12-2010

Experimentally Reducing Preset and Hysteresis Effects in Creating a Non-Linear Model for Brake Hoses

Jai Thomas
Western Michigan University

Follow this and additional works at: http://scholarworks.wmich.edu/dissertations

Recommended Citation
http://scholarworks.wmich.edu/dissertations/631

This Dissertation-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 Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
EXPERIMENTALLY REDUCING PRESET AND HYSTERESIS EFFECTS IN CREATING A NON-LINEAR MODEL FOR BRAKE HOSES

by

Jai Thomas

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Industrial and Manufacturing Engineering
Advisor: Mitchel J. Keil, Ph.D.

Western Michigan University
Kalamazoo, Michigan
December 2010
This research investigates a brake hose simulation model that includes the effect of nonlinear torsional stiffness in addition to the usually considered bending stiffness on brake hose shape. A simulation model consisting of beams and torsion springs is presented in this research to predict brake hose shape when it is twisted through different angles. This knowledge can help reduce the possibility of a significant source of failure related to brake hose abrasion on nearby structures, thus eliminating the safety hazard of a premature failure of hoses. This would also eliminate the need for polymer bumpers at the rub points since an appropriate length that does not rub against rigid components can be found. The bumpers cause high stress in the hose during the vehicle operation, and thus pose a safety hazard. The ability to model flexible components also leads to a reduction in ergonomical issues due to the accurate prediction of hand clearance for assembly. The United States Council of Automotive Research Digital Virtual Tools Task Force calculated a present value cost savings of $5.78M from the development of a virtual tool for designing brake hoses.

A fixture was fabricated to hold hoses of different lengths firmly after initiating a specific twist at one end. A digitizer was used to obtain scanned point cloud data of hose
shapes between coplanar and non-coplanar attachment points for different lengths of hoses. These non-contact means of taking measurements were essential in reducing errors in data collection. The torque values for various angular deformations were adjusted in order to define the torsional stiffness curve for all torsion springs in the model so that the predicted hose shape would lie near the center of the point cloud data for every 10° of twist, from 0°-180° for 11”, 13”, and 16” brake hoses held between coplanar attachment points. A cubic torsional stiffness curve was obtained from a regression analysis of the three torsional stiffness curves for 11”, 13”, and 16” hoses.

The method for measuring deviations between brake hose samples and the simulation model using digitizer post-processing software is presented for the first time. The average deviation of the torsion spring model for a hose length typically used in mid-size cars and SUVs when twisted to the maximum angle possible in these vehicles was 2.803mm. A one-sample t-test of average deviations for ten samples of 10” and 13” hoses showed that the population mean of average deviations is less than 5.15mm (hose radius) at a significance level of 0.05. The method to construct the simulation model and data analysis to determine its accuracy can be used for other flexible components such as robot dresses and cable harnesses.
ACKNOWLEDGMENTS

I am deeply indebted to Dr. Mitchel J. Keil for his support, guidance and confidence in me for the completion of the Dissertation. The concept and the progress of this research were largely due to his intellect, hard work and encouragement. I am also thankful to Dr. Steven Butt, Dr. Tarun Gupta, Dr. Azim Houshyar and Dr. Damon Miller for challenging me to think further than my limited scope of vision and thus showing me the requirements for valuable research. I am thankful to Western Michigan University and the donors of the Center for Integrated Design lab for providing the equipment that was essential for increasing the scope of this dissertation. Lastly but not in the least I thank God Almighty for blessing me with a family which made me realize the priceless value of the enduring perseverance, patience and support of my wife in my difficult times and the love of my children and parents.

Jai Thomas
# TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ ii

LIST OF TABLES .................................................................................................................. vii

LIST OF FIGURES ............................................................................................................... viii

CHAPTER

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

  Importance of Predicting the Shape of a Brake Hose ................................................. 1

  Research Objectives ..................................................................................................... 2

  Different Techniques ................................................................................................... 3

    The Virtual Reality Approach ............................................................................... 3

    Finite Element Analysis Approach ....................................................................... 5

  Modeling of Hoses Using Flexible Beam Elements .............................................. 6

  Chapter Summary ....................................................................................................... 6

II. LITERATURE REVIEW OF SIMULATION MODEL FOR BRAKEHOSES ......................... 8

  Hose Model Using Flexible Beams .......................................................................... 8

  Hose Model Using Beams and Translational Springs .......................................... 14

  Chapter Summary ...................................................................................................... 18

III. METHOD FOR DATA COLLECTION TO DEVELOP AND VALIDATE THE SIMULATION MODEL OF BEAMS AND TORSION SPRINGS ......................................................... 19

  Simulation Model with Beams and Torsion Springs ............................................. 19
# Table of Contents—continued

## CHAPTER

Method for Collecting Data for Modeling a Brake Hose................. 23

Scanned Point Cloud Data for Hose Shape between Coplanar Attachment Points ......................................................... 24

Steps in Obtaining Scanned Point Cloud Data for Hose Shape between Non-Coplanar Attachment Points .......................... 49

Chapter Summary ........................................................................ 54

### IV. FINDING BEST-FIT TORSIONAL STIFFNESS CURVE ................. 56

Building the Simulation Model with Beam and Torsion Springs for the Coplanar Position.......................................................... 56

Locating the Vector Points Using the Digitizer ............................... 57

Adjusting Torsional Stiffness Curve for Centering the Model in the Scans ................................................................. 62

Torsional Stiffness Curve for 13” and 16” Hose Lengths ............... 68

Torsional Stiffness Curve for Non-Coplanar Attachment Points...... 74

Difference in Axial Forces Profile between Coplanar and Non-Coplanar Position ............................................................... 79

Axial Forces in Beams for Hose in Coplanar Position .................... 79

Axial Forces in Beams for Hose in Non-Coplanar Position ......... 82

Chapter Summary ........................................................................ 83

### V. VALIDATION OF CUBIC TORSIONAL STIFFNESS CURVE MODEL ................................................................. 85

Comparison of Hose Shapes for Different Lengths with Scans .......... 85
Table of Contents—continued

CHAPTER

Future Work ........................................................................................................... 127

REFERENCES ........................................................................................................ 129

APPENDICES

A. Vector Direction at the Vector Points at Either End Resulting in
   Different Geometries ......................................................................................... 132

B. CAD Drawings of Parts of the Fixture ................................................................. 134

C. The ANOVA Table for Polynomial Regression Analysis for 11”, 13”,
   and 16” Hoses ................................................................................................. 147

D. Deviations of Torsion Spring Model from Four Scans (N = 1) ............... 149

E. Deviations of Translational Spring Model from Scans of One Sample
   from Different Initial Orientations (N = 1) .................................................. 151

F. Deviations of Torsion Spring Model from Scans of Ten Samples.......... 153

G. Summary of Average Deviations for 10”, 13”, and 16” Hoses............. 155
LIST OF TABLES

1. Time Required for Performing the Steps in Obtaining Point Cloud of a Hose Length at a Particular Angle of Twist .......................................................... 40

2. Maximum, Minimum, Average Deviation, and Standard Deviation among the Three Locations for Torsion Spring Model (N = 1) ........................................ 95

3. Mean and Standard Deviation of Average Deviation Grouped by Length and Twist Angle for Torsion Spring Model (N=1) .............................................. 96

4. Maximum, Minimum, Average Deviation, and Standard Deviation among the Three Locations for Translational Spring Model (N = 1) ........................................ 98

5. Mean and Standard Deviation of Average Deviation Grouped by Length and Twist Angle for Translational Spring Model (N=1) ........................................ 100

6. Mean, Standard Deviation, and Standard Error of the Mean of Average Deviations of Torsion and Translational Spring Models ........................................ 101

7. Performance Comparison of Translational Vs Torsion Spring Hose Models .................................................................................................................. 102

8. Maximum, Minimum, Average Deviations, and Standard Deviation of Deviations Among Three Locations for Each of Ten Samples of Hose Lengths for 15° and 25° Twist ........................................ 113

9. Mean and Standard Deviation of Average Deviation Grouped by Length and Twist Angle (N=10) ............................................................................. 114

10. The Values for First Quartile (Q1), Median, and Third Quartile (Q3) for Average and Maximum Deviations .............................................................. 116

11. Summary Statistics for Average Deviations and 95% CI of Mean for Each Length ........................................................................................................... 117

12. ANOVA Results and Tukey Homogeneous Subsets .................................................................................................................. 120
LIST OF FIGURES

1. Brake Hose with Bumpers at Rub Points ........................................ 2

2. Linear Hose Model Consisting of Connected Flexible Beams.................. 8

3. Relative Translational and Rotational Displacements of the Point M with Respect to the point N as Expressed in the X-, Y-, and Z-axis, Respectively, of Point N .......................................................... 9

4. Matrix of Equations for Force and Torque Components in the Coordinate System of Point N Due to the Relative Translation and Rotational Displacements of Point M with Respect to Point N ....... 9

5. Linear Hose Model with No Twist, with Uniform Bending and Torsional Stiffness, and with Increased Torsional Stiffness ........................................ 11

6. Scanned Images of the Hose at 0° and 180° Twist ................................ 13

7. Front View of Scanned Point Cloud and Hose Shape as Per Linear Model at 0° Twist ............................................................... 13

8. Isometric View of Scanned Point Cloud and Hose Shape as Per Linear Model at 180° Twist ............................................................... 14

9. Springs Placed between the Adjacent Hose Elements throughout the Length of the Hose ............................................................... 15

10. Simplified Line Diagram of a Spring Placed between the Adjacent Hose Elements ................................................................. 16

11. Geometry of the Placement of Springs in Top View before Simulation .... 16

12. Front View of Model with Off-Axis Translational Springs and Beams with Arrows Showing the Direction of Spring Forces and the Length Corresponding to their Magnitude ............................................. 17

13. Enlarged View of Translational Springs between Beams. Top View of Translational Springs ......................................................... 17
List of Figures—continued

14. Front View and Isometric View of CAD Model of Two Hose Elements
    Connected with a Beam and Torsion Spring ........................................ 19

15. Front View and Isometric View in Wireframe Showing Two Hose
    Elements Connected with a Beam and Torsion Spring in Adams™/View
    Simulation Software ............................................................................. 20

16. Front View of 11” Hose Model in Wireframe with Beam and Torsion
    Springs in the Twist-Free Position ....................................................... 21

17. Vector Directions for the Attachment Points ......................................... 21

18. Spline Curve of Torque Vs Angular Deformation for Torsion Springs .... 22

19. The Angular Deformation of the Springs and Beam during the Twisting
    Motion ............................................................................................... 23

20. CAD Model of Fixture .......................................................................... 24

21. Plug Gauge with Outer Diameter Made to Fit the Inner Diameter of the
    Hose. Plug Gauge Being Inserted into the Hose. Plug Gauge Partially
    Inserted into the Hose. Plug Gauge Completely Inserted into the Hose .... 25

22. Hose Being Inserted into the Clamp. Clamped End of the Hose. Fixture
    with the Hose Clamped at One End ..................................................... 26

23. Plug Gauge for the Other End of the Hose. Plug Gauge after Being
    Inserted into the Hose ...................................................................... 27

24. Hose after Being Inserted into the Square Shaped Clamp. The Hose End
    at the Dial after Being Clamped Showing the Coplanar Points .......... 28

25. Dowel Pin Being Inserted into the Clamp-On Collar. Dowel Pin Being
    Held by the Clamp-On Collar ............................................................. 29

26. Collar with the Pointer Clamped to the Dowel Pin and Bushing
    Slid over the Dowel .......................................................................... 30
List of Figures—continued

27. The Dowel with the Assembly is Clamped to the Collar Welded onto the Plate. Dial with the Pointer to Read the Twist Given to the Hose ................................................................. 31


29. Assembly at the Dial Being Rotated Counterclockwise. Hose Position after Being Released. Rectangular Plate Being Tapped with Crescent Wrench until Final Resting Position of the Hose Indicated by the Non-Movement of the Pointer Is Identified ................................................................. 34

30. Assembly at the Dial Being Rotated Counterclockwise to the Calculated Mean Value (+1.5°) .................................................................................................................. 35

31. Collar Clamp Holding the Pointer (Collar B) Being Loosened. Collar B Being Tightened after Rotating the Collar so that the Pointer Points to 0° on the Dial .................................................................................................................................................................................. 36

32. Collar and Dowel Pin Assembly Removed Completely from the Dial End. Marking A Aligned with Line A. Clamp Being Loosened to Rotate the Hose. Marking B Aligned with Line A at the End of Rotation. Hose and the Collar and Dowel Assembly after Clamp was Tightened .................................................................................................. 39

33. Collar and Dowel Pin Assembly Along with Hose Being Twisted by 10° at the Dial End after Loosening Collar C. Front View of the Hose in the Fixture at the End of 10° Twist. Side View of the Hose in the Fixture at the End of 10° Twist .................................................................................. 41

34. Front View and Side View of the First Scan at Initial Orientation (0°) at 10° Twist ................................................................................................................................. 42

35. Front View and Side View of the First and Second Scan after the First Counterclockwise Rotation of 11” hose by 90° from Initial Orientation for a 10° Twist ................................................................................................................. 42
36. Front View and Side View of the First, Second Scan after the First Counterclockwise Rotation of 11" Hose by 90° and Third Scan after the Second Counterclockwise Rotation of 90° (180° from Initial Orientation) for a 10° Twist .......................................................................................................................... 43

37. Front View and Side View of the First, Second Scan after the First Counterclockwise Rotation of 90°, Third Scan after the Second Counterclockwise Rotation of 90° and Fourth Scan after the Third Counterclockwise Rotation of 90° (270° from Initial Orientation) for a 10° Twist .......................................................................................................................... 43

38. Scans Showing Hysteresis Effect for 16" Hose and 11" Hose .................. 45

39. Hose Shape at 30° Twist ........................................................................... 45

40. Collar and Dowel Pin Assembly Being Twisted by 180° at the Dial End after Loosening Collar C. Side View of the Hose Held in the Fixture at 180° Twist .......................................................................................................................... 46

41. Front View and Side View of the First Scan at 180° Twist .................... 46

42. Front View and Side View of the First and Second Scans at 180° Twist .............................................................................................................................. 46

43. Front View and Side View of the First, Second, and Third Scans at 180° Twist .............................................................................................................................. 47

44. Front View and Side View of the First, Second, Third, and Fourth Scans at 180° Twist .............................................................................................................................. 47

45. Front View and Side View of the Scanned Point Cloud of 11" Hose at Increments of 10° Twist from 0° to 180° ................................................................. 48

46. Front View and Side View of the Scanned Point Cloud of 13" Hose at Increments of 10° Twist from 0° to 180° ................................................................. 48

47. Front View and Side View of the Scanned Point Cloud of 16" Hose at Increments of 10° Twist from 0° to 180° ................................................................. 49

48. Fixture with X, Y, and Z Axes for Rotation. Hole for Viewing the Gear Tooth that Indicates the Amount of Rotation about a Given Axis .................. 49
List of Figures—continued

49. Toggle Clamp for Rotation about the Y-Axis in the Released Position. Toggle Clamp Engaged after Rotating the Hose End about the Y-Axis by 30° .......................................................... 50

