subjected to Different Load Intensities for Durometer Hardness 70 and 50

<table>
<thead>
<tr>
<th>Load Intensities (N/rad)</th>
<th>Durometer Hardness 70 (mm)</th>
<th>Durometer Hardness 50 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 N/rad</td>
<td>1.753</td>
<td>3.336</td>
</tr>
<tr>
<td>25 N/rad</td>
<td>4.329</td>
<td>10.009</td>
</tr>
<tr>
<td>50 N/rad</td>
<td>8.517</td>
<td>19.793</td>
</tr>
<tr>
<td>75 N/rad</td>
<td>12.597</td>
<td>28.818</td>
</tr>
<tr>
<td>100 N/rad</td>
<td>16.587</td>
<td>30.406</td>
</tr>
<tr>
<td>200 N/rad</td>
<td>32.004</td>
<td>*</td>
</tr>
</tbody>
</table>

* Model failure occurred for the this load intensity

**Figure 14.** Deflection of Node 421 of Model M1, Subjected to Static Loading for Different Durometer Hardness of Rubber Material.
Deflections of Node 421 on Models M1, M2, M3 and M4 for Different Static Loading Conditions (Uniform Pressures) Applied on the Surface of the Models

<table>
<thead>
<tr>
<th>Pressure (KPa)</th>
<th>Model M1 Deflections (mm)</th>
<th>Model M2 Deflections (mm)</th>
<th>Model M3 Deflections (mm)</th>
<th>Model M4 Deflections (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.201</td>
<td>0.154</td>
<td>0.266</td>
<td>0.149</td>
</tr>
<tr>
<td>10</td>
<td>0.382</td>
<td>0.291</td>
<td>0.508</td>
<td>0.297</td>
</tr>
<tr>
<td>15</td>
<td>0.562</td>
<td>0.428</td>
<td>0.749</td>
<td>0.446</td>
</tr>
<tr>
<td>25</td>
<td>0.923</td>
<td>0.703</td>
<td>1.233</td>
<td>0.735</td>
</tr>
<tr>
<td>35</td>
<td>1.282</td>
<td>0.976</td>
<td>1.725</td>
<td>1.028</td>
</tr>
<tr>
<td>40</td>
<td>1.461</td>
<td>1.112</td>
<td>1.955</td>
<td>1.174</td>
</tr>
<tr>
<td>100</td>
<td>3.594</td>
<td>2.726</td>
<td>4.821</td>
<td>2.912</td>
</tr>
<tr>
<td>300</td>
<td>10.412</td>
<td>7.817</td>
<td>14.012</td>
<td>8.479</td>
</tr>
</tbody>
</table>

uniformly distributed pressure load intensities over the surface of each model. The deflections of node 421 on the surface of the model are shown in Table 4. The effect of variations in the geometries are visualized in Figure 15. The model M3 gave results whose magnitude is very high compared to the other models, due to high fluid column. As the pressure load is increased there is a steep rise in the deflections. Model M4 with the diaphragm had deflections which ranged in between models M1 and M2.
Figure 15. Deflection Profiles of Node 421 for Models M1, M2, M3, and M4, Subjected to Different Static Loading (Uniform Pressure) Conditions.

Modal Analysis

The modal analysis is carried for the models M1, M2, M3, M4 for the evaluation of their natural frequencies and mode shapes. As the number of the mode increased there is a rise in the frequencies. Table 5 presents the natural frequencies for the first 4 modes of the models M1, M2, M3 and M4. Table 6 illustrates the values of the natural frequencies for different durometer hardness of rubber material for model M1. It can be seen from Table 5 that the natural frequencies for the respective modes, an increasing trend is observed for models whose column width is increased and the length decreased. Exceptionally the model M4 have a lower frequency due to the introduction of a diaphragm at the fluid and rubber interface.
Table 5

The Natural Frequencies of 1st Four Modes of Models M1, M2, M3 and M4 Resulted from Modal Analysis

<table>
<thead>
<tr>
<th>Modes</th>
<th>Model M1 Frequency (Hz)</th>
<th>Model M2 Frequency (Hz)</th>
<th>Model M3 Frequency (Hz)</th>
<th>Model M4 Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>121.861</td>
<td>127.219</td>
<td>130.780</td>
<td>101.238</td>
</tr>
<tr>
<td>Mode 2</td>
<td>175.080</td>
<td>179.332</td>
<td>148.437</td>
<td>121.078</td>
</tr>
<tr>
<td>Mode 3</td>
<td>196.448</td>
<td>236.637</td>
<td>177.980</td>
<td>142.728</td>
</tr>
<tr>
<td>Mode 4</td>
<td>234.379</td>
<td>296.732</td>
<td>240.226</td>
<td>172.365</td>
</tr>
</tbody>
</table>