50. Toggle Clamp for Rotation about the Z-Axis in the Released Position. Toggle Clamp Engaged after Rotating the Hose End about the Z-Axis by 30° .......................................................... 51

51. Toggle Clamp for Rotation about X-Axis in the Released Position. Toggle Clamp Engaged after Rotating the Hose End about the X-Axis by 30° .......................................................... 52

52. The Scanned Point Clouds of 11” Hose at 30° (right), 60° (middle) and 90° (left) Twist Positions .......................................................... 53

53. The Scanned Point Clouds of 11” Hose at 30° (right), 60° (middle), and 90° (left) Twist Positions after Repeating Steps 1 to 9 for Rotation Angles of 30°, 30° and 60°. The Scanned Point Clouds of 11” Hose at 30° (right), 60° (middle), and 90° (left) Twist Positions after Repeating Steps 1 to 9 for Rotation Angles of 60°, 60° and 60° .......................................................... 54

54. Position of Vector Points a, b, c, and d on the Fixture .......................................................... 56

55. Plane Created on Surface of a Square Clamp. Planes Created on the Upper Surface of the Square Clamps at Each End. .......................................................... 57

56. Cylinder Created Perpendicular to the Plane Created in Step 1 on Both Ends .......................................................... 58

57. Endpoint (point_c0) created on the Cylinder Axis Closest to the Plane. Endpoint on the Cylinder Axis Projected to the Plane to Locate the Vector Point c .......................................................... 59

58. Line cd Created Perpendicular to the Plane from Point c. Lines cd and ab Created at Both Ends. .......................................................... 60

59. Endpoints a and d Created on Lines ab and cd Respectively .......................................................... 60

60. Global XYZ Coordinates of Vector Point d .......................................................... 61
List of Figures—continued

61. Front View of Rendered Hose Model with Scans of Point Cloud Data at Twist Angles in Increments of 10° ................................. 61

62. Torque Value of Zero Assigned to the Angular Deformation (deg) of all the Torsion Springs for Twist of 10°. Model Not Centered in the Scan........ 63

63. Plot Showing the Angular Deformation (deg) of all the Torsion Springs from 0° to a Twist of 10° in Order to Identify the Value of Maximum (m) among all Torsion Springs ......................................................... 63

64. Torque Value Being Adjusted Manually for the Angular Deformation Value (L) Greater than the Maximum Angular Deformation for a Twist of 10° for 11” Hose. ................................................................. 64

65. Plot Showing the Best-Fit Torque Value for the Angular Deformation L. Hose Shape Centered in the Scans ......................................................... 64

66. Plot Showing the Maximum Angular Deformation (k) in Degrees amongst All the Torsion Springs at Twist of 10°. Plot Showing Torque Value for the Maximum Angular Deformation (k) in Degrees for a Twist of 10° for 11” Hose ................................................................. 65

67. Torque Value Being Adjusted Manually for the Angular Deformation Value Greater than the Maximum Angular Deformation for a Twist of 20° for 11” Hose after Holding the Torque Value at 10° Constant .............. 66

68. Plot Showing Torque Value for the Maximum Angular Deformation for a Twist of 20° for 11” Hose ......................................................... 67

69. Torsional Stiffness Curve for an 11” Hose that Centered the Model in the Scans ......................................................................................... 67

70. Angular Deformation of all the Torsion Springs for Angles of Twist from 0°-180° for an 11” Hose ......................................................... 68

71. Angular Deformation of all the Torsion Springs for Angles of Twist from 0°-180° for 13” Hose .............................................................. 69

72. Torsional Stiffness Curve for 13” Hose that Centered the Model in the Scans ......................................................................................... 69
List of Figures—continued

73. Angular Deformation of All the Torsion Springs for Angles of Twist from 0°-180° for a 16” Hose. ................................................................. 70

74. Torsional Stiffness Curve for 16” Hose that Centered the Model in the Scans. ................................................................................................. 70

75. Best-Fit Torsional Stiffness Curves for 11”, 13”, and 16” Hoses. ............ 71

76. Akima Spline through the Torque Values in Adams™/View Simulation Software. .................................................................................................. 72

77. Flowchart of the Procedure for Collecting Raw Data for Regression Analysis ............................................................................................... 73

78. Cubic Curve Fit through the Torsional Stiffness Curves for 11”, 13”, and 16” Hoses. ......................................................................................... 74

79. Torsional Stiffness Curve that Satisfied the Criterion of the Hose Being within Scans at 30°, 60°, and 90° Twist for Each of the Three Non-Coplanar Orientations for the 11” Hose. .............................................. 75

80. The Final Position of the Model and Scanned Point Cloud Data of 11” Hose for 30°, 30°, and 60° Non-Coplanar Position at the End of 30°, 60°, and 90° Twist Positions ................................................................. 76

81. The Final Position of the Model and Scanned Point Cloud Data of 11” Hose for 30°, 30°, and 30° Non-Coplanar Position at the End of (a) 30°, 60°, and 90° Twist Positions .......................................................... 77

82. The Final Position of the Model and Scanned Point Cloud Data of 11” Hose for 60°, 60°, and 60° Non-Coplanar Position at the End of 30°, 60°, and 90° Twist Positions ................................................................. 78

83. Comparison of Best-Fit Torsional Stiffness Curve for 11” Hose for Coplanar and Non-Coplanar Attachment Points .......................................... 79

84. Crossover of Axial Forces for the Beams in 11” Hose .............................. 80

85. Decreasing Angular Deformation with Increasing Twist Beyond Approximately 80° ....................................................................................... 81
List of Figures—continued

86. Crossover of Axial Forces for a 13” Hose ......................................................... 81
87. Crossover of Axial Forces for a 16” Hose ............................................................. 82
88. High Axial Forces in Beams for Non-Coplanar Attachment Points ......................... 82
89. Model Centered in the Scans for 11” Hose at 20° and 50° Twist Angles .................... 85
90. Comparison of Model and Scans for 13” Hose at 30°, 60°, and 90° Twist Angles ........ 86
91. Comparison of Model and Scans for 16” Hose at 40°, 70°, and 80° Twist ................ 87
92. Simulated Position of 16” Hose at 10° Twist Position in Digitizer Software ................ 88
93. Three Points Created on the Hose Model at 25%, 50%, and 75% of the Length of the Hose from Attachment Point d .............................................. 88
94. A Line Created along the Edge of the Hose Element at a Point dev25 ........... 89
95. A Plane Created Perpendicular to the Line Created at Point dev25. Three Planes Created Perpendicular to the Lines Created in Step 2 .................. 90
96. Group of Scans Imported to Be Compared to the Simulated Hose Model ................ 90
97. Section through the Hose Model and Scans at 25% of the Hose Length ............... 91
98. Points Lying on the Section through the Hose Model and Scans at 25% of Hose Length ................................................................. 91
99. Best-Fit Circle for Selected Number of Points. Radius of the Best-Fit Circle along with 3D Coordinates of its Center .............................................. 92
100. Four Best-Fit Circles for Points on the Scans along with their Centers ............ 92
101. Selected Points on the Model to Create the Best-fit Circle. Best-Fit Circle for the Model along with Those of the Scans ........................................... 93
List of Figures—continued

102. Distance between the Center of the Model and the Centers of Each Scan (dev_25_1, dev_25_2, dev_25_3, and dev_25_4) at 10° Twist for 16” Hose. ......................................................... 94

103. Individual Value Plot for Average Deviations from Minitab® Software.... 96

104. Interval Plot of 95% CI of Mean of Average Deviations Grouped by Length and Twist Angle from Minitab® Software (N=1) ..................... 97

105. Individual Value Plot of Average Deviations........................................ 99

106. Interval Plot of Average Deviations for Torsion and Translational Springs from Minitab® Software. .................................................. 100

107. Individual Value Plot of Average Deviations for Torsion and Translational Springs from Minitab® Software.................................. 101

108. GY5052 Brake Hose from Manufacturer ....................................... 105

109. Ten Samples Each of Approximately 11”, 14”, and 17” Lengths .......... 105

110. A Length of 10” Being Measured along the Hose from the Top Surface of Square Clamp. Distinct Marking Being Made with a Scriber 10” .... 106

111. Hose in 15° Twist Position................................................................. 107

112. Hoses Marked with Sample Numbers after Being Scanned ............ 107

113. Model alongside Scans of Ten Samples of 10” Hose at 15° and 25° Twist Angles........................................................................... 108

114. Model alongside Scans of Ten Samples of 13” Hose at 15° Twist Angle. Model alongside Scans of Ten Samples of 13” Hose at 25° Twist Angle .............................................................................. 109

115. Model alongside Scans of Ten Samples of 16” Hose at 15° and 25° Twist Angles............................................................... 110

116. 10” Model at 15° Twist with Ten Scans and Plane at 50% of the Length ....................................................................................... 110

117. Points on Section through the Plane at 50% of Length .................. 111
List of Figures—continued

118. Ten Best-Fit Circles and Circle Corresponding to Hose Model................................................................. 111

119. Distances Measured from Center of Hose Model Circle to Center of Each of the Best-Fit Circles................................................................. 112

120. Interval Plot of 95% CI of Mean of Average Deviations Grouped by Length and Twist Angle from Minitab® Software.................................................. 114

121. Boxplot of Average Deviations Grouped by Length from Minitab® Software .................................................................................................................. 115

122. Boxplot of Maximum Deviations Grouped by Length ................................................. 118

123. One-Sample T-Test for Average Deviations of 10” Hose from Minitab® Software .............................................................................................................. 118

124. Boxplot of Comparison of 95% CI of Mean of Average Deviations for 10” Hose and Hypothesized Population Mean of 5.15mm............................................. 118

125. One-Sample T-Test for Average Deviations of 13” Hose ........................................... 119

126. Boxplot of Comparison of 95% CI of Mean and Hypothesized Population Mean of 5.15mm........................................................................................................... 119

127. Main Effects Plot of Length and Twist Angle for Mean of Average Deviation...................................................................................................................... 121

128. Hose Model in a Dynamic Simulation Model of Front Suspension .............. 125
CHAPTER I

INTRODUCTION

Importance of Predicting the Shape of a Brake Hose

Flexible components, such as brake hoses, are subject to large elastic deformations during movement of the rigid components to which they are attached. According to the United States Council of Automotive Research (USCAR) Digital/Virtual Tools (DVT) Task Force (2006), there are no computer tools for modeling operations involving flexible parts such as wiring harnesses, hoses, and robot dress and tooling. Thus, manufacturing engineers have to rely on experience, judgment, and physical prototypes for assembly of flexible components. It was estimated by the USCAR DVT team that manufacturing issues related to wiring harnesses, hoses, and robot dress/tooling, if left unchecked, would cost USCAR member companies a combined $210M in present value dollars from 2005-2015. The team calculated a present value cost savings (in 2005) of $5.78M from development of a virtual tool for designing brake hoses (USCAR DVT Task Force, 2006). This estimate is based on responses to a questionnaire sent to member companies (General Motors™, Chrysler™, and Ford™) and indirect savings identified from the Quality Function Deployment process. The inability to model flexible components also leads to ergonomical issues due to inaccurate prediction of hand clearance for assembly.

Usually different lengths of brake hose are manually cut and twisted in an attempt to discover rub points against any of the components as the actual suspension moves through the limits of its motion (Chrysler™ Internal Document, 2001). Polymer bumpers
are fused to the hose at the rub points as shown in Figure 1. These bumpers cause high stress in the hose during operation of the vehicle. This can result in premature failure of brake hoses and thus poses a safety risk.

A modeling solution was implemented into a full vehicle dynamic simulation, in order to enable a designer to determine whether the hose of a particular length will touch any of structures on the chassis during motion of the wheels. This knowledge can help reduce the possibility of a significant source of failure due to abrasion of brake hoses on nearby structures, thus eliminating the safety hazard due to premature failure of hoses. The need for bumpers is also eliminated since an appropriate length that does not rub against rigid components can be found. Further estimation of appropriate length in the design phase would reduce delays on the assembly line, resulting in reduced vehicle launch time (Technical Innovations, 2005). It would also reduce the material cost due to reduced scrap.

**Research Objectives**

This project was performed to develop and establish the fidelity of a simulation model to predict the shape of the hose between any two attachment points (typically
coplanar) for mid-size cars when twisted at one end during the turning of wheels. The maximum steering angle for mid-size cars like the PT Cruiser™ is typically 25° (R. Hathaway, personal communication, March 15, 2010). The length of hose in a PT Cruiser™ is approximately 10” between mount points. Hence, it is especially important to predict the hose shape for twist angles within 25° and hose lengths in 10”-13” range.

The effect of nonlinear torsional stiffness in addition to the usually considered bending stiffness on brake hose shape was studied, which resulted in more accurate prediction of hose shape for different twist angles. Specifically, the shape of a GY5052 brake hose used in the PT Cruiser™ has been predicted in this research. This hose meets FMVSS-106, SAE J1401, MS-EA70, and ESA-M96D4-A specifications. It is a two-braid Poly Vinyl Alcohol (PVA) reinforced hose. The inside of each PVA layer is attached to a Chlorobutyl Rubber (CIIR) layer. The outer covering of the hose is made of Ethylene Propylene Diene Monomer Rubber (Goodyear™ Internal Document, 2001).

**Different Techniques**

**The Virtual Reality Approach**

Virtual reality software, VRHose, developed by Virtual Reality Applications Center at Iowa State University, has sought to overcome limitations in CAD software for modeling of flexible elements. The VRHose program was developed using a virtual reality software tool called VRJuggler, which provides a framework for the development of virtual reality applications (Chipperfield & Vance, 1999). VRHose has been used to facilitate modeling of a hose in the Jack™ software due to its suitability for virtual reality applications, with its enhanced feature of supporting other CAD file formats (Fischer,
Chipperfield, & Vance, 2002). Further, a user can use VRHose to modify the hose geometry using a preprocessor of commercial simulation software, and then import the geometry into the Jack™ software into which the adjacent CAD geometry has already been imported and is present. First, the user defines the control points inside Jack™ in order to prevent the hose from touching other structures (Chipperfield & Vance, 2002). These control points serve as the new input to the VRHose program, which uses the Adams™ simulation software preprocessor and obtains the more accurate hose geometry with associated bending properties. Validation of the hose model has been carried out for a real hose deflected in one plane. This model cannot predict the hose shape due to twisting through a user-defined angle of twist. Further, the hose shape of varying hose lengths between two fixed mount points cannot be predicted, since the hose model is based on the initial assumption of approximate intermediate points along the hose path.

Professor Leon at INPG Domaine University in Grenoble, France has also conducted research on modeling flexible parts for virtual reality assembly simulations. The shape of a flexible part through user defined points in configuration space is predicted based on Real Time (RTM) and Interactive Mechanical Models (IMM) in a virtual reality environment (Mikchevitch, Leon, & Gouskov, 2004). The IMM supplies the material characteristics (Young’s Modulus and Shear Modulus) for the part based on experimental data.

Researchers at Heriott Watt University propose an approach to enhance design engineering that is enabled by products of advanced information technology through cognitive ergonomics and human factors engineering (Holt, Ritchie, Day, Simmons, Robinson, Russell, & Ng, 2004). In their approach, a cable harness is considered an
integral and important component of the final product right at the beginning of the design process. This group is mostly focused on advanced human factors research. The physical properties of the cable harness have not been incorporated into their simulations. Their approach appears to be mostly geometric in terms of designing a layout for the cables. Since they did not consider material properties in a deformation model and considered forces such as gravity and friction, realistic and dynamic simulation of cable harnesses is not described. They identified a list of technical gaps which were mostly related to virtual reality technology improvements.

IDO:Flexible is a commercial software developed by ICIDO GmbH for modeling of hoses, cables and cable harnesses, thus supporting design, layout, planning and working with such flexible components (IDO: Flexible User Manual, 2007). The shape of a hose of a particular length and diameter is determined by material density, the modulus of elasticity, and Poisson's ratio. However, twisting and bending is implemented by user interaction. IDO:Flexible appears to be a tool for routing formed hose or restrained hose such as for an automobile radiator. The location of the unsupported sections of brake hose are determined by mount points and twist, and cannot be arbitrarily positioned as shown in the IDO:Flexible examples. There is no data presented that validates the shape predicted by the model.

**Finite Element Analysis Approach**

Marc™, commercial FEA software from MSC Corporation® was used by Kusunoki and Miyashita for brake hose routing (Kusunoki & Miyashita, 2004). The input to the model was vector data corresponding to the mount points. A simplified homogeneous and orthotropic material property of rubber was used; however, the amount
of twist induced and the deviation from an actual hose was not made clear. Fuji Heavy Industries Ltd. has used this technique for brake hose routing design.

Modeling of Hoses Using Flexible Beam Elements

Sugiyama (Sugiyama & Otaki, 1992) made a brake hose model by dividing it into flexible beam elements and particles. The shape of the hose was determined by solving the equations of static equilibrium resulting from the element forces on the particles. The final hose shape was sensitive to initial conditions. The paper focused on ease of computation of the element forces and claims to have reduced the time required for solving equations for static equilibrium. Elliott (Elliott, 1996) made a hose model in commercial simulation software and studied the effects of pressure and temperature on the stiffness properties of hydraulic hose. A linear regression was done on the force-deflection data of the hose to determine the values of stiffness parameters for a particular temperature and pressure.

Chapter Summary

A virtual tool for brake hoses would result in present value cost savings (in 2005) of $5.78M over a period of 10 years (USCAR DVT Task Force, 2006). Knowledge of the appropriate length of hose in the design phase that prevents rubbing against other rigid bodies on the vehicle chassis would result in increased safety and reduced vehicle launch time. The GY5052 brake hose used in the PT Cruiser™ has been modeled in this research. From the literature review, it was observed that the time required for simulating a hose model consisting of flexible beams was significantly less than finite element
models. A detailed review of a hose model with flexible beams is presented in the next chapter.
Hose Model Using Flexible Beams

Keil (Keil, Rodriguez, & Hemmye, 2001) implemented a hose model consisting of beams in Adams™ commercial simulation software. Linear beam theory is limited to small deflections ($\Delta Y$), i.e., $\Delta Y \leq 0.2L$; where $L$ is the length of the beam. The theory deviates significantly if $\Delta Y$ is larger. Hence, in that work several small beams were used in the hose model to have small $\Delta Y$ locally. The accumulation of the deflection over several beams is large thus facilitating modeling of large deflections. Beam torque increases linearly with increases in the twist angle about its axis. Figure 2 shows the linear hose model consisting of flexible beams with a circular cross section with $\Delta Y \leq 0.2L$ connected end to end to depict a hose shape between two mount (attachment) points.

Figure 2. Linear Hose Model (Keil, Rodriguez, & Hemmye, 2001) Consisting of Connected Flexible Beams.

Figure 3 shows a flexible beam between endpoints N and M. $X$, $Y$, and $Z$ are the translational displacements of point M with respect to point N. $\theta_X$, $\theta_Y$, and $\theta_Z$ are the relative rotational displacements of point M with respect to point N.
Constitutive equations of a beam (Oden & Ripperger, as cited in Adams™ Software Reference Manual, 2007) shown in Figure 4 have been implemented in Adams™ simulation software. This matrix gives the force and torque components about x-axis, y-axis and z-axis respectively measured at endpoint N on the beam due to the translation and rotational displacements of endpoint M.

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
T_x \\
T_y \\
T_z
\end{bmatrix} = \frac{EA}{L} \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_{zz}}{E'(1+P_z)} & 0 & 0 & 0 & -\frac{6EI_{zz}}{E'(1+P_z)} \\
0 & 0 & \frac{12EI_{yy}}{E'(1+P_y)} & 0 & \frac{6EI_{yy}}{E'(1+P_y)} & 0 \\
0 & 0 & 0 & \frac{6EI_{xx}}{E'(1+P_x)} & 0 & 0 \\
0 & 0 & 0 & \frac{(4+P_x)EI_{xx}}{L(1+P_x)} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{(4+P_y)EI_{yy}}{L(1+P_y)} & \frac{4+P_z)EI_{zz}}{L(1+P_z)}
\end{bmatrix} \begin{bmatrix}
X - L \\
Y \\
Z \\
\theta_x \\
\theta_y \\
\theta_z
\end{bmatrix}
\]

Figure 4. Matrix of Equations for Force and Torque Components in the Coordinate System of Point N Due to the Relative Translation and Rotational Displacements of Point M with Respect to Point N (Adams™ Software Reference Manual, 2007).

In the matrix,

\[E = \text{Young's modulus of elasticity for the beam material;}\]

\[G = \text{Shear modulus of elasticity for the beam material;}\]
A = Uniform area of the beam cross section;

L = Undeformed length of the beam along the x-axis;

$I_{xx}$, $I_{yy}$ and $I_{zz}$ = Polar moments of inertia about x-axis, y-axis and z-axis, respectively.

For a beam with a circular cross section (shaft) $I_{xx}$, $I_{yy}$ and $I_{zz}$ are given by:

\[ I_{xx} = \frac{\pi d^4}{32} \]  \hspace{1cm} (Equation 1)

\[ I_{yy} = I_{zz} = \frac{\pi d^4}{64} \]  \hspace{1cm} (Equation 2)

$T_x$, $T_y$, and $T_z$ are the torque components in the coordinate system of endpoint N.

The relationship between the angle of twist ($\theta_x$) about the x-axis and torque ($T_x$) for a beam with a circular cross section of length $L$ is given by:

\[ T_x = \frac{\theta_x GI_{xx}}{L} \]  \hspace{1cm} (Gere & Timoshenko, 1997). (Equation 3)

The quantity $\frac{GI_{xx}}{L}$ in the equation 3 is called torsional stiffness of the beam and is the torque required to produce a unit angle of rotation. Same relation as stated in equation 3 exists between the angle of twist ($\theta$) and torque ($T$) about the y-axis and z-axis. In the matrix, $P_y$ and $P_z$ are constants as given in equations 4 and 5 (Oden et al., as cited in Adams™ Software Reference Manual, 2007).

\[ P_y = \frac{12 \, E \, I_{zz} \, ASY}{(GAL^2)} \]  \hspace{1cm} (Equation 4)

\[ P_z = \frac{12 \, E \, I_{yy} \, ASY}{(GAL^2)} \]  \hspace{1cm} (Equation 5).
Here, ASY = Correction factor (shear area ratio) for shear deflection in the y-direction and in the z-direction respectively for Timoshenko beams. A correction factor was not considered in the model and hence ASY is set to zero. Therefore, $P_y$ and $P_z$ in equations 4 and 5 reduce to zero.

Figure 5(a) shows a linear model for a length of hose with no twist. Figure 5(b) shows the maximum deflection in the model (as a result of twisting one end by 180°) with uniform bending and torsional stiffness. It was observed from experiments that the brake hose was much stiffer in torsion than in bending. Subsequently, the torsional stiffness of the beams was increased by increasing the value of $I_{xx}$ manually and the resulting maximum deflection as shown in Figure 5(c) matches more closely with experimental results.

Keil, Rodriguez, and Hemmye (2002) noted that it is imperative to be very precise regarding the orientation and mount points of the hoses. They stated that it is very time consuming and cumbersome to set up the model with the flexible beams and its associated joints for modeling of a flexible body without any user errors. A flexible element model was automatically built in simulation software using the principles of spatial orientation and vector mathematics (Thomas, Keil, & Rodriguez, 2005). These
mathematical principles maintain the precision in the flexible element model as suggested by Keil, Rodriguez, and Hemmye (2002) while reducing the time for building a hose model from hours to minutes.

Keil, Rodriguez, and Hemmye (2002) placed their prime concern in accurately predicting the properties of the hose and used it as a driving force in predicting hose geometry in the flexible beam model. They conducted tests on a set of samples in order to determine the bending and torsional stiffness of a hose, and concluded that the stiffer hose in bending is not the stiffest in torsion. There was a variation by a factor of two for bending and torsional stiffness in a single batch of hoses with the same specifications (Keil, 2002). Hence, it was difficult to accurately specify bending and torsional stiffness and mass and area moment of inertia properties of a hose based on manufacturer data.

The uniform properties of a hose determine the hose geometry in bending and twisting in the flexible element model. Thus, the hose shape is not sensitive to initial conditions as is the case with Sugiyama’s model (Sugiyama & Otaki, 1992); neither is the accuracy of the predicted hose shape a function of initial approximations of points along the hose path as in Chipperfield’s modeling technique (Chipperfield & Vance, 2002).

Validation of the linear model was performed by comparing the predicted shape to a point cloud of a hose of similar length. A hose length of 13” (+/- 0.0625”) was firmly attached at one end of a fixture. The hose was bent and inserted into the hollow recess at the other end of the fixture. This represents a 0° twist. The hose was scanned using the ATOS II scanning system manufactured by GOM mbH Optical Measuring Techniques Inc. One end of the hose was rotated through 180° about the axis as shown in Figure 6. The hose was scanned again. The two files, one containing point cloud data at 0° twist
and the other at $180^\circ$ twist, was imported to simulation software and the merged image of the two positions are shown in Figure 6.

![Figure 6. Scanned Images (Point Cloud) of the Hose at $0^\circ$ and $180^\circ$ Twist.](image)

The linear hose model alongside the scanned image at $0^\circ$ twist is shown in Figure 7. The linear torsional stiffness of the beams was adjusted manually by using a different value of $I_{xx}$ for each trial in an attempt to reduce the deviations between the model and scanned image at $180^\circ$ twist. Figure 8 shows the hose shape that matched most closely with the scan using this technique with torsional stiffness being 7.24 times the bending stiffness.

![Figure 7. Front View of Scanned Point Cloud and Hose Shape as Per Linear Model at $0^\circ$ Twist.](image)
Figure 9. Springs Placed between the Adjacent Hose Elements throughout the Length of the Hose (Thomas, 2004).

Figure 10 shows a simplified line diagram of a spring made between adjacent hose elements. Figure 11 shows the line diagram of the sixteen springs in top view along with the associated geometrical measurements.

Variables in the Equations 6 through 10 signify the following:

lhose = Length of the hose;

len_h = Length of the adjacent side of the spring angle;

sprang = Angle of the spring with the horizontal (could be varied from 52° - 90°);

sp_length = spring length;

noel = Number of elements in the hose;

subang = Angle subtended at the center of the octagon;

b_angle = base angle of the isosceles triangle;

rad = radius of the circle circumscribing the hexagon;

\[
\text{len}_h = \frac{(\text{lhose}/\text{noel})}{\tan(\text{sprang}\pi/180)}. \quad \text{(Equation 6)}
\]

\[
\text{sp\_length} = \frac{(\text{len}_h)}{\cos(\text{sprang}\pi/180)}. \quad \text{(Equation 7)}
\]

\[
\text{subang} = \frac{(360)}{\text{stside}}. \quad \text{(Equation 8)}
\]
Hose Model Using Beams and Translational Springs

The model with flexible beams was augmented with off-axis stiffeners. It was sought to mimic the behaviors of the two strands in the GY5052 hose with the stiffeners. The stiffeners were in the form of translational spring elements. The linear deformation of the translational springs during the twisting motion induced a force that depended on a spline curve drawn through values specified in a table that could be defined in simulation software. The deviation in the linear model was sought to be reduced by the incorporation of the off-axis translational spring elements (Thomas & Keil, Prepublished, 2010).

Trials involving different numbers of springs (8, 9, and 16) between planes containing start and end points of each beam were carried out. Previous study of a model with translational springs yielded least deviation between scans and model when sixteen springs were used between adjacent hose elements as shown in Figure 9 (Thomas, 2004).
\[ b_{\text{angle}} = \frac{\left(\frac{180 - s_{\text{ang}}}{2}\right) \cdot \pi}{180} \]  

(Equation 9)

\[ \text{rad} = \frac{\text{len}_h}{2 \cdot \cos(b_{\text{angle}})} \]  

(Equation 10)

Figure 10. Simplified Line Diagram of a Spring Placed between the Adjacent Hose Elements (Thomas, 2004).

Figure 11. Geometry of the Placement of Springs in Top View before Simulation.
Figure 12 shows the model in a simulated position. Figure 13(a) shows enlarged view of springs and hose elements. Figure 13(b) show top view of the model with translational springs before simulation.

Figure 12. Front View of Model with Off-Axis Translational Springs and Beams (Thomas et al., Prepublished, 2010) with Arrows Showing the Direction of Spring Forces and the Length Corresponding to their Magnitude.

Figure 13. (a) Enlarged View of Translational Springs between Beams. (b) Top View of Translational Springs.

The deviations in the model with translational springs and beams were less than for the linear model, indicating that this is a promising approach.

However, the model with translational springs and flexible beams is not easily scalable. Moreover, visually, the motion of the translational spring model was not smooth.
for twist angles between 0° and 180°. The motion was much smoother when torsional stiffness for each of the beams was different from one another. The required variation in torsional stiffness of the beams was modeled by using torsion springs. The model with torsion springs was found to be more scalable than one with translational springs. It was also visually observed that motion of the torsion spring model was much smoother for twist angles between 0° and 180°. A fixture was designed to validate the shape predicted by the torsion spring model for twist angles between and including 0° and 180°.

Chapter Summary

The torsional stiffness of the beams in the linear model (Keil, Rodriguez, & Hemmye, 2002) had to be increased in order to achieve the large deflections seen in an actual hose. The deviation of the hose model with flexible beams from the point cloud of an actual hose for twist angles of 0° and 180° was reduced by augmenting the model with translational springs. However, larger deflections than those seen in a brake hose were observed for twist angles between 0° and 180°. The deflections were less when different torsional stiffness values were specified for some of the beams. The method for varying the torsional stiffness along the length of the hose using torsion springs has been described in the next chapter. The model with torsion springs was also found to be more scalable than the one with translational springs. A fixture as described in the next chapter was fabricated in order to validate the model with beams and torsion springs for angles between and including 0° and 180°.
CHAPTER III

METHOD FOR DATA COLLECTION TO DEVELOP AND VALIDATE THE SIMULATION MODEL OF BEAMS AND TORSION SPRINGS

Simulation Model with Beams and Torsion Springs

A particular hose length was divided into hose elements of equal length in the simulation model. The centers of the hose elements were connected by flexible beams. In this research, torsion springs were added between the start and end points of each individual beam. Figures 14(a) and 14(b) show a CAD model of the front view and the isometric view of a torsion spring and a flexible beam with a circular cross section (diameter equal to that of the hose) connected to two hose elements.