Effect of Variation in Pressure Loading

Static analysis on models with concentrated loading and the effect of geometry and durometer hardness are considered so far. The model M1 with durometer hardness of 50 is subjected to a loading case in static analysis where the pressure loading is varied in radial direction depending upon the area of application. Though the pressure intensities are varied as seen in Figure 16, the force acting on the mount in all the cases has a constant value of 10 N/rad. Figure 17 presents a plot for deflection of node 421, in which the effect of loading cases such as concentrated loading case turning out to uniformly distributed load can be studied. The plot in Figure 17 presents variation of deflections vs the ratio of the radius of load application (Rp) to that of the maximum radius of the mount surface (Ro). For
Table 6

Natural Frequencies for Different Durometer Hardness of the Model M1. The First 5 Modes are Considered

<table>
<thead>
<tr>
<th>Durometer Hardness</th>
<th>Mode 1 Frequency (Hz)</th>
<th>Mode 2 Frequency (Hz)</th>
<th>Mode 3 Frequency (Hz)</th>
<th>Mode 4 Frequency (Hz)</th>
<th>Mode 5 Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duro 80</td>
<td>136.091</td>
<td>186.375</td>
<td>208.169</td>
<td>261.726</td>
<td>283.904</td>
</tr>
<tr>
<td>Duro 70</td>
<td>121.861</td>
<td>175.080</td>
<td>196.448</td>
<td>234.378</td>
<td>278.874</td>
</tr>
<tr>
<td>Duro 60</td>
<td>103.203</td>
<td>151.159</td>
<td>188.044</td>
<td>198.420</td>
<td>268.010</td>
</tr>
<tr>
<td>Duro 50</td>
<td>88.501</td>
<td>130.333</td>
<td>169.879</td>
<td>180.670</td>
<td>214.708</td>
</tr>
<tr>
<td>Duro 40</td>
<td>74.313</td>
<td>109.769</td>
<td>142.603</td>
<td>168.260</td>
<td>211.605</td>
</tr>
<tr>
<td>Duro 30</td>
<td>63.027</td>
<td>93.280</td>
<td>120.893</td>
<td>151.809</td>
<td>188.707</td>
</tr>
</tbody>
</table>

Figure 16. Variations of Loading Conditions from Concentrated Load to Uniformly Distributed Load. The Total Force on Model is Kept Constant (10 N/rad).
Table 7

Deflections of Node 421 for Varying Pressure Load Intensities

<table>
<thead>
<tr>
<th>(Rp/Ro) ratio</th>
<th>Pressure Load Intensity (KPa)</th>
<th>Deflection of Node 421 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>800.000</td>
<td>3.488</td>
</tr>
<tr>
<td>0.10</td>
<td>200.000</td>
<td>1.581</td>
</tr>
<tr>
<td>0.20</td>
<td>50.000</td>
<td>0.777</td>
</tr>
<tr>
<td>0.30</td>
<td>22.222</td>
<td>0.505</td>
</tr>
<tr>
<td>0.40</td>
<td>12.500</td>
<td>0.357</td>
</tr>
<tr>
<td>0.50</td>
<td>8.000</td>
<td>0.264</td>
</tr>
<tr>
<td>0.60</td>
<td>5.557</td>
<td>0.203</td>
</tr>
<tr>
<td>0.70</td>
<td>4.081</td>
<td>0.016</td>
</tr>
<tr>
<td>0.80</td>
<td>3.125</td>
<td>0.013</td>
</tr>
<tr>
<td>0.90</td>
<td>2.469</td>
<td>0.011</td>
</tr>
<tr>
<td>1.00</td>
<td>2.000</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Example for a load case of 10 N/rad concentrated load on Model M1 for durometer hardness 50, node 421 has a deflection of 0.0035m as seen in Figure 14. In Figure 17, as the load approaches a point loading condition, the deflection is almost near to 0.0035m. As the loading converts to a uniformly distributed loading case, an exponential reduction of deflections was observed.
Figure 17. Deflections of Node 421 for Model M1, Subjected to Different Intensities of Pressure Loading.
CHAPTER V

NONLINEAR TRANSIENT DYNAMIC ANALYSIS

The nonlinear dynamic analysis solves for the large displacement dynamic response of the structure under the action of the applied time dependent loads. Newton-Raphson procedure option was chosen for the large deflection analysis using ANSYS. The structure does not have any initial velocity and acceleration, (Kay(5)=2). No stress stiffening was assumed throughout the analysis, (Kay(8)=0). The nonlinear constants $A = (4E/30)$ and $B = (E/30)$ in the Mooney-Rivlin function for a hyperelastic material were established from the typical Mooney-Rivlin plot [6], where $E$ is the Young’s modulus.

The Mooney-Rivlin strain-energy function, apart from its use in stress analysis, has also had wide use in the characterization of elastomers. The reason for this lies in its simplicity and that the constants $A$ and $B$ in it can be readily measured my simple extension experiments. It appears that the form of Mooney-Rivlin plot is a typical one for rubber materials. This is evidenced in the experiments of Saunders and Rivlin [6] in which such plots were obtained for various natural rubber vulcanizers covering a wide range of hardness and some plots are obtained for various natural and synthetic vulcanizers swollen to various degrees with variety of organic solvents.