Figure 14. (a) Front View (b) Isometric View of CAD Model of Two Hose Elements Connected with a Beam and Torsion Spring.

Figure 15(a) and Figure 15(b) show front and isometric views in wireframe of the icons used for graphical display of the beam and torsion spring in Adams™ Simulation software. This is not intended to be a mechanical representation of the model. Length of the beam and torsion spring is the same as that of the hose element.
Figure 15. (a) Front View in Wireframe Showing Two Hose Elements Connected with a Beam and Torsion Spring in Adams™/View Simulation Software. (b) Isometric View in Wireframe of Hose Elements Connected with a Beam and Torsion Spring in Adams™/View Simulation Software.

Figure 16 shows the model with the torsion springs and beams for an 11" hose in the twist-free position. The hose length of 11" was divided into 42 hose elements with a length of 0.262" (6.652mm). The centers of the hose elements were connected with 41 beams and torsion springs.

The simulation model is made in the vector direction from A to B and C to D as shown in Figure 17. A change in the vector direction at the vector points at either end can result in different geometries as shown in Appendix A since these vectors determine the start and finish directions of the hose curve tangents. A C++ program was used to write a
text file containing the global locations and orientations of the geometry of the hose model with flexible beams and torsion springs. The text file was imported into the simulation software.

Figure 16. Front View of 11" Hose Model in Wireframe with Beam and Torsion Springs in the Twist-Free Position.

Figure 17. Vector Directions for the Attachment Points.

The angular deformation of the springs during the twisting motion induces a torque that is dependent on a spline curve as shown in Figure 18 drawn through values specified in a table in simulation software.
Figure 18. Spline Curve of Torque Vs Angular Deformation for Torsion Springs.

Total torque in the model is due to beams and springs given by:

\[ T_{beam + spring} = T_{beam} + T_{spring} \]  
(Equation 11)

Torque in the model due to beams \( T_{beam} \) is given by equation 3. The twist angle in the flexible beam \( (\theta_{x}) \) increases linearly with increase in twist given to the hose at one end. Thus, \( T_{beam} \) reduces to a linear function of \( \theta_{x} \).

\[ T_{beam} = M \times f(\theta_{x}), \text{ where } M = \frac{GI_{xx}}{L} \text{ is a constant as per equation 3.} \]  
(Equation 12)

Torque in the spring is a function of the angular deformation of the torsion spring \( (\theta_{spring}) \). Chapter IV describes the procedure for finding the non linear equation for \( T_{spring} \) in terms of \( \theta_{spring} \).

\[ T_{spring} = f(\theta_{spring}) \]  
(Equation 13)
The sign of torque as a result of the angular deformation of the spring is as per the right-hand rule. The angular deformation of the torsion spring ($\theta_{spring}$) and a twist angle in the flexible beam ($\theta_x$) as shown in Figure 19 is measured about the coincident axes of both. Since in this case both the spring and beam are attached between the same bodies we have:

$$\theta_x = \theta_{spring}.$$  

Figure 19. The Angular Deformation of the Springs and Beam during the Twisting Motion.

Using a similar characteristic (single torsional stiffness curve) for all torsion springs duplicates the homogeneous property of an actual hose.

**Method for Collecting Data for Modeling a Brake Hose**

There was a need to design a fixture for holding the hose firmly in position while being scanned in order to test the proposed brake hose model. The criteria for designing
the fixture were:

a) ability to hold the hose firmly at both ends during the scanning process after twisting one end of the hose in increments of 10° from 0° to 180°;

b) ability to measure angles of rotation about three axes needed to orient the attachment points in a non-coplanar position; and

c) accurately measure the angle at which the hose was twisted at one end.

The fixture was designed in CAD software as shown in Figure 20 to accomplish the criteria mentioned above. The assembly was simulated in order to ensure that the parts on the fixture did not interfere with the hose when it was twisted. The technical drawings of the parts of the fixture needed for fabrication are given in Appendix B.

Figure 20. CAD Model of Fixture.

Scanned Point Cloud Data for Hose Shape between Coplanar Attachment Points

Point cloud data for the hose shape between coplanar attachment points was
obtained in the following thirteen steps:

Step 1: A Class Z individual plug gauge (0.1300" diameter) was inserted into one end of the hose as shown in Figures 21(a), 21(b), 21(c), and 21(d). This ensured a better grip on the hose when clamped and thus prevented it from shifting when twisted.

Figure 21. (a) Plug Gauge with Outer Diameter Made to Fit the Inner Diameter of the Hose. (b) Plug Gauge Being Inserted into the Hose. (c) Plug Gauge Partially Inserted into the Hose. (d) Plug Gauge Completely Inserted into the Hose.

Step 2: Figure 22(a) shows end with the plug gauge being inserted between two halves of a square clamp after loosening the screws. The clamp was retightened after inserting the hose as shown in Figure 22(b). A hose length of 11" (+/- 0.0625") was measured from the top surface of the square clamp as shown in Figure 22(b). The hose length inserted into the clamp was 0.5" which is equal the width of the clamp shown in Figure 22(b).
Figure 22(c) shows the hose after being clamped at one end.

Figure 22. (a) Hose Being Inserted into the Clamp. (b) Clamped End of the Hose. (c) Fixture with the Hose Clamped at One End.

Step 3: Figure 23(a) shows the plug gauge (0.1300" diameter) for the other end of the hose. Figure 23(b) shows the plug gauge after being fully inserted into the hose.
Step 4: The hose was inserted between two halves of the square-shaped clamp at the dial end after loosening the two screws that hold the two halves together as shown in Figure 24(a). The clamp half with the threaded holes for the screw was welded to a machinable-face one-piece clamp-on collar (Collar A). The 11" marking on the hose was aligned with the top surface of the clamp. The square clamp halves were then tightened. The attachment points a and b are located at the intersection of the bottom and upper surfaces of the clamp and the hose axis at the end opposite to the dial. The attachment points c and d are at the intersection of the upper and bottom surfaces of the clamp at the dial end and the hose axis. The attachment points a, b, c and d as shown in Figure 24(b) are coplanar.
Figure 24. (a) Hose after Being Inserted into the Square Shaped Clamp. (b) The Hose End at the Dial after Being Clamped Showing the Coplanar Points.

Step 5: Figure 25(a) shows an alloy steel dowel pin (1/2" Diameter) being inserted into Collar A. The screw in the clamp on the collar was tightened to hold the dowel pin in the collar as shown in Figure 25(b).
Step 6: The weldable shaft one-piece collar (Collar B) with the pointer is slid over the dowel pin. The collar with the pointer is then clamped to the dowel pin as shown in Figure 26. A Steel Press-Fit Drill Bushing (.5010" ID, 3/4" OD, 1/2" Length) is slid over the dowel pin as shown in Figure 26.
Figure 26. Collar with the Pointer Clamped to the Dowel Pin and Bushing Slid over the Dowel.

Step 7: The dowel holding the assembly is then inserted into another weldable shaft one-piece collar (Collar C) welded onto a rectangular plate as shown in Figure 27(a). The dial with a pointer as shown in Figure 27(b) is used to read the amount of twist given to the hose. The dial has graduations at every 1°; therefore in order to twist the hose through a given angle the collar welded to the plate can be loosened and the hose twisted through an angle as indicated by the pointer and the collar retightened to hold the dowel pin.
There is a lag between the application and the removal of a force on brake hoses due to the hysteresis property of rubber. Steps 8, 9, 10 and 11 detail the procedure for hysteresis elimination and determining the true zero position.

Step 8: Collar C was loosened and assembly at the dial end was rotated counterclockwise as shown in Figure 28(a) and then released. The sign convention adopted for the angle was positive for counterclockwise and negative for clockwise direction respectively. The hose sprung back to a position close to 0° as shown in Figure 28(b). The rectangular plate was gently tapped with a crescent wrench as shown in Figure 28(c) to ensure that the hose was free of any twist. The final position “m” (+8° in this case) of the pointer when there was no movement of the hose was noted as show in Figure 28(d).
Figure 28. (a) Assembly at the Dial Being Rotated Counterclockwise. (b) Hose Position after Being Released. (c) Rectangular Plate Being Tapped with Crescent Wrench. (d) The Final Resting Position of the Hose Indicated by the Non-Movement of the Pointer.

Step 9: The dial end was rotated in the clockwise direction as shown in Figure 29(a) and then released as shown Figure 29(b). The rectangular plate was tapped as shown in Figure 29(c) and the final resting position “n” (-5° in this case) noted.
Figure 29. (a) Assembly at the Dial Being Rotated Counterclockwise. (b) Hose Position after Being Released. (c) Rectangular Plate Being Tapped with Crescent Wrench until Final Resting Position of the Hose Indicated by the Non-Movement of the Pointer Is Identified.

Step 10: The mean of the two angles \((m, n)\) in steps 8 and 9 was calculated. Collar C holding the assembly was loosened and the assembly was rotated counterclockwise so that the pointer pointed to the calculated mean value \((+1.5^\circ)\) as shown in Figure 30. Collar C was retightened.
Step 11: The collar clamp holding the pointer (Collar B) was loosened as shown in Figure 31(a). The pointer was rotated to point to 0° on the dial and Collar B retightened as shown in Figure 31(b).
Figure 31. (a) Collar Clamp Holding the Pointer (Collar B) Being Loosened. (b) Collar B Being Tighened after Rotating the Collar So That the Pointer Points to 0° on the Dial.

The ATOS II digital scanning system is capable of providing an accurate point cloud data of objects without any physical contact. This non-contact means of taking measurement was essential in reducing errors in data collection. The ATOS digitizer is based on the principle of triangulation using a stereo camera setup. It has a sensor head that projects different fringe patterns onto an object surface. These patterns are recorded by two cameras, forming a phase shift based upon sinusoidal intensity distributions on the CCD chips. The ATOS uses multiple phase shifts in a heterodyne principle to achieve highest sub pixel accuracy. This is the only commercially available digitizer whose algorithm for registration of meshes has been approved by the National Institute of Standards and Technology (NIST).

The measuring volume of 250 x 200 x 200mm was used for scanning the hose. The measuring distance of the object from the camera is 750mm. The calibration of the camera for this volume was performed using the procedure described by the manufacturer. It was ensured that maximum deviation of reference points for the selected volume was within the acceptable range of 0.019-0.04 pixels for the calibration of the
camera. The reference points are used in order to align the meshes (point cloud data) acquired through multiple scans of object. The deviation of reference points in the acceptable range (in pixels) ensured that the maximum transformation deviation between meshes after aligning was 0.035mm. The scanned section is automatically transformed into the correct body coordinate position based upon the reference marker position (Capture 3D, 2007).

Step 12: The point cloud data of the hose in pure bending (0° twist position) at the end of step 11 was obtained through successive scans with the help of the ATOS II camera. The targets (white circular dots with black borders) placed on the fixture facilitates aligning of the meshes.

Step 13: Collar C at the dial is loosened and the collar and dowel pin assembly removed completely from that end and held vertically at the other end as shown in Figure 32(a). A line (line A) was made perpendicular to the edge of the square clamp and located at half its length as shown in Figure 32(b). Marking A was made on the hose corresponding to line A. Another marking (B) was made on the hose to the line with the meeting edge of the two halves of the clamp. Then the square clamp was loosened as shown in Figure 32(c) and the hose rotated in the counterclockwise direction until the marking B lines up with line A as shown in Figure 32(d) and the clamp retightened. This corresponds to the rotation of entire length of hose by 90° (also indicated by change in direction of the pointer) as shown in Figure 32(e). Then the dowel pin and collar assembly was reinserted back into Collar C at the end with the dial. Then Collar C was tightened. Steps 8-11 were repeated and then the hose was scanned a second time.
(a) Pointer

(b) Meeting edge of two clamp halves
Marking A
Marking B
Line A

(c)
Figure 32. (a) Collar and Dowel Pin Assembly Removed Completely from the Dial End. (b) Marking A Aligned with Line A. (c) Clamp Being Loosened to Rotate the Hose. (d) Marking B Aligned with Line A at the End of Rotation. (e) Hose and the Collar and Dowel Assembly after Clamp was Tightened.

Step 13 was repeated two times, i.e., the entire hose was rotated counterclockwise by 90° each time followed by steps 8-11 and the third and fourth scans obtained. The time required in performing the steps 1-12 to scan a particular length of hose in a single position is shown in Table 1. An initial setup time of 1 hour is required for preparing the surfaces for scanning. This includes placing the targets on the fixture to be scanned and spraying the surface with non-chlorinated solvent developer to make them dull enough to
facilitate their easy recognition by the camera. Steps 1 to 7 need to be performed only once for each hose length. Steps 8 to 13 need to be performed four times for each twist angle for a hose length.

Table 1

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Time (hr:mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:01</td>
</tr>
<tr>
<td>2</td>
<td>00:05</td>
</tr>
<tr>
<td>3</td>
<td>00:01</td>
</tr>
<tr>
<td>4</td>
<td>00:03</td>
</tr>
<tr>
<td>5</td>
<td>00:01</td>
</tr>
<tr>
<td>6</td>
<td>00:01</td>
</tr>
<tr>
<td>7</td>
<td>00:01</td>
</tr>
<tr>
<td>8</td>
<td>00:02</td>
</tr>
<tr>
<td>9</td>
<td>00:02</td>
</tr>
<tr>
<td>10</td>
<td>00:01</td>
</tr>
<tr>
<td>11</td>
<td>00:01</td>
</tr>
<tr>
<td>12</td>
<td>00:30</td>
</tr>
<tr>
<td>13</td>
<td>00:05</td>
</tr>
<tr>
<td><strong>Total Time</strong></td>
<td><strong>00:54</strong></td>
</tr>
</tbody>
</table>

Figure 33(a) shows the dowel and collar assembly along with the hose being twisted through 10° after loosening Collar C. Figures 33(b) and 33(c) show the collar
being tightened after the $10^\circ$ twist.

Figure 33. (a) Collar and Dowel Pin Assembly Along with Hose Being Twisted by $10^\circ$ at the Dial End after Loosening Collar C. (b) Front View of the Hose in the Fixture at the End of $10^\circ$ Twist. (c) Side View of the Hose in the Fixture at the End of $10^\circ$ Twist.
Figures 34(a) and 34(b) show the front view and the side view of the scan at a 10° twist. The subsequent three scans at a 10° twist after performing step 13 for each counterclockwise rotation of 90° followed by steps 8-12 for finding the true zero position is shown in Figures 35(a) and 35(b), 36(a) and 36(b), and 37(a) and 37(b).

![Figure 34](image1)

Figure 34. (a) Front View (b) Side View of the First Scan at Initial Orientation (0°) at 10° Twist.

![Figure 35](image2)

Figure 35. (a) Front View (b) Side View of the First and Second Scan after the First Counterclockwise Rotation of 11” hose by 90° from Initial Orientation for a 10° Twist.
Figure 36. (a) Front View (b) Side View of the First, Second Scan after the First Counterclockwise Rotation of 11" Hose by 90° and Third Scan after the Second Counterclockwise Rotation of 90° (180° from Initial Orientation) for a 10° Twist.