33
Effect of Concentrated Load

The models that are analyzed are subjected to a triangular load as shown in Figure 18. The concentrated load is applied over the top surface of the mount at the top along the axis of symmetry (node 421). The loading pulse frequency was varied from very impulsive to resonant to long duration quasi-static loads as shown in Figure 19. An impulse load pulse has a very low time period compared to that of the natural time period of the model. The resonant load pulse has the same time period as that of the model natural period. A quasi-static load pulse has a large time period.
Figure 19. Illustration of Impulsive, Resonant and Quasi-Static Loading Conditions Applied on Models.
Figure 20. Deflection Profile of Node 421 for Impulsive Loading Pulse.

Figure 21. Deflection Profile of Node 421 for Resonant Loading Pulse.
Figure 22. Deflection Profile of Node 421 for Quasi-Static Loading Pulse.

compared to the model natural time period. A dynamic load which has a configuration similar to the one shown in Figure 18 was applied on the models and the effect of the above discussed loading conditions are studied. Figures 20, 21 and 22 present that the deflection of node 421 on model M1 with durometer hardness 70 gave identical maximum deflections in case of quasi-static and resonant load pulses, whereas in the case of impulsive load, the deflection is lower.

Each geometry was subjected to a concentrated load with a peak of 10N. For each transient analysis, the peak displacements at the top center (node 421) was recorded. The durometer hardness of the rubber material is changed for each model and the respective nodal deflections of the four models were studied. The peak values

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 8
Deflections on Node 421 Due to the Dynamic Loading on Geometry 1 (M1) for Different Durometer Hardness

<table>
<thead>
<tr>
<th>Load Pulse Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Durometer Hardness 80 Deflection (mm)</th>
<th>Durometer Hardness 70 Deflection (mm)</th>
<th>Durometer Hardness 60 Deflection (mm)</th>
<th>Durometer Hardness 50 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00010</td>
<td>10000</td>
<td>0.387</td>
<td>0.434</td>
<td>0.518</td>
<td>0.609</td>
</tr>
<tr>
<td>0.00020</td>
<td>5000</td>
<td>0.632</td>
<td>0.734</td>
<td>0.943</td>
<td>1.147</td>
</tr>
<tr>
<td>0.00050</td>
<td>2000</td>
<td>0.912</td>
<td>1.112</td>
<td>1.504</td>
<td>1.952</td>
</tr>
<tr>
<td>0.00075</td>
<td>1333</td>
<td>0.939</td>
<td>1.157</td>
<td>1.611</td>
<td>2.149</td>
</tr>
<tr>
<td>0.00100</td>
<td>1000</td>
<td>0.974</td>
<td>1.171</td>
<td>1.635</td>
<td>2.207</td>
</tr>
<tr>
<td>0.00500</td>
<td>200</td>
<td>1.357</td>
<td>1.654</td>
<td>2.258</td>
<td>2.985</td>
</tr>
<tr>
<td>0.00800</td>
<td>125</td>
<td>1.429</td>
<td>1.748</td>
<td>2.410</td>
<td>3.206</td>
</tr>
<tr>
<td>0.01000</td>
<td>100</td>
<td>1.447</td>
<td>1.776</td>
<td>2.463</td>
<td>3.292</td>
</tr>
<tr>
<td>0.05000</td>
<td>20</td>
<td>1.414</td>
<td>1.749</td>
<td>2.455</td>
<td>3.334</td>
</tr>
<tr>
<td>0.10000</td>
<td>10</td>
<td>1.408</td>
<td>1.741</td>
<td>2.438</td>
<td>3.305</td>
</tr>
</tbody>
</table>

of the deflections are used to compare the models and the effects of durometer hardness of the used hyperelastic material.

Tables 8, 9 and 10 present the peak values of deflections at node 421 of each geometry, obtained for different pulse frequencies. Also Semi-Logarithmic plots,
Table 9

Deflection on Node 421 Due to the Dynamic Loading on Model M2 for Different Durometer Hardness