Figure 37. (a) Front View (b) Side View of the First, Second Scan after the First Counterclockwise Rotation of 90°, Third Scan after the Second Counterclockwise Rotation of 90° and Fourth Scan after the Third Counterclockwise Rotation of 90° (270° from Initial Orientation) for a 10° Twist.

The first, second, and third scans were close to each other. The fourth scan was observed to be different from the other three scans.

The spread of the hose scans would be significantly higher if a hysteresis elimination procedure was not carried out. For example, Figure 38(a) shows five scans for a 16" hose. The scan on the extreme left shows the position after the dowel and collar assembly with the hose was rotated counterclockwise and released. The second hose scan from the left shows the position after the rectangular plate was tapped with the crescent
wrench. The third scan from the left shows true zero position. The extreme right scan shows the position after the hose was rotated clockwise and released. The second scan from the right shows the position after the rectangular plate was tapped with the crescent wrench. Distance between farthest scans was 59.27mm for the 16” hose. Figure 38(b) shows that spread for the 11” hose is comparatively smaller.
Figure 38. (a). Scans Showing Hysteresis Effect for 16” Hose. (b). Scans Showing Hysteresis Effect for 11” Hose.

The hose was twisted in increments of 10° and four scans obtained for each twist angle. Figure 39 shows the hose position after being twisted through 30°. Figure 40(a) shows the hose position being twisted through 180° and Figure 40(b) shows the side view of the hose position at 180° twist.

Figure 39. Hose Shape at 30° Twist.
Figure 40. (a) Collar and Dowel Pin Assembly Being Twisted by 180° at the Dial End after Loosening Collar C. (b) Side View of the Hose Held in the Fixture at 180° Twist.

Figures 41(a) and 41(b) show the front view and the side view of the first scan at 180° twist. The subsequent three scans at 180° twist are shown in Figures 42(a) and 42(b), 43(a) and 43(b), and 44(a) and 44(b).

Figure 41. (a) Front View (b) Side View of the First Scan at 180° Twist.

Figure 42. (a) Front View (b) Side View of the First and Second Scans at 180° Twist.
Figure 43. (a) Front View (b) Side View of the First, Second, and Third Scans at 180° Twist.

Figure 44. (a) Front View (b) Side View of the First, Second, Third, and Fourth Scans at 180° Twist.

It was visually observed that the amount of spread of the hose shapes increased with the increase in the angle of twist. The difference in hose shapes increased significantly above 110° twist. The same characteristic was observed for different lengths of hoses. It was observed that an increase in the spread of scans with a 3” increase in length was more significant than with an increase in twist angle of 10°.

The four scans for each twist angle were grouped together and exported from the digitizer software as stereolithography (.stl) files. One group at a time was then imported into the simulation software. The group of scans corresponding to a particular twist angle
was made of the same color for ease of distinguishing between them. Figures 45(a) and 45(b) show the front view and side view of groups of scans for each twist angle for an 11” hose length in simulation software.

Hose lengths of 13” (+/- 0.0625”) and 16” (+/- 0.0625”) between upper surfaces of the square clamps were also scanned in a similar manner and the resulting point cloud data of the hose shapes in the simulation software is as shown in Figures 46(a), 46(b), 47(a), and 47(b) respectively.

Figure 45. (a) Front View and (b) Side View of the Scanned Point Clouds of 11” Hose at Increments of 10° Twist from 0° to 180°.

Figure 46. (a) Front View and (b) Side View of the Scanned Point Cloud of 13” Hose atIncrements of 10° Twist from 0° to 180°.
Steps in Obtaining Scanned Point Cloud Data for Hose Shape between Non-Coplanar Attachment Points

Three toggle clamps index one gear each that rotate the hose end opposite to the one at the dial about the 3 perpendicular axes shown in Figure 48(a). One gear tooth corresponds to a rotation of $15^\circ$. A hole drilled in the gear cover plate as shown in Figure 48(b) allows the counting of the number of gear teeth traversed and, hence, the angle by which the hose end is rotated about a particular axis.

The steps involved in scanning a hose in a non-coplanar position are as described
Step 1: Clamp the hose of a particular length (11" in this case) in the coplanar position with no twist in the hose.

Step 2: Release the toggle clamp for rotating about the Y-axis as shown in Figure 49(a). This unlocks the gear and thus enables the rotation of the hose end around the Y-axis. Lock the gear by engaging the toggle clamp after counting off the required number of gear teeth traversed by viewing through the hole. One gear tooth corresponds to a 15° rotation. Figure 49(b) shows the toggle clamp engaged after rotating the hose end counterclockwise about the Y-axis by 30°.

![Toggle Clamp for Rotating about Y-axis](a)

![Toggle Clamp Engaged after Rotating the Hose End about the Y-Axis by 30°.](b)

Figure 49. (a) Toggle Clamp for Rotation about the Y-Axis in the Released Position. (b) Toggle Clamp Engaged after Rotating the Hose End about the Y-Axis by 30°.

Step 3: Release the toggle clamp for rotating about the Z-axis as shown in Figure 50(a). This unlocks the gear and thus enables the rotation of the hose end around the Z-axis. Figure 50(b) shows the toggle clamp engaged after rotating the hose end counterclockwise about the Z-axis by 30°.
Figure 50. (a). Toggle Clamp for Rotation about the Z-Axis in the Released Position. (b). Toggle Clamp Engaged after Rotating the Hose End about the Z-Axis by 30°.

Step 4: Release the toggle clamp for rotating about the X-axis as shown in Figure 51(a). This unlocks the gear and thus enables the rotation of the hose end around the X-axis. Figure 51(b) shows the toggle clamp engaged after rotating the hose end counterclockwise about the X-axis by 30°. This is the final position after rotations about the X-, Y- and Z-axes by 30°, 30°, and 30° respectively.
Step 5: The steps 8-11 (detailed in the coplanar attachment points section) for hysteresis elimination and finding the true zero position were performed at the dial end of the hose.

Step 6: Collar C holding the dowel and collar assembly was loosened and the hose was rotated by 30° (twist) in the counterclockwise direction and the clamp retightened. The hose was digitally scanned at this position.

Step 7: The collar at the dial end was loosened and this enabled the hose to untwist by
approximately 30° in the opposite direction of the twist given in step 6.

Step 8: The rotations in the clockwise direction of 30° about the X-, Z-, Y-axes (reverse order of steps 2, 3 and 4) were performed to get the hose in the coplanar position as in step 1.

Step 9: Collar C was loosened and the hose along with the dowel and collar assembly held vertically at the end opposite to the dial. This is similar to step 13 mentioned for the hose held between coplanar attachment points. The entire hose was rotated in a counterclockwise direction by 90°.

Steps 2 to 9 were repeated three times resulting in four different scans for 30°. Four scans were also obtained for 60° and 90° twist angles. The four scans for each of 30°, 60°, and 90° were grouped and imported into simulation software as shown in Figure 52.

![Scans at 30°, 60°, and 90°](image)

Figure 52. The Scanned Point Clouds of 11" Hose at 30° (right), 60° (middle), and 90° (left) Twist Positions in 30°, 30°, and 30° non-coplanar position.

Scans were also taken by repeating steps 1-9 four times for two more non-coplanar positions, each with rotation angles of 30°, 30°, 60° and 60°, 60°, 60° respectively. The corresponding scans are shown in Figure 53(a) and 53(b). It was observed that the four hose shapes were not consistent for the same angle of twist from
different initial no-twist positions. The spread increased with an increase in rotation angles. Figure 53(b) for rotation angles of 60°, 60°, and 60° shows the maximum spread of the scanned hose shapes among the non-coplanar positions for a particular angle of twist.

![Figure 53](image)

Figure 53. The Scanned Point Clouds of 11" Hose at 30° (right), 60° (middle), and 90° (left) Twist Positions after Repeating Steps 1 to 9 for Rotation Angles of (a) 30°, 30°, and 60° and (b) 60°, 60°, and 60°.

**Chapter Summary**

A description of a simulation model for brake hoses using beams and torsion springs was presented. A fixture was fabricated to collect the data necessary to validate the model. The hose is typically held between coplanar attachment points on the vehicle chassis. Hence, three lengths of hoses (11", 13", and 16") were held between coplanar attachment points in the fixture and scanned after twisting one end in increments of 10° from 0° to 180°. This was necessary for comparison of the deflection of the torsion springs model for twist angles between and including 0° to 180° with that of an actual hose.
The hose was given the same amount of twist from four initial orientations 90° apart in order to straighten the bends (preset) in the hose. The hysteresis effect of rubber was reduced with the taps of the crescent wrench. It was observed from the point cloud data that the initial assumption that hoses would assume approximately the same shape when twisted through the same angle from different initial orientations was not valid. This was evident from the difference in the four hose shapes for the same angle of twist. An 11" hose was also scanned in three different non-coplanar positions. This was done in order to find out if the torsional stiffness curve for the torsion springs in the non-coplanar position would be the same as that for coplanar. The procedure for finding the torsional stiffness curve for torsion springs in the model that would align the model to the center of the scanned point cloud data has been described in the next chapter.
CHAPTER IV

FINDING BEST-FIT TORSIONAL STIFFNESS CURVE

Building the Simulation Model with Beam and Torsion Springs for the Coplanar Position

The simulation model with flexible beams and torsion springs was created programmatically using the principles of vector mathematics (Thomas, Keil, & Rodriguez, 2005). Figure 54 shows the location of vector points which serve as inputs to the program. The attachment points at the intersection of lower and upper surfaces of the clamp and the hose axis respectively at the end opposite to the dial serve as the vector points a and b. The vector points c and d are at the intersection of the upper and lower surfaces of the clamp at the dial end and the hose axis, respectively. The vector directions used for building the simulation model are shown in Figure 17 in the previous chapter.

Figure 54. Position of Vector Points a, b, c, and d on the Fixture.
Locating the Vector Points a, b, c, and d Using the Digitizer

The digitizer post-processing software was used to create geometrical features using points on scans in order to determine the 3D coordinates of vector points a, b, c and d as described in the following steps:

Step 1: A plane was created using three coplanar points as shown in Figure 55(a) on the scan of the upper surface of the square clamp at the dial end. Another one was created on the opposite end. Figure 55(b) shows the two planes on the upper surface of the square clamp at each end.

![Figure 55. (a) Plane Created on Surface of a Square Clamp. (b) Planes Created on the Upper Surface of the Square Clamps at Each End.](image)

Step 2: A best-fit cylinder passing through the points close to the upper surface of the clamp was created at each end as shown in Figure 56. The axis of the cylinder was constrained to be perpendicular to the plane created at each end in step 1. The radius of the cylinders as shown in Figure 56 were compared to the actual radius of the hose (5.15mm) and was within +/-0.2mm of the hose radius.
Step 3: The endpoint on the axis of the cylinder closest to the plane (point_c0) as shown in Figure 57(a) was projected onto the plane. The projected point created on the plane corresponds to vector point c as shown in Figure 57(b). A similar step was performed on the other end to identify vector point b.
Step 4: Line cd with a length of 0.5" perpendicular to the plane was created from point c as shown in Figure 58(a). A line ab was created at the other end from point b. Figure 58(b) shows the geometry at both ends.
Figure 58. (a). Line cd Created Perpendicular to the Plane from Point c. (b). Lines cd and ab Created at Both Ends.

Step 5: Endpoints a and d were created on the lines ab and cd respectively as shown in Figure 59.

Figure 59. Endpoints a and d Created on Lines ab and cd Respectively.

Step 6: The global 3D coordinates of vector points a, b, c, and d were obtained from the digitizer software. Figure 60 shows the global coordinates for vector point d.
Figure 60. Global XYZ Coordinates of Vector Point d.

Figure 61 shows the model along with the point cloud data of scans at twist angles in increments of 10°. The hose length of 11” (279.4mm) was divided into 42 elements (41 beams and torsion springs) with a length of 0.262” (6.652mm) for each of them. The length of the beam was small enough to ensure compliance with the assumption of linear beam theory when the hose model was twisted from 0°-180°.

Figure 61. Front View of Rendered Hose Model with Scans of Point Cloud Data at Twist Angles in Increments of 10°.
It was desired that the brake hose shape predicted by the simulation model would be at the center of the scans at each angle of twist. A single torsional stiffness curve will be defined for all the torsion springs in the model for each hose length to achieve the aforesaid objective.

**Adjusting Torsional Stiffness Curve for Centering the Model in the Scans**

The appearance of the point cloud data for the twist angle of interest was turned on in the simulation software and the rest were turned off. This facilitated the visual comparison of the model with the scans for a particular twist angle. The steps involved in finding the torsional stiffness curve for centering the model in the scans are as mentioned below.

Step 1: A torque value of zero was assigned for angular deformation of torsion springs as shown in Figure 62(a). The beams in the model were made equally stiff in bending and torsion. The model was given a twist of 10° about the axis of the cylinder corresponding to the dial end in the fixture. The corresponding shape of the hose after the 10° twist is shown in Figure 62(b). The model shape was not centered in the scans at a 10° twist.
Figure 62. (a) Torque Value of Zero Assigned to the Angular Deformation (deg) of All the Torsion Springs for Twist of 10°. (b) Model Not Centered in the Scan.

Step 2: Figure 63 shows the angular deformations of torsion springs in the model (Y-axis) versus the twist angle (X-axis) from 0° to 10°. The maximum absolute value (m) at a 10° twist was noted from the plot.

Figure 63. Plot Showing the Angular Deformation (deg) of All the Torsion Springs from 0° to a Twist of 10° in Order to Identify the Maximum Value (m) of Angular Deformation among All Torsion Springs.
Step 3. The torque value corresponding to an arbitrarily chosen angular deformation \((L)\) greater than the maximum absolute value \((m)\) from Step 2 was adjusted manually as shown in Figure 64. The objective was to find the slope that would align the hose shape at the end of a \(10^\circ\) twist with the center of the scan.

![Figure 64. Torque Value Being Adjusted Manually for the Angular Deformation Value \((L)\) Greater than the Maximum Angular Deformation for a Twist of \(10^\circ\) for 11” Hose.](image)

Step 4. Figure 65(a) shows the torque value for the angular deformation, \(L\), that centered the hose model in the scan as shown in Figure 65(b).

![Figure 65. (a) Plot Showing the Best-Fit Torque Value for the Angular Deformation \(L\). (b) Hose Shape Centered in the Scans.](image)
Step 5. Figure 66(a) shows the plot of angular deformation of all the torsion springs from 0° to 10° twist after the model was centered in the scans for twist of 10°. The torque value corresponding to the maximum angular deformation (k) amongst all springs was isolated on the torsional stiffness curve as shown in Figure 66(b). The torsional stiffness curve was made symmetric.

Figure 66. (a) Plot Showing the Maximum Angular Deformation (k) in Degrees amongst All the Torsion Springs at Twist of 10°. (b) Plot Showing Torque Value for the Maximum Angular Deformation (k) in Degrees for a Twist of 10° for 11” Hose.

The torque value for the 10° twist was held constant and steps 2-5 were repeated
after twisting the model at the dial end further by 10° to obtain a total of a 20° twist. Figure 67 shows the torque value being adjusted for angular deformation greater than maximum angular deformation at 20°. Figure 68 shows the torque value corresponding to maximum angular deformation after the model was centered in the scans at 20°. Steps 2-4 were repeated for a twist angle obtained after twisting the model in increments of 10° and holding the torque value of the preceding twist angle constant. The resulting torsional stiffness curve for the 11" hose model is as shown in Figure 69.