<table>
<thead>
<tr>
<th>Load Pulse Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Durometer Hardness 80 Deflection (mm)</th>
<th>Durometer Hardness 70 Deflection (mm)</th>
<th>Durometer Hardness 60 Deflection (mm)</th>
<th>Durometer Hardness 50 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00010</td>
<td>10000</td>
<td>0.373</td>
<td>0.431</td>
<td>0.529</td>
<td>0.489</td>
</tr>
<tr>
<td>0.00020</td>
<td>5000</td>
<td>0.519</td>
<td>0.675</td>
<td>0.875</td>
<td>0.871</td>
</tr>
<tr>
<td>0.00050</td>
<td>2000</td>
<td>0.779</td>
<td>0.958</td>
<td>1.321</td>
<td>1.382</td>
</tr>
<tr>
<td>0.00075</td>
<td>1333</td>
<td>0.789</td>
<td>0.976</td>
<td>1.433</td>
<td>1.454</td>
</tr>
<tr>
<td>0.00100</td>
<td>1000</td>
<td>0.849</td>
<td>1.021</td>
<td>1.466</td>
<td>1.462</td>
</tr>
<tr>
<td>0.00500</td>
<td>200</td>
<td>1.099</td>
<td>1.344</td>
<td>1.801</td>
<td>1.971</td>
</tr>
<tr>
<td>0.00800</td>
<td>125</td>
<td>1.142</td>
<td>1.398</td>
<td>1.899</td>
<td>2.052</td>
</tr>
<tr>
<td>0.01000</td>
<td>100</td>
<td>1.148</td>
<td>1.412</td>
<td>1.933</td>
<td>2.063</td>
</tr>
<tr>
<td>0.05000</td>
<td>20</td>
<td>1.124</td>
<td>1.386</td>
<td>1.947</td>
<td>2.059</td>
</tr>
<tr>
<td>0.10000</td>
<td>10</td>
<td>1.123</td>
<td>1.381</td>
<td>1.937</td>
<td>2.052</td>
</tr>
</tbody>
</table>

Figure 23, 24 and 25 of these deflections are presented to study the behavior of each geometry and the expected changes in deflections when the rubber of different durometer hardness values are used. Geometry 3 had a greater deflection at node 421 when compared to other geometries. Geometry 4 has a mean effect of the geometries...
Table 10
Deflections on Node 421 Due to the Dynamic Loading on Model M3 and Model M4 for Durometer Hardness of 70

<table>
<thead>
<tr>
<th>Load Pulse Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Model 4 Deflection (mm)</th>
<th>Model 3 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00010</td>
<td>10000</td>
<td>0.431</td>
<td>0.743</td>
</tr>
<tr>
<td>0.00020</td>
<td>5000</td>
<td>0.774</td>
<td>1.418</td>
</tr>
<tr>
<td>0.00050</td>
<td>2000</td>
<td>1.128</td>
<td>2.085</td>
</tr>
<tr>
<td>0.00075</td>
<td>1333</td>
<td>1.213</td>
<td>2.225</td>
</tr>
<tr>
<td>0.00100</td>
<td>1000</td>
<td>1.258</td>
<td>2.327</td>
</tr>
<tr>
<td>0.00500</td>
<td>200</td>
<td>1.427</td>
<td>3.236</td>
</tr>
<tr>
<td>0.00800</td>
<td>125</td>
<td>1.490</td>
<td>3.463</td>
</tr>
<tr>
<td>0.01000</td>
<td>100</td>
<td>1.518</td>
<td>3.534</td>
</tr>
<tr>
<td>0.05000</td>
<td>20</td>
<td>1.490</td>
<td>3.486</td>
</tr>
<tr>
<td>0.10000</td>
<td>10</td>
<td>1.497</td>
<td>3.431</td>
</tr>
</tbody>
</table>

1 and 2. A rise in the deflection is the usual trend seen as the frequency of the pulse is reduced. The models reached a static value of deflections for load frequencies less than the respective resonant frequency of each models. Change in durometer hardness of rubber displayed similar profiles of the time history behavior for each model considered.
Figure 23. Deflection Profiles of the Models M1, M2, M3 and M4 Subjected to Point Loading of 10 N/rad.

Figure 24. Deflection Profiles of Model M1 for different Durometer Hardness Subjected to Point Loading of 10 N/rad.
Similar to the concentrated load case, the models were subjected to a pressure pulse load as shown in Figure 26. The pressure load was applied uniformly over the top surface of the model. The pressure pulse frequency is varied from very impulsive to resonant to long duration quasi-static loads. Each geometry was subjected to a pressure load with a peak of 200 KPa. For each transient analysis, the peak displacement at the top center (node 421) was recorded. The durometer hardness of the rubber is also changed and the influence of the transient load was studied. The peak values of each transient analysis was used to compare the behavior of the mount for the dynamic loads.
Figure 26. Uniform Pressure Loading of the Model M1, and the Time Dependent Triangular Pulse.

Figure 27. Deflection Profiles for Different Models M1, M2 and M4 for Durometer Hardness of 60.
Table 11

Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M1 for Different Durometer Hardness of Rubber Material

<table>
<thead>
<tr>
<th>Pulse Load Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Durometer Hardness 80 Deflection (mm)</th>
<th>Durometer Hardness 70 Deflection (mm)</th>
<th>Durometer Hardness 60 Deflection (mm)</th>
<th>Durometer Hardness 50 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1000</td>
<td>2.134</td>
<td>2.526</td>
<td>3.317</td>
<td>2.267</td>
</tr>
<tr>
<td>0.005</td>
<td>200</td>
<td>8.742</td>
<td>10.733</td>
<td>13.363</td>
<td>16.441</td>
</tr>
<tr>
<td>0.008</td>
<td>125</td>
<td>9.038</td>
<td>11.315</td>
<td>15.491</td>
<td>20.689</td>
</tr>
<tr>
<td>0.010</td>
<td>100</td>
<td>8.556</td>
<td>10.933</td>
<td>15.423</td>
<td>21.215</td>
</tr>
<tr>
<td>0.050</td>
<td>20</td>
<td>5.943</td>
<td>7.657</td>
<td>9.423</td>
<td>13.521</td>
</tr>
<tr>
<td>0.100</td>
<td>10</td>
<td>6.014</td>
<td>7.117</td>
<td>10.006</td>
<td>12.725</td>
</tr>
</tbody>
</table>