Figure 67. Torque Value Being Adjusted Manually for the Angular Deformation Value Greater than the Maximum Angular Deformation for a Twist of 20° for 11" Hose after Holding the Torque Value at 10° Constant.
Figure 68. Plot Showing Torque Value for the Maximum Angular Deformation for a Twist of $20^\circ$ for 11" Hose.

Figure 69. Torsional Stiffness Curve for 11" Hose that Centered the Model in the Scans.

It was observed from the plot shown in Figure 70 that the torsion spring at the end opposite to the one being twisted had the maximum angular deformation for all angles of twist from $0^\circ$-$180^\circ$. 
Figure 70. Angular Deformation of All the Torsion Springs for Angles of Twist from $0^\circ$-
$180^\circ$ for an 11” Hose.

**Torsional Stiffness Curve for 13” and 16” Hose Lengths**

The hose length of 13” (330.2mm) was divided into 50 elements (49 beams and
torsion springs) with a length of 6.604mm each. The 16” (406.35mm) hose was divided
into 62 elements (61 beams and torsion springs) with a length of 6.554mm each. The
hose element sizes ensured compliance with the linear beam theory. Torque values for
angular deformation of springs in 13” and 16” hose models were adjusted manually in
order to bring the model close to the center of the point cloud data for different angles of
twist. Figures 71 and 72 show the angular deformations of all the springs and the best-fit
torsional stiffness curve for the 13” hose respectively. Figures 73 and 74 show the
angular deformations of all the springs and the best-fit torsional stiffness curve for the
16” hose respectively. It can be noted from the plots that the angular deformations
decrease with an increase in hose length.
Figure 71. Angular Deformation of all the Torsion Springs for Angles of Twist from 0°-180° for 13” Hose.

Figure 72. Torsional Stiffness Curve for 13” Hose that Centered the Model in the Scans.
Figure 73. Angular Deformation of All the Torsion Springs for Angles of Twist from 0°-180° for a 16" Hose.

Figure 74. Torsional Stiffness Curve for 16" Hose that Centered the Model in the Scans.

Figure 75 shows the overplot of the torsional stiffness curves for 11", 13", and 16" hoses. A generalized torsional stiffness curve from the three torsional stiffness curves
for 151 (41 for 11” + 49 for 13” + 61 for 16”) torsion springs needed to be obtained. The
torque values for twist angles of 70° and 80° for 13” hose were observed to be slightly
higher than those for 11” and 16”. This can be attributed to the structural variation in the
hose.

![Torque vs Angular Deformation](image)

**Figure 75. Best-Fit Torsional Stiffness Curves for 11”, 13”, and 16” Hoses.**

The simulation software has the capability of fitting an Akima spline through the
torque and angular deformation values specified as shown in Figure 76. The Akima
interpolation algorithm is based on piecewise function composed of a set of third order
polynomials. The coefficients of each polynomial representing a portion of curve
between a pair of given points is determined by calculating the slope locally at the points
and their coordinates (Akima, as cited in R Documentation, 2010).
The interpolated values from the simulation software were then exported as a spreadsheet. This larger dataset of torque and deformation values were used as raw data for a regression analysis.

Figure 76. Akima Spline through the Torque Values in Adams™/View Simulation Software.

A flowchart of the procedure mentioned in this section for collecting data for regression analysis is shown in Figure 77.
Scan the hoses of length \((l_i = 11"", 13", 16"")\) attached to two points in 19 positions \((0^\circ - 180^\circ)\) twist in increments of \(10^\circ\) for each length.

Construct the hose model consisting of torsion springs and flexible beams for length \((l_i)\) in the simulation software between 3D coordinates \((x, y, z)\) of attachment points obtained from the scan using the following parameters to obtain the hose shape. (a) Material properties of hose \((\text{Mass}, E, G, \text{Poisson's ratio})\); (b) Length of the hose: \(11", 13", \text{and} 16"\) for beam cross section.

Measure the maximum and minimum angular deformation amongst all the torsion springs in the hose shapes for particular twist angle.

Assign a torque value \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) for angular deformations of -\(\phi\) and \(\phi\) where \(\phi > \max(\text{abs}(\theta_{\text{sprng,ext}}), \text{abs}(\theta_{\text{sprng,slab}}))\) for all torsion springs in the model.

Is the model visually at the center of the scans for the particular angle of twist?

Adjust Torque values \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) manually.

Isolate the torque value \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) corresponding to the \(\phi = \max(\text{abs}(\theta_{\text{sprng,ext}}), \text{abs}(\theta_{\text{sprng,slab}}))\) on the torsional stiffness curve.

Twist the hose further by \(10^\circ\).

Has the model been compared successfully to scans at all twist positions for length \((l_i)\)?

Interpolate torque and deformation values \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) for length \((l_i)\) using the Akima spline function in simulation software to increase the amount of raw data for regression.

Record interpolated torque and deformation values \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) for length \((l_i)\) for regression.

Have all lengths of hoses been scanned?

Conduct regression analysis with the torque and deformation values \([T_{\text{sprng}}(\theta_{\text{sprng}})]\) for lengths \((l_i = 11", 13", 16")\).

STOP

Figure 77. Flowchart of the Procedure for Collecting Raw Data for Regression Analysis.
Figure 78 shows the fitted cubic curve using polynomial regression analysis. The cubic curve equation (R-Sq = 99.0%) obtained from statistical software Minitab®, Version 15 (Minitab®, 2009) is given by:

\[ T = -47.30 + 4383 \theta - 3741 \theta^2 + 1498 \theta^3. \]  
(Equation 12)

Here: \( T \) = Torque (N-mm); and \( \theta \) = Angular Deformation of the torsion spring (degrees).

The ANOVA table for the polynomial regression analysis is in Appendix C.

![Figure 78. Cubic Curve Fit through the Torsional Stiffness Curves for 11”, 13”, and 16” Hoses.](image)

**Torsional Stiffness Curve for Non-Coplanar Attachment Points**

The optimal torsional stiffness curve for the 11” hose in the coplanar position was used for the same length of hose in the non-coplanar position. However, it had to be modified in order to ensure that the model was centered in the scans for the 30°, 60°, and 90° twist. The torsional stiffness curves that centered the hose in the scans for each of the three non-coplanar orientations for the 11” hose were significantly different from each
other. Further trials were done to find a common torsional stiffness curve that would at least position the hose model within the scans at 30°, 60°, and 90° twist for the three non-coplanar orientations. Figure 79 shows the common curve that satisfied the criterion.

![Torsional Stiffness Curves for 11in hose (Non-coplanar)](image)

Figure 79. Torsional Stiffness Curve that Satisfied the Criterion of the Hose Being within Scans at 30°, 60°, and 90° Twist for Each of the Three Non-Coplanar Orientations for the 11” Hose.

Figure 80(a) shows the hose model at the end of the 30° twist lying within the point cloud data of the 11” hose at the 30° twist for 30°, 30°, and 60° non-coplanar position. Figure 80(b) shows the comparison for 60° and Figure 80(c) for 90° twist positions respectively. Figures 81(a), 81(b), and 81(c) show the comparison for 30°, 30°, and 30° non-coplanar position and Figures 82(a), 82(b), and 82(c) show the comparison for 60°, 60°, and 60°.
Figure 80(a). The Final Position of the Model and Scanned Point Cloud Data of 11" Hose for 30°, 30°, and 60° Non-Coplanar Position at the End of (a) 30°, (b) 60°, and (c) 90° Twist Positions.
Figure 81. The Final Position of the Model and Scanned Point Cloud Data of 11" Hose for 30°, 30°, and 30° Non-Coplanar Position at the End of (a) 30°, (b) 60°, and (c) 90° Twist Positions.
Figure 82. The Final Position of the Model and Scanned Point Cloud Data of 11" Hose for 60°, 60°, and 60° Non-Coplanar Position at the End of (a) 30°, 60°, and 90° Twist Positions.

Figure 83 shows the torsional stiffness curve for the above configurations and coplanar position for an 11" hose. It can be observed from the torsional stiffness curves that the magnitude of the torque value for a given angular deformation was higher for the
non-coplanar attachment points.

Figure 83. Comparison of Best-Fit Torsional Stiffness Curve for 11" Hose for Coplanar and Non-Coplanar Attachment Points.

**Difference in Axial Forces Profile between Coplanar and Non-Coplanar Position**

**Axial Forces in Beams for Hose in Coplanar Position**

Figure 84 shows axial force in the beam (Y-axis) at the end being twisted (dial end) and one at other end for the 11" hose length between attachment points. The X-axis is the twist angle given to the hose at the dial end.
Significant axial loads in coplanar mount configurations did not develop until mount twists above 80°. The high axial force in beams prevents the magnitude (absolute value) of angular deformation of the springs beyond an 80° twist from increasing as shown in Figure 85. Thus the angular deformation of springs decreases with an increase in the twist angle beyond approximately 80°. The ability of controlling the shape using the torsional stiffness curve is restricted as the torque values for the angular deformation beyond 80° have already been defined for twist angles below it. Thus, torsional stiffness curve cannot be optimized for twist angles beyond 80° for matching the model with the center of scans. Similar characteristics of axial forces were also observed for 13” and 16” hose as shown in Figures 86 and 87.
Figure 85. Decreasing Angular Deformation with Increasing Twist beyond Approximately 80°.

Figure 86. Crossover of Axial Forces for a 13” Hose.
Figure 87. Crossover of Axial Forces for a 16" Hose.

Axial Forces in Beams for Hose in Non-Coplanar Position

Non-coplanar mounts generate significant axial loads in hose even in the twist-free position as shown in Figure 88.

Figure 88. High Axial Forces in Beams for Non-Coplanar Attachment Points.
A higher torque value had to be specified for the model in non-coplanar rather than coplanar position for the same angular deformation to account for higher axial forces in beams at the twist-free position. Thus, the torsional stiffness curve for matching the model with scans between non-coplanar attachment points was significantly different from that when they were coplanar.

Chapter Summary

Digitizer post-processing software was used to find 3D coordinates of the four vector points needed to build the torsion spring hose model. The slope of the torsional stiffness curve that centered the hose model in the point cloud data for every 10° of twist angle from 0° to 180° was found. It was also found that the torsional stiffness curve could not be optimized for twist angles beyond 80° for matching the model with the center of scans. This is because of the high axial force in the beam at the end being twisted. The torsional stiffness curves for 11", 13", and 16" hoses were approximated by a cubic curve from polynomial regression analysis. The axial force characteristics of the beams in the non-coplanar position were different from that in the coplanar position. It is advisable to refrain from attaching hose between non-coplanar attachment points to prevent high axial loads in initial assembly. The torsional stiffness curve for the hose with non-coplanar attachment points was different from coplanar points due to the difference in magnitude of axial forces in beams.

Images of the model with scans of different hose lengths at various twist angles between 0° to 90° for the coplanar position have been presented in the next chapter. The steps involved in using the digitizer post processing software for measuring the distance
between center of the model and center of each of the scans have been detailed in the next chapter.
CHAPTER V

VALIDATION OF CUBIC TORSIONAL STIFFNESS CURVE MODEL

Comparison of Hose Shapes for Different Lengths with Scans

The cubic curve was used as the generalized torsional stiffness curve for evaluating the performance of the model in predicting hose shapes for 11”, 13”, and 16” hose lengths at various angles of twist in the coplanar position. Figure 89(a) and 89(b) show a comparison of the model centered in the scans for an 11” hose at 20° and 50° twist angles, respectively, using the cubic torsional stiffness curve. It was visually observed that the deviation of the model from the center of the scans increased for twist angles above 80°.

Figure 89. Model Centered in the Scans for 11” Hose at (a) 20° and (b) 50° Twist Angles.

Figures 90(a), 90(b), and 90(c) show a comparison of the model and scans for the 13” hose at 30°, 60°, and 90° twist angles, respectively. The model was visually centered in the scans for twist angles up to 50°. The deviation was higher for the 13” in comparison to the 11” hose for twist angles from 50° - 80°. This could be attributed to the
slight structural variation in the 13” hose. The deviation increased beyond an 80° twist as observed in the case of the 11” hose.

Figures 90(a), 90(b), and 90(c) show comparisons of the model and scans for the 13” hose at 30°, 60°, and 90° twist angles, respectively.

Figures 91(a), 91(b), and 91(c) show comparisons of the model and scans for the 16” hose at 40°, 70°, and 80° twist angles, respectively. It was observed from the visual comparison that the deviation of the model from the scans was comparable to the 11” hose for twist angles of 80° or less.
Figure 91. Comparison of Model and Scans for 16" Hose at (a) 40°, (b) 70°, and (c) 80° Twist.

Procedure for Obtaining Deviations of the Model from the Scans

It was visually observed that the model was closer to the scans near the attachment points than along the mid-span of the hose. Thus, obtaining deviations at 25%, 50%, and 75% of the length of the hose from the dial end would include a region where maximum deviation of the model from the scan could be expected. It would also ensure consistency for comparison of deviations among the 11", 13", and 16" hose lengths. The digitizer post-processing software has the capability of constructing geometric entities based on user selected points in the scans. It can also construct best-fit geometrical entities. The software is used for quality inspection since it can measure the deviation of a manufactured part from its CAD model. The steps involved in measuring the deviation of the model from the center of the scans using post-processing software are:
Step 1: Import the simulated position of the hose model at a particular twist angle into the digitizer post processing software in IGES file format. Figure 92 shows the 16" hose at a 10° twist position.

Figure 92. Simulated Position of 16" Hose at 10° Twist Position in Digitizer Software.

Step 2: Three points were made on the hose model at 25%, 50%, and 75% of the length of the hose from the attachment point d at dial end as shown in Figure 93.

Figure 93. Three Points Created on the Hose Model at 25%, 50%, and 75% of the Length of the Hose from Attachment Point d.
Step 3: A line was created along the edge of the hose element at each of the points created in step 2 as shown in Figure 94.

Figure 94. A Line Created along the Edge of the Hose Element at a Point dev25.

Step 4: A plane perpendicular to each of the lines in step 3 and passing through the corresponding point from step 2 was created. Figure 95(a) shows the plane being created perpendicular to the line from the point at 25% hose length. Figure 95(b) shows three planes created perpendicular to each of the lines.
Figure 95. (a) A Plane Created Perpendicular to the Line Created at Point dev25. (b) Three Planes Created Perpendicular to the Lines Created in Step 2.

Step 5: The group of four scans for the 10° twist position for 16" hose was imported to enable comparison with the simulated hose model as shown in Figure 96.

Figure 96. Group of Scans Imported to Be Compared to the Simulated Hose Model.
Step 6: The section through the hose model and scans was created along each of the three planes. Figure 97 shows the section being created along the plane at 25% of the hose length.

![Figure 97. Section through the Hose Model and Scans at 25% of the Hose Length.](image)

Step 7: Figure 98 shows the points on the section at 25% of the hose length. The complete circle is from the hose model whereas the other four circles belong to each of the four scans.