Figure 27 presents plots of the peak axial displacement versus the pulse frequency obtained by the dynamic analysis for the different geometry models. For high frequencies of loading (>200 Hz) i.e., as the loading phenomenon became very impulsive, there was a significant drop in the deflections at the top center of the model. When the loading frequencies were close to the resonant frequencies the displacements reached their peak values and for lower frequencies (<20Hz) the deflections reduced to the static loading values. Similar phenomenon is observed with
Table 12

Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M2 for Different Durometer Hardness of Rubber Material

<table>
<thead>
<tr>
<th>Pulse Load Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Durometer Hardness 80 Deflection (mm)</th>
<th>Durometer Hardness 70 Deflection (mm)</th>
<th>Durometer Hardness 60 Deflection (mm)</th>
<th>Durometer Hardness 50 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1000</td>
<td>1.208</td>
<td>2.142</td>
<td>1.999</td>
<td>2.882</td>
</tr>
<tr>
<td>0.005</td>
<td>200</td>
<td>5.853</td>
<td>7.243</td>
<td>9.369</td>
<td>11.732</td>
</tr>
<tr>
<td>0.008</td>
<td>125</td>
<td>6.193</td>
<td>7.578</td>
<td>9.726</td>
<td>11.324</td>
</tr>
<tr>
<td>0.010</td>
<td>100</td>
<td>6.231</td>
<td>7.147</td>
<td>9.801</td>
<td>11.793</td>
</tr>
<tr>
<td>0.050</td>
<td>20</td>
<td>4.861</td>
<td>5.655</td>
<td>7.507</td>
<td>7.456</td>
</tr>
<tr>
<td>0.100</td>
<td>10</td>
<td>4.537</td>
<td>5.572</td>
<td>7.326</td>
<td>7.633</td>
</tr>
</tbody>
</table>

different rubber hardness properties, Figure 28. Tables 11, 12 and 13 present node 421 deflection values for the models M1, M2 and M4. The smaller the hardness, the larger the deflection. Figure 29 is a typical plot representing the nodal deflections in X and Y directions, of the nodes 421, 431 and 441 located at the top surface of the mount as seen in the figure. If the UY deflections are observed for all the three nodes, we can visualize the incompressibility effect for the mount. Node 441 is at the outside diameter of the mount, node 421 is at the center and node 431 is midway between nodes 441 and 421.
Figure 28. Deflection Profiles of Model M4 With Varying Durometer Hardness of Rubber.

Figure 29. Effect of Incompressibility on the Model M4, in Dynamic Analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 13

Deflections of the Node 421 of a Model With a Uniform Pressure (Dynamic Load of 200 KPa) on Model M4 for Different Durometer Hardness of Rubber Material

<table>
<thead>
<tr>
<th>Pulse Load Time (sec)</th>
<th>Pulse Frequency (Hz)</th>
<th>Durometer Hardness 80 Deflection (mm)</th>
<th>Durometer Hardness 70 Deflection (mm)</th>
<th>Durometer Hardness 60 Deflection (mm)</th>
<th>Durometer Hardness 50 Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1000</td>
<td>2.385</td>
<td>2.845</td>
<td>3.334</td>
<td>3.659</td>
</tr>
<tr>
<td>0.005</td>
<td>200</td>
<td>7.694</td>
<td>8.562</td>
<td>11.106</td>
<td>12.679</td>
</tr>
<tr>
<td>0.008</td>
<td>125</td>
<td>7.623</td>
<td>8.892</td>
<td>12.136</td>
<td>15.075</td>
</tr>
<tr>
<td>0.010</td>
<td>100</td>
<td>6.983</td>
<td>8.623</td>
<td>11.748</td>
<td>15.197</td>
</tr>
<tr>
<td>0.050</td>
<td>20</td>
<td>5.172</td>
<td>6.034</td>
<td>9.019</td>
<td>10.198</td>
</tr>
<tr>
<td>0.100</td>
<td>10</td>
<td>4.835</td>
<td>5.993</td>
<td>8.692</td>
<td>9.798</td>
</tr>
</tbody>
</table>
CHAPTER VI

CONCLUSIONS

Just as the mounts have become more sophisticated, so has the analysis and problem definition. In order to most effectively design a mount, a modal analysis is required to define the spectral behavior (frequency and amplitude) in the working range. Hydroelastic mounts such as these discussed in this study occupy a prominent position in challenging applications where complicated mounting systems and auxiliary devices are necessary to satisfy ride demands. Hydraulic mounts can be cost saving where they eliminate the need for devices such as engine to chassis shock absorbers.

A method was proposed to simulate and evaluate the equivalent hyperelastic elements that could replace the fluid elements for the nonlinear analysis. Models of simple geometries were considered for the parametric study and the effect of the variations of the geometries and durometer hardness of the rubber were studied.

More detailed models can be designed which include components such as the inertia track and decouplers and the real time problem can be analyzed based on the proposed method of finite element analysis. This method can replace the use of the trial and error methods that are now employed in the development of hydroelastic mounts.
Appendix A

ANSYS Code for Static Analysis for Model MH
/PREP7
/TITLE, Hyperelastic Elements, Static Loading.
KAN,0  * Static Analysis
ITER,1,1
KAY,6,1
KAY,9,1
KAY,8,1
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
MP,EX,1,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,66e2
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
NL,2,7,8.8e2
NL,2,13,2.2e2
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
/PNUM,NODE,1
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,5,21,201,220
MAT,2
TYPE,2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,10,21,301,310
D,1,UX,,21
D,1,UY,,21
D,1,UZ,,21
D,1,UX,,421,21
F,421,FY,-1
/PBC,ALL,1
AFWRITE
FINISH
/INPUT,27
FINISH
/POST1
SET,1,1
PLDISP
FINISH
/EOF
Appendix B

ANSYS Code for Static Analysis for Model MF
/PREP7
/TITLE, Hyperelastic + Fluid Elements, Static Loading.
KAN, 0
ITER, 1, 1
KAY, 6, 1
KAY, 9, 1
KAY, 8, 1
KNL, 1
ET, 1, 84, 1, 9
ET, 2, 79, 1
MP, EX, 1, 3.6096e6
MP, NUXY, 1, 0.499
MP, EX, 2, 1.45e6
MP, NUXY, 2, 0.4999
MP, DENS, 1, 1400
MP, DENS, 2, 1000
NL, 1, 7, 0.48128e6
NL, 1, 13, 0.12032e6
N, 1
N, 21, 0.10
FILL
NGEN, 21, 21, 1, 21, 1, 0.005
/PNUM, NODE, 1
NALL
E, 1, 2, 23, 22
EGEN, 20, 1, 1, 20
EGEN, 5, 21, 1, 20
E, 116, 117, 138, 137
EGEN, 10, 1, 101, 110
EGEN, 10, 21, 101, 110
E, 316, 317, 338, 337
EGEN, 20, 1, 201, 220
EGEN, 5, 21, 201, 220
MAT, 2
TYPE, 2
E, 106, 107, 128, 127
EGEN, 10, 1, 301, 310
EGEN, 10, 21, 301, 310
D, 1, UX, 0.21
D, 1, UY, 0.21
D, ALL, UZ
D, 1, UX, 0.421, 21
F, 421, FY, -1
/PBC,ALL,1
AFWRITE
FINISH
/INPUT,27
FINISH
/POST1
SET,1,1
PLDISP
FINISH
/EOF
Appendix C

ANSYS Code for Modal Analysis for Model MH
/PREP7
/TITLE, Hyperelastic Elements, Modal Analysis.
KAN,2
ITER,1
KAY,1,1
KAY,2,4
KAY,3,0
KAY,6,1
KAY,7,4
KAY,9,1
KAY,10,0
KAY,8,0
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
MP,EX,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,66e2
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
NL,2,7,8.8e2
NL,2,13,2.2e2
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
/PNUM,NODE,1
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,5,21,201,220
MAT,2
TYPE,2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,10,21,301,310
TOTAL,200,0
D,1,UX,,21
D,1,UY,,21
D,ALL, UZ
D,1,UX,,421,21
acel,,9.81
AFWRITE
FINISH
/INPUT,27
FINISH
/POST1
SET,1,1
PLDISP
FINISH
/EOF
Appendix D

ANSYS Code for Modal Analysis for Model MF
/PREP7
/TITLE, HE + Fluid Elements, Modal Analysis.
KAN,2
ITER,1,1
KAY,2,4
KAY,3,0
KAY,6,1
KAY,7,50
KAY,9,1
KAY,10,0
KAY,8,0
KNL,1
ET,1,84,,1,,9
ET,2,79,,1
MP,EX,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,12.4E5
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,5,21,201,220
MAT,2
TYPE,2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,10,21,301,310
TOTAL,200,0
D,1,UX,,21
D,1,UY,,21
D,ALL,UZ
D,1,UX,,,421,21
acel,,9.81
AFWRITE
FINISH
/INPUT,27
FINISH
/POST1
SET,1,1
PLDISP
FINISH
/EOF
Appendix E