![Figure 98. Points Lying on the Section through the Hose Model and Scans at 25% of Hose Length.](image)
Step 8: A best-fit circle was created after preselecting the points from each scan separately. Figure 99(a) shows the best-fit circle being created for points from a scan. The radius of the best-fit circle created was within +/- 0.3mm of the hose radius (5.15mm). Figure 99(b) shows the radius of the best-fit circle.

![Best-Fit Circle Radius](image)

Figure 99. (a) Best-Fit Circle for Selected Number of Points. (b) Radius of the Best-Fit Circle along with 3D Coordinates of its Center.

Step 9: Figure 100 shows four best-fit circles, one for each of the scans, along with the position of their centers.

![Four Best-Fit Circles](image)

Figure 100. Four Best-Fit Circles for Points on the Scans along with their Centers.
Step 10: The points on the model were selected as shown in Figure 101(a) to create the best-fit circle for the model and locate its center as shown in Figure 101(b).

Figure 101. (a). Selected Points on the Model to Create the Best-Fit Circle. (b). Best-Fit Circle for the Model along with Those of the Scans.
Step 11: The distances between the center of the model and the center of each of the four scans were measured. Figure 102 shows the distances from the center of the model to each of the four scans.

Figure 102. Distance between the Center of the Model and the Centers of Each Scan (dev_25_1, dev_25_2, dev_25_3, and dev_25_4) at 10° Twist for 16” Hose.

Steps 1-11 were repeated for 10°, 20° and 30°, twist angles at 25%, 50%, and 75% of the hose length for 11”, 13”, and 16” hose models.

**Performance of the Model with Beams and Torsion Springs**

Table 2 shows the maximum, minimum, average deviation, and standard deviation of deviations in millimeters for the three locations along the length of the hose. Scan number “1” corresponds to the initial orientation of 0°, scan number “2” to the first
counter-clockwise rotation of 90°, scan number "3" to 180°, and finally, "4" to the 270°
counter-clockwise direction. Deviations of the model from each of the four scans at the
three locations grouped by length and twist angle are shown in Appendix D.

Table 2

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Scan Number</th>
<th>Maximum Deviations (mm)</th>
<th>Minimum Deviations (mm)</th>
<th>Average Deviations (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>1</td>
<td>3.349</td>
<td>2.461</td>
<td>2.989</td>
<td>0.467</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.462</td>
<td>1.328</td>
<td>1.920</td>
<td>0.569</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.385</td>
<td>0.763</td>
<td>1.161</td>
<td>0.345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.339</td>
<td>1.325</td>
<td>1.969</td>
<td>0.552</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1</td>
<td>3.645</td>
<td>2.249</td>
<td>3.058</td>
<td>0.724</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.257</td>
<td>1.355</td>
<td>1.716</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.397</td>
<td>0.889</td>
<td>1.467</td>
<td>0.813</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.818</td>
<td>1.674</td>
<td>2.289</td>
<td>0.577</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>1</td>
<td>3.653</td>
<td>1.282</td>
<td>2.421</td>
<td>1.188</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.964</td>
<td>1.961</td>
<td>2.237</td>
<td>0.630</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.132</td>
<td>2.904</td>
<td>3.454</td>
<td>0.624</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.833</td>
<td>2.567</td>
<td>3.102</td>
<td>0.656</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>1</td>
<td>4.621</td>
<td>1.194</td>
<td>3.043</td>
<td>1.729</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.116</td>
<td>0.994</td>
<td>2.027</td>
<td>1.062</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.393</td>
<td>3.317</td>
<td>3.845</td>
<td>0.538</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>5.173</td>
<td>2.571</td>
<td>4.240</td>
<td>1.448</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1</td>
<td>5.687</td>
<td>2.258</td>
<td>4.205</td>
<td>1.761</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4.902</td>
<td>2.733</td>
<td>3.721</td>
<td>1.097</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.518</td>
<td>2.280</td>
<td>3.095</td>
<td>1.236</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.315</td>
<td>1.972</td>
<td>2.891</td>
<td>1.250</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>1</td>
<td>5.884</td>
<td>3.359</td>
<td>5.027</td>
<td>1.445</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4.415</td>
<td>1.961</td>
<td>2.831</td>
<td>1.374</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>6.045</td>
<td>3.042</td>
<td>4.597</td>
<td>1.504</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.904</td>
<td>1.852</td>
<td>2.666</td>
<td>1.095</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>1</td>
<td>9.785</td>
<td>4.140</td>
<td>6.436</td>
<td>2.966</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.905</td>
<td>1.629</td>
<td>5.052</td>
<td>2.968</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.074</td>
<td>1.519</td>
<td>4.702</td>
<td>3.282</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>6.401</td>
<td>1.024</td>
<td>3.178</td>
<td>2.844</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1</td>
<td>9.791</td>
<td>3.672</td>
<td>6.367</td>
<td>3.124</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.900</td>
<td>3.014</td>
<td>5.226</td>
<td>1.998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.122</td>
<td>3.714</td>
<td>5.005</td>
<td>1.848</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>6.146</td>
<td>3.534</td>
<td>4.744</td>
<td>1.316</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>1</td>
<td>9.219</td>
<td>3.383</td>
<td>6.108</td>
<td>0.861</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.858</td>
<td>3.050</td>
<td>4.731</td>
<td>1.484</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.930</td>
<td>2.797</td>
<td>4.039</td>
<td>1.664</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>6.899</td>
<td>3.271</td>
<td>5.058</td>
<td>1.815</td>
</tr>
</tbody>
</table>
Figure 103 shows the Individual Value plot of the average deviation grouped by length and twist angle. The minimum value of average deviation for a particular twist angle increases with an increase in length.

![Individual Value Plot of Average Deviation](image)

Figure 103. Individual Value Plot for Average Deviations from Minitab® Software.

Table 3 shows the mean, standard deviation, and 95% Confidence Interval (CI) of the mean of the average deviations grouped by length and twist angle from Table 2. Figure 104 shows the interval plot corresponding to CI values in Table 3.

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
<th>95% CI of Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>2.007</td>
<td>0.751</td>
<td>(0.813, 3.201)</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>2.133</td>
<td>0.707</td>
<td>(1.008, 3.257)</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>2.803</td>
<td>0.572</td>
<td>(1.894, 3.713)</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>3.289</td>
<td>0.977</td>
<td>(1.734, 4.844)</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>3.478</td>
<td>0.599</td>
<td>(2.524, 4.432)</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>3.779</td>
<td>1.209</td>
<td>(1.854, 5.702)</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>4.842</td>
<td>1.339</td>
<td>(2.712, 6.972)</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>5.335</td>
<td>0.715</td>
<td>(4.197, 6.473)</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>4.984</td>
<td>0.861</td>
<td>(3.613, 6.355)</td>
</tr>
</tbody>
</table>
Figure 104. Interval Plot of 95% CI of Mean of Average Deviations Grouped by Length and Twist Angle from Minitab® Software (N=1).

The mean of the average deviation increases with an increase in length. The 95% CI of the mean also shows a similar trend due to the increase in the spread of scans with an increase in length.

Performance of the Model with Beams and Translational Springs

As mentioned towards the end of Chapter II, the model with sixteen translational springs resulted in the least deviations. Thus a simulation model with flexible beams and sixteen translational springs between adjacent hose elements was created for hose lengths of 11”, 13”, and 16”. The spring length was constrained to be in a range required to use the quadratic equation from regression analysis defining the force versus linear deformation curve (Thomas, 2004). The length of the beam and spring angle was varied in order to achieve the required spring length for each hose length of 11”, 13”, and 16”. Hose length was divided by the beam length to obtain the appropriate number of hose elements. Force Vs Linear deformation curve from regression was used for all the
translational springs for a particular hose length. Distances were measured between the center of the model and the center of each of the four scans using the same method as for torsion springs. Deviations of the model from each of the four scans at the three locations grouped by length and twist angle are shown in Appendix E. Table 4 shows the maximum, minimum, average deviation, and standard deviation of deviations in millimeters for the three locations along the length of the hose.

Table 4

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Scan Number</th>
<th>Maximum Deviation (mm)</th>
<th>Minimum Deviation (mm)</th>
<th>Average Deviation (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>1</td>
<td>3.480</td>
<td>0.681</td>
<td>2.490</td>
<td>1.569</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.475</td>
<td>2.346</td>
<td>2.989</td>
<td>0.581</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.873</td>
<td>0.739</td>
<td>1.835</td>
<td>1.068</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.781</td>
<td>3.341</td>
<td>3.531</td>
<td>0.226</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>2</td>
<td>3.875</td>
<td>2.086</td>
<td>3.147</td>
<td>0.940</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.136</td>
<td>0.476</td>
<td>1.986</td>
<td>1.366</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.493</td>
<td>0.739</td>
<td>1.628</td>
<td>0.873</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>4.594</td>
<td>1.266</td>
<td>3.453</td>
<td>1.895</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.956</td>
<td>1.381</td>
<td>1.611</td>
<td>0.237</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.222</td>
<td>1.606</td>
<td>3.194</td>
<td>1.395</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.467</td>
<td>2.723</td>
<td>3.509</td>
<td>0.886</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>1</td>
<td>6.630</td>
<td>2.621</td>
<td>5.118</td>
<td>2.178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.960</td>
<td>2.208</td>
<td>2.870</td>
<td>0.961</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.735</td>
<td>0.753</td>
<td>1.831</td>
<td>1.654</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>5.782</td>
<td>3.548</td>
<td>4.540</td>
<td>1.130</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>2</td>
<td>9.111</td>
<td>4.977</td>
<td>7.151</td>
<td>2.075</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.214</td>
<td>3.506</td>
<td>4.269</td>
<td>0.869</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.705</td>
<td>2.192</td>
<td>3.558</td>
<td>1.271</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>4</td>
<td>4.283</td>
<td>3.239</td>
<td>3.728</td>
<td>0.526</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>14.274</td>
<td>7.994</td>
<td>10.616</td>
<td>3.266</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>6.659</td>
<td>4.868</td>
<td>5.630</td>
<td>0.925</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.800</td>
<td>5.274</td>
<td>7.818</td>
<td>2.262</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>1</td>
<td>10.099</td>
<td>6.071</td>
<td>7.638</td>
<td>2.157</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9.284</td>
<td>0.800</td>
<td>5.838</td>
<td>4.461</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.494</td>
<td>4.184</td>
<td>5.752</td>
<td>2.863</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.066</td>
<td>1.554</td>
<td>4.515</td>
<td>3.999</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>2</td>
<td>11.249</td>
<td>7.402</td>
<td>8.953</td>
<td>2.029</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>9.184</td>
<td>3.627</td>
<td>6.650</td>
<td>2.690</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>7.507</td>
<td>0.816</td>
<td>5.074</td>
<td>3.700</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>4</td>
<td>4.061</td>
<td>1.904</td>
<td>3.167</td>
<td>1.068</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>11.957</td>
<td>3.780</td>
<td>8.608</td>
<td>1.638</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.025</td>
<td>4.677</td>
<td>5.689</td>
<td>1.216</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>8.545</td>
<td>2.241</td>
<td>4.776</td>
<td>3.328</td>
</tr>
</tbody>
</table>
Figure 105 shows the Individual Value plot of the average deviation grouped by length and twist angle. The average deviations for 13" and 16" hose were more than that for an 11".

![Individual Value Plot of Average Deviation](image)

Figure 105. Individual Value Plot of Average Deviations.

Table 5 shows the mean, standard deviation, and 95% CI of the mean of the average deviations grouped by length and twist angle from Table 4. The CI for 13" and 16" hose was seen to be more than the 11". The force deformation curve for translational springs was found using 0° and 180°. The results from Table 5 show that it has to be refined by defining additional points on the curve that align the model with hose scans for the intermediate angles (between 0° and 180°). Figure 106 shows the interval plot corresponding to CI values in Table 5.
Table 5

Mean and Standard Deviation of Average Deviation Grouped by Length and Twist Angle for Translational Spring Model (N=1)

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
<th>95%CI of Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>2.711</td>
<td>0.722</td>
<td>(1.562,3.861)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2.229</td>
<td>0.650</td>
<td>(1.194,3.263)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>2.942</td>
<td>0.898</td>
<td>(1.514,4.370)</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>3.590</td>
<td>1.511</td>
<td>(1.186,5.994)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4.676</td>
<td>1.678</td>
<td>(2.007,7.346)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>7.348</td>
<td>2.445</td>
<td>(3.458,11.238)</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>5.936</td>
<td>1.286</td>
<td>(3.890,7.982)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5.961</td>
<td>2.451</td>
<td>(2.061,9.861)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>6.376</td>
<td>1.638</td>
<td>(3.770,8.982)</td>
</tr>
</tbody>
</table>

Figure 106. Interval Plot of Average Deviations for Torsion and Translational Springs from Minitab® Software.

Comparison of Translational and Torsion Spring Models

Figure 107 shows the individual value plot of the average deviations for torsion and translational springs. The spread of the average deviations for 13” and 16” hoses in the translational model was more than that in the torsion spring model.
Paired T-Test for Average Deviations of Torsion and Translational Spring Models

A paired t-test was conducted for average deviations of translational and torsion springs. The mean, standard deviation, and standard error of the mean are given in Table 6. The 95% CI for the mean of the difference (torsion - translational) in average deviations was -1.502mm to -0.525mm. The results of the paired t-test show that average deviations of the torsion spring model is less than that of the translational spring (T-value = -4.21, P-value = 0.000).

Table 6

Mean, Standard Deviation, and Standard Error of the Mean of Average Deviations of Torsion and Translational Spring Models

<table>
<thead>
<tr>
<th>Average Deviations</th>
<th>N</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
<th>SE Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion</td>
<td>36</td>
<td>3.628</td>
<td>1.408</td>
<td>0.235</td>
</tr>
<tr>
<td>Translational</td>
<td>36</td>
<td>4.641</td>
<td>2.259</td>
<td>0.377</td>
</tr>
<tr>
<td>Torsion - Translational</td>
<td>36</td>
<td>-1.013</td>
<td>1.443</td>
<td>0.241</td>
</tr>
</tbody>
</table>
Table 7 shows the performance comparison of translational and torsion springs for 11", 13", and 16" hose models with respect to the time required to build models automatically and simulate it and maximum deviation at 30°.

Table 7

Performance Comparison of Translational Vs Torsion Spring Hose Models

<table>
<thead>
<tr>
<th>Hose Length(in)</th>
<th>Twist Angle (deg)</th>
<th>Translational Build/Simulation Time (min)</th>
<th>Torsion Build/Simulation Time (min)</th>
<th>Translational Maximum Deviation(mm)</th>
<th>Torsion Maximum Deviation(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>9</td>
<td>2.6</td>
<td>3.781</td>
<td>3.349</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>9.5</td>
<td>2.8</td>
<td>3.875</td>
<td>3.645</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>10</td>
<td>3</td>
<td>4.594</td>
<td>4.132</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>12</td>
<td>4</td>
<td>6.630</td>
<td>5.173</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>13</td>
<td>4.5</td>
<td>9.111</td>
<td>5.687</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>14</td>
<td>5</td>
<td>14.274</td>
<td>6.045</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>26</td>
<td>5</td>
<td>10.099</td>
<td>9.785</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>28</td>
<td>6</td>
<td>11.249</td>
<td>9.791</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
<td>7</td>
<td>11.957</td>
<td>9.219</td>
</tr>
</tbody>
</table>

Chapter Summary

The digitizer post-processing software was used to construct geometric entities needed to measure the deviation of the model from the scan. The deviations between the two were measured at 25%, 50%, and 75% of the length of the hose from the dial end. The average of the deviations at the three locations was calculated. The maximum and minimum deviations amongst the three locations were also found. Tables of the deviation of the model from the four scans for each of the three lengths have been presented. Each scan corresponded to one of the four initial orientations that were 90° apart. The deviations have been grouped by length and twist angle. The mean of the average
deviation of the torsion spring model for a hose length typically used in mid-size cars and SUVs when twisted to the maximum angle possible in these vehicles was 2.803mm.