ANSYS Code for Dynamic Analysis for Model MH
/PREP7
/TITLE, Hyperelastic elements, Dynamic loading.
KAN, 4
KAY, 3, 0
KAY, 5, 2
KAY, 8, 0
KAY, 6, 1
KAY, 9, 0
KNL, 1
ET, 1, 84,., 1, 9
ET, 2, 84,., 1, 9
MP, EX, 1, 3.6096e6
MP, NUXY, 1, 0.499
MP, EX, 2, 66e2
MP, NUXY, 2, 0.4999
MP, DENS, 1, 1400
MP, DENS, 2, 1000
NL, 1, 0.48128e6
NL, 1, 13, 0.12032e6
NL, 2, 7, 8.8e2
NL, 2, 13, 2.2e2
N, 1
N, 2, 0, 10
FILL
NGEN, 21, 21, 1, 21,., 0.005
/PNUM, NODE, 1
NALL
E, 1, 2, 23, 22
EGEN, 20, 1, 1, 20
EGEN, 5, 2, 1, 20
E, 116, 117, 138, 137
EGEN, 10, 1, 101, 110
EGEN, 10, 21, 101, 110
E, 316, 317, 338, 337
EGEN, 20, 1, 201, 220
EGEN, 5, 2, 201, 220
MAT, 2
TYPE, 2
E, 106, 107, 128, 127
EGEN, 10, 1, 301, 310
EGEN, 10, 21, 301, 310
D, 1, UX,., 21
D, 1, UY,., 21

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
D, ALL, UZ
D, 1, UX,, 421, 21
*** DYNAMIC LOADING
ITER, 1,, 1
TIME, 0
F, 421, FY, 0
LWRITE
ITER, 4,, 1
TIME, 0.008
F, 421, FY, -1
LWRITE
ITER, 1,, 1
TIME, 0.008001
F, 421, FY, 0
LWRITE
ITER, 20,, 1
TIME, 0.02
F, 421, FY, 0
LWRITE
AFWRITE
FINISH
/INPUT, 27
FINISH
*** Post processing
*** displaying the deformed structure
/POST1
SET, 4, 2
PLDISP
FINISH
*** Graphic display
/POST26
DISP, 2, 421, uy
PLVAR, 2
FINISH
/EOF
Appendix F

ANSYS Code for Dynamic Analysis for Model MF
/PREP7
/TITLE, HE + Fluid Elements, Dynamic Loading.
KAN,4
KAY,3,0
KAY,5,2
KAY,8,0
KAY,6,1
KAY,9,0
KNL,1
ET,1,84,,1,,9
ET,2,79,,1
MP,EX,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,1.24e6
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
/PNUM,NODE,1
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,20,1,201,220
MAT,2
TYPE,2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,10,21,301,310
D,1,UX,,21
D,1,UY,,21
D,ALL,UZ
D,1,UX,,421,21
*** DYNAMIC LOADING
ITER,1,,1
TIME,0
F,421,FY,0
LWRITE
ITER,4,,1
TIME,0.008
F,421,FY,-1
LWRITE
ITER,1,,1
TIME,0.008001
F,421,FY,0
LWRITE
ITER,20,,1
time,0.02
F,421,FY,0
LWRITE
AFWRITE
FINISH
/INPUT,27
FINISH
*** Post processing
*** displaying the deformed structure
/POST1
SET,4,2
PLDISP
FINISH
/EOF
Appendix G

ANSYS Code for Nonlinear Transient Dynamic Analysis for Model M1
/PREP7
/TITLE, Model M1, Dynamic loading
KAN,4
KAY,3,3
KAY,5,2
KAY,8,0
KAY,6,1
KAY,9,0
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
MP,EX,1,3.5782e6
MP,NUXY,1,0.499
MP,EX,2,60e2
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.477le6
NL,1,13,0.1193e6
NL,2,7,8e2
NL,2,13,2e2
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
/PNUM,NODE,1
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,5,21,201,220
MAT,2
TYPE,2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,10,21,301,310
D,1,UX,,21
D,1,UY,,21
D,1,UX,,421,21
D,1,UZ,,21
*** DYNAMIC LOADING
ITER,1,,1
TIME,0
P,421,422,0,,441
LWRITE
ITER,5,,1
TIME,0.00375
P,421,422,200000,441
LWRITE
ITER,5,,1
TIME,0.0075
P,421,422,0,,441
LWRITE
ITER,10,,1
TIME,0.009
P,421,422,0,,441
LWRITE
AFWRITE
FINISH
/INPUT,27
FINISH
*** Graphic display
/POST26
DISP,2,421,uy
PLVAR,2
PRVAR,2
FINISH
/EOF
Appendix H

ANSYS Code for Nonlinear Transient Dynamic Analysis
for Model M2
/PREP7
/TITLE, Model M2, Dynamic loading
KAN,4
KAY,3,0
KAY,5,2
KAY,6,1
KAY,8,0
KAY,9,0
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
MP,EX,1,2,5516e6
MP,NUXY,1,0,499
MP,EX,2,60e2
MP,NUXY,2,0,4999
MP,DENS,1,1400
MP,DENS,2,1000
NI,1,7,0,3402E6
NL,1,13,0,0851e6
NL,2,7,8e2
NL,2,13,2e2
N,1
N,21,0,10
FILL
NGEN,21,21,1,21,,0,005
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,8,21,1,20
E,185,186,207,206
EGEN,4,1,161,164
EGEN,4,21,161,164
E,253,254,275,274
EGEN,20,1,177,196
EGEN,8,21,177,196
MAT,2
TYPE,2
E,169,170,191,190
EGEN,16,1,337,352
EGEN,4,21,337,352
D,1,UX,,21
D,1,UY,,21
D,1,UC,,21

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
D,1,UX,,421,21
ACEL,,9.81
*** dynamic loading
ITER,1,,1
TIME,0
P,421,422,0,,441
LWRITE
ITER,5,,1
TIME,0.0005
P,421,422,200000,,441
LWRITE
ITER,5,,1
TIME,0.001
P,421,422,0,,441
LWRITE
ITER,10,,1
TIME,0.002
P,421,422,0,,441
LWRITE
AFWRITE
FINISH
/INPUT,27
FINISH
*** Graphic display
/POST26
DISP,2,421,uy
PLVAR,2
PRVAR,2
FINISH
/EOF
Appendix I

ANSYS Code for Nonlinear Transient Dynamic Analysis for Model M3
/PREP7
/TITLE, Hyperelastic Elements, Dynamic Loading
KAN,4
KAY,3,0
KAY,5,2
KAY,8,0
KAY,6,1
KAY,9,0
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
MP,EX,1,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,66e2
MP,NUXY,2,0.4999
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
NL,2,7,8.8e2
NL,2,13,2.2e2
N,1
N,2,1,0.10
FILL
NGEN,21,21,1,21,,0.005
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,2,21,1,20
E,51,52,73,72
EGEN,12,1,41,63
EGEN,16,21,41,63
E,379,380,401,400
EGEN,20,1,233,252
EGEN,2,21,233,252
MAT,2
TYPE,2
E,43,44,65,64
EGEN,8,1,273,280
EGEN,16,21,273,280
D,1,UX,,21
D,1,UY,,21
D,ALL,UZ
D,1,UX,,421,21
ACEL,,9.81
*** dynamic loading
ITER,1,,1
TIME,0
P,421,422,0,,441
LWRITE
ITER,5,,1
TIME,0.00025
P,421,422,200000,,441
LWRITE
ITER,5,,1
TIME,0.0005
P,421,422,0,,441
LWRITE
ITER,10,,1
TIME,0.0005
P,421,422,0,,441
LWRITE
AFWRITE
FINISH
/INPUT,27
FINISH
*** Graphic display
/POST26
DISP,2,421,UY
PLVAR,2
PRVAR,2
FINISH
/EOF
Appendix J

ANSYS Code for Nonlinear Transient Dynamic Analysis for Model M4
/PREP7
/TITLE, Hyperelastic Elements, Dynamic Loading
KAN,4
KAY,3,0
KAY,5,2
KAY,8,0
KAY,6,1
KAY,9,0
KNL,1
ET,1,84,,1,,9
ET,2,84,,1,,9
ET,3,84,,1,,9
MP,EX,1,3.6096e6
MP,NUXY,1,0.499
MP,EX,2,60e2
MP,NUXY,2,0.4999
MP,EX,3,6E6
MP,NUXY,3,0.499
MP,DENS,3,1400
MP,DENS,1,1400
MP,DENS,2,1000
NL,1,7,0.48128e6
NL,1,13,0.12032e6
NL,2,7,8e2
NL,2,13,2e2
NL,3,7,0.79999E6
NL,3,13,0.2E6
N,1
N,21,0.10
FILL
NGEN,21,21,1,21,,0.005
/PNUM,NODE,1
NALL
E,1,2,23,22
EGEN,20,1,1,20
EGEN,5,21,1,20
E,116,117,138,137
EGEN,10,1,101,110
EGEN,10,21,101,110
E,316,317,338,337
EGEN,20,1,201,220
EGEN,5,21,201,220
MAT,2
TYPE, 2
E,106,107,128,127
EGEN,10,1,301,310
EGEN,4,21,301,310
E,190,191,212,211
EGEN,2,1,341,342
EGEN,2,21,341,342
E,232,233,254,253
EGEN,10,1,345,354
EGEN,4,21,345,354
MAT,3
TYPE,3
E,192,193,214,213
EGEN,8,1,385,392
EGEN,2,21,385,392
D,1,UX,,21
D,1,UY,,21
D,ALL, UZ
D,1, UX,,421,21
*** DYNAMIC LOADING
ITER,1,,1
TIME,0
p,421,422,0,,441
LWRITE
ITER,,5,,1
TIME,0.0005
p,421,422,200000,,441
LWRITE
ITER,,5,,1
TIME,0.001
p,421,422,0,,441
LWRITE
ITER,10,,1
time,0.003
p,421,422,0,,441
LWRITE
AFWRITE
FINISH
/INPUT,27
FINISH
*** Graphic display
/POST26
DISP,2,421,uy
PLVAR,2
PRVAR,2
FINISH
/EOF
BIBLIOGRAPHY