A paired t-test was conducted between average deviations of translational and torsion springs to evaluate if there was a statistically significant difference. The results of the paired t-test showed that average deviations of the torsion spring model are statistically less than that of the translational spring. The time required to build and simulate the translational spring model was three times that for the torsion spring model for longer hoses.

The generality of the torsional stiffness curve used for the torsion springs in the model was tested by scanning a length of hose not used in defining the torsional stiffness curve. Thus the length of brake hose (approximately 10”) used in the PT Cruiser™ was chosen as one of the three lengths to be scanned. The accuracy of the model was tested by scanning more samples of a given length. Thus ten samples of 10”, 13”, and 16” were scanned after twisting them through angles of 15° and 25° as described in the next chapter. The deviations of the model from each of the samples were measured using the method described in the present chapter. The tabulated results are presented in the next chapter.
CHAPTER VI

CONDUCTING STATISTICAL TESTS FOR LARGER SAMPLE SIZE

Statistical significance of different lengths and twist angles in effecting deviations for larger sample sizes was studied. This better characterized the predictability of the model. Also a length was chosen outside the range of those considered previously as a test of generality of the model. A length of brake hose used in the PT Cruiser™ is approximately 10” between coplanar attachment points. It has been stated that an acceptable length is found when a clearance of 1” or more can be ensured from adjacent components on the chassis during motion of the vehicle from full rebound to jounce (Chrysler™ Internal Document, 2001).

Procedure for Conducting Experiment with Larger Sample Size

The GY5052 brake hose from the manufacturer as shown in Figure 108 was cut into ten samples each of approximately 11”, 14”, and 17” lengths, which result in 10”, 13”, and 16” hose lengths between attachment points, as shown in Figure 109. Hoses were sprayed with non-chlorinated solvent developer for ease of obtaining point cloud data.
Steps involved in conducting the experiment for 10" hose lengths between attachment points are as follows:

Step 1: The plug gauge was inserted into one end of the hose and it was tightened between two halves of the square clamp similar to step 1 mentioned in Chapter III under the section for obtaining point cloud data between coplanar attachment points.

Step 2: A length of 10" (+/- 0.03125") was measured along the hose from the top surface of the square clamp as shown in Figure 110 (a). A distinct marking was made with a scriber at that length as shown in Figure 110 (b).
Figure 110. (a) A Length of 10” Being Measured along the Hose from the Top Surface of Square Clamp. (b) Distinct Marking Being Made with a Scriber at 10”.

Step 3: The second plug gauge was inserted into the other end of the hose and hose was inserted between halves of square clamp at the dial end. The clamp was tightened after aligning the 10” marking with the edge of the top surface of the square clamp. This is similar to steps 3 and 4 described in Chapter III for obtaining point cloud data between coplanar attachment points.

Step 4: Steps 8, 9, 10, and 11 described in Chapter III for eliminating hysteresis in the hose were conducted.

Step 5: The dowel and collar assembly along with the hose was twisted through 15° after
loosening Collar C at the dial end. Figure 111 shows the hose at a 15° twist.

![Figure 111. Hose in 15° Twist Position.](image)

Step 6: Point cloud data corresponding to the hose shape at a 15° twist was obtained.

Step 7: The dowel and collar assembly along with the hose was twisted further by 10° after loosening the collar at the dial end to obtain a total twist of 25°.

Step 8: Point cloud data corresponding to the hose shape at a 25° twist was obtained.

Steps 1 to 8 were repeated for each of ten samples of 11", 14", and 17" hoses. The length of hose between attachment points for 14" and 17" hoses were 13" and 16" respectively.

Figure 112 shows the hoses marked with sample numbers after being scanned.

![Figure 112. Hoses Marked with Sample Numbers after Being Scanned.](image)
Comparison of the Model with Scans

Ten scans (one scan per sample) for each length at each twist angle (15° and 25°) were grouped together and exported from the digitizer software as stereolithography (.stl) files. One group at a time was then imported into the simulation software. The simulation model with torsion springs having the cubic torsional stiffness curve characteristic was created between attachment points for 10”, 13”, and 16” hose lengths. Figures 113(a) and 113(b) show the model alongside scans of ten samples (one scan per sample) of 10” hose at 15° and 25° twist angles, respectively.

Figure 113. Model alongside Scans of Ten Samples of 10” Hose at (a) 15° and (b) 25° Twist Angles.

Figures 114(a) and 114(b) show the model alongside scans of ten samples of 13” hose at 15° and 25° twist angles respectively.
Figures 114(a) and 114(b) show the model alongside scans of ten samples of 13” hose at (a) 15° and (b) 25° Twist Angles.

Figures 115(a) and 115(b) show the model alongside scans of ten samples of 16” hose at 15° and 25° twist angles respectively. It was observed that an increase in spread of scans with a 3” increase in length was more significant than with an increase in twist angle of 10°. It was particularly large for the 16” hose at a 25° twist angle.
Figure 115. Model alongside Scans of Ten Samples of 16" Hose at (a) 15° and (b) 25° Twist Angles.

Figure 116 shows the 10" model at a 15° twist with ten scans (one scan per sample) in digitizer post-processing software and the plane at 50% of the length.

Figure 116. 10" Model at 15° Twist with Ten Scans (One Scan Per Sample) and Plane at 50% of the Length.
Figure 117 shows a circle corresponding to the hose model along with points on ten scans corresponding to each of the ten samples on the section created through the plane.

Figure 117. Points on Section through the Plane at 50% of Length.

Figure 118 shows ten best-fit circles (one per sample) and the circle corresponding to the hose model.

Figure 118. Ten Best-Fit Circles (One per Sample) and Circle Corresponding to Hose Model.

Figure 119 shows distances measured from the center of the hose model circle to each of the best-fit circles corresponding to a sample. Deviation of the model from the
center of ten best-fit circles corresponding to each sample of hose length at each of the two twist angles was measured at 25%, 50%, and 75% of the length of the hose from the dial end in digitizer post-processing software.

![Graph showing distances measured from center of hose model circle to center of each of the best-fit circles.](image)

Figure 119. Distances Measured from Center of Hose Model Circle to Center of Each of the Best-Fit Circles.

The table of deviation at the three locations are given in Appendix F. Table 8 gives maximum, minimum, average, and standard deviations of deviations measured at the three locations for each sample for each length at each twist angle.
# Table 8

Maximum, Minimum, Average Deviations, and Standard Deviation of Deviations among Three Locations for Each of Ten Samples of Hose Lengths for 15° and 25° Twist

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Sample</th>
<th>Deviations (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2.190</td>
<td>1.461</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.954</td>
<td>0.762</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.839</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.040</td>
<td>2.439</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>2.914</td>
<td>1.939</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.194</td>
<td>1.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>3.702</td>
<td>2.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.867</td>
<td>1.560</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>2.399</td>
<td>0.570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>2.221</td>
<td>1.520</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1</td>
<td>4.050</td>
<td>2.540</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.630</td>
<td>1.970</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.770</td>
<td>2.240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>5.530</td>
<td>3.390</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>4.950</td>
<td>1.770</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>5.260</td>
<td>2.660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>4.990</td>
<td>2.220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>5.760</td>
<td>2.610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>4.750</td>
<td>0.760</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3.360</td>
<td>1.620</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>5.450</td>
<td>4.130</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.420</td>
<td>3.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.260</td>
<td>4.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>5.560</td>
<td>2.840</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>5.600</td>
<td>2.840</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>3.360</td>
<td>2.260</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>4.820</td>
<td>2.630</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>3.940</td>
<td>2.640</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>3.680</td>
<td>2.050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>2.710</td>
<td>0.870</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1</td>
<td>6.650</td>
<td>3.650</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.900</td>
<td>2.300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.400</td>
<td>3.660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.830</td>
<td>4.410</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>6.160</td>
<td>1.890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>4.400</td>
<td>2.700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5.370</td>
<td>1.760</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>4.320</td>
<td>2.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>4.710</td>
<td>1.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>5.160</td>
<td>1.110</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>10.684</td>
<td>1.616</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7.910</td>
<td>3.590</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>14.850</td>
<td>6.570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.850</td>
<td>2.890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>7.430</td>
<td>3.140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>9.470</td>
<td>5.560</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>10.190</td>
<td>3.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>9.410</td>
<td>3.680</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>6.760</td>
<td>3.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>6.020</td>
<td>4.500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>12.420</td>
<td>2.190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9.770</td>
<td>4.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>16.260</td>
<td>6.210</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.710</td>
<td>4.290</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8.690</td>
<td>4.860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>10.050</td>
<td>5.720</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>11.780</td>
<td>4.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>10.580</td>
<td>3.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>7.390</td>
<td>3.850</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>7.060</td>
<td>4.610</td>
</tr>
</tbody>
</table>
Table 9 shows the mean, standard deviation, and 95% CI of the mean of the average deviations grouped by length and twist angle. Figure 120 shows the interval plot corresponding to CI values in Table 8.

Table 9

Mean and Standard Deviation of Average Deviation Grouped by Length and Twist Angle (N=10)

<table>
<thead>
<tr>
<th>Length</th>
<th>Twist Angle (deg)</th>
<th>Mean(mm)</th>
<th>Standard Deviation(mm)</th>
<th>95%CI of Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10&quot;</td>
<td>15</td>
<td>2.178</td>
<td>0.550</td>
<td>(1.784,2.572)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.443</td>
<td>0.505</td>
<td>(3.082,3.804)</td>
</tr>
<tr>
<td>13&quot;</td>
<td>15</td>
<td>3.547</td>
<td>1.014</td>
<td>(3.391,4.278)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4.123</td>
<td>0.825</td>
<td>(3.533,4.713)</td>
</tr>
<tr>
<td>16&quot;</td>
<td>15</td>
<td>6.987</td>
<td>1.709</td>
<td>(5.764,8.209)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>7.839</td>
<td>1.723</td>
<td>(6.607,9.071)</td>
</tr>
</tbody>
</table>

Figure 120. Interval Plot of 95% CI of Mean of Average Deviations Grouped by Length and Twist Angle from Minitab® Software.

Figure 121 shows the boxplot for average deviations grouped by length. There are two outliers for the 16” hose. The average deviations for 10” and 13” lengths are more symmetric than their maximum deviations. Average deviations for the 16” hose are, however, negatively skewed. The variability in average deviation for 10” and 13” hose is
less than for the 16” hose. This is because of a greater hysteresis effect in longer hoses when attached between the same attachment points used for shorter ones (in this case 10” and 13”). The variability would have been less if the attachment points for the 16” hose was farther apart than the 10” and 13” hoses.

Figure 121. Boxplot of Average Deviations Grouped by Length from Minitab® Software.

Figure 122 shows the boxplot with quartile endpoints of maximum deviations grouped by length. The bottom and top of the boxes are the first quartile (Q1) and the third quartile (Q3) respectively and the line in the middle corresponds to the median.

Figure 122. Boxplot of Maximum Deviations Grouped by Length.
The values for first quartile (Q1), median, and third quartile (Q3) for average and maximum deviations are given in Table 10.

Table 10

The Values for First Quartile (Q1), Median, and Third Quartile (Q3) for Average and Maximum Deviations

<table>
<thead>
<tr>
<th>Length</th>
<th>Deviations (mm)</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>1.993</td>
<td>2.830</td>
<td>3.579</td>
</tr>
<tr>
<td>10&quot;</td>
<td>Maximum</td>
<td>2.509</td>
<td>3.666</td>
<td>4.910</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>3.275</td>
<td>3.948</td>
<td>4.601</td>
</tr>
<tr>
<td>13&quot;</td>
<td>Maximum</td>
<td>4.340</td>
<td>5.210</td>
<td>5.590</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>6.052</td>
<td>7.276</td>
<td>7.821</td>
</tr>
<tr>
<td>16&quot;</td>
<td>Maximum</td>
<td>7.550</td>
<td>9.740</td>
<td>11.403</td>
</tr>
</tbody>
</table>

One-Sample T-Test for Average Deviations

The Anderson Darling (A-D) Normality Test and corresponding p-values for 10" and 13" hose lengths in Appendix G indicate normal distribution of average deviations. However, average deviations for the 16" hose length are less normally distributed (p-value = 0.041). The $F$ distribution is used for testing a hypothesis of population variances in the Analysis of Variances (ANOVA) procedure. This distribution has been found to be unaffected by failure to meet the normality assumption of treatment populations (Kirk, 1968). Average deviations for the 16" hose length excluding the two outliers are normally distributed as per the p-value (0.26) for A-D Normality test. The large average deviation for two samples of 16" hose could be attributed to the effect of initial orientation on the final hose shape as discussed in Chapter III. As noted in that chapter, the spread amongst four hose shapes from four initial orientations was largest for the 16" hose. The distance between the attachment points on the fixture was maintained constant for all three lengths. It was observed during the experiment that deflection in the 16" hose was visually significant. This was because the distance between attachment points was not
sufficient to allow the 16" hose to spring back during the hysteresis elimination procedure as described in Chapter III.

The summary statistics for average deviations for each length and 95% CI of the mean is given in Table 11.

Table 11

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Average Deviations (mm)</th>
<th>Standard Deviation (mm)</th>
<th>95%CI of Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
<td>Mean</td>
</tr>
<tr>
<td>10</td>
<td>4.210</td>
<td>1.601</td>
<td>2.811</td>
</tr>
<tr>
<td>13</td>
<td>5.587</td>
<td>1.533</td>
<td>3.835</td>
</tr>
<tr>
<td>16</td>
<td>11.787</td>
<td>5.017</td>
<td>7.413</td>
</tr>
</tbody>
</table>

One-Sample T-Test Results for Average Deviations of 10" Hose

Since the assumption of normality is valid for average deviations of 10", the one-sample t-test was used to test statistically if the mean of average deviations was less than the hose radius (5.15mm). The allowed clearance for the brake hose from adjacent components in a PT Cruiser™ is 25.4mm. The value of 5.15mm was chosen in order to attain a capability index (C_p) of greater than 1.6. The capability index for clearance of 5.15mm is given by:

$$\frac{25.4}{(5.15 \times 2)} = 2.47.$$  \hspace{1cm} (Equation 13)

The null hypothesis was of a population mean for average deviations being equal to 5.15mm and alternate hypothesis was of it being less than 5.15mm. The null hypothesis is rejected as per one-sample t-test with 95% CI of the mean at a significance level of 0.05 due to the lower p-value as shown in Figure 123. It can be concluded that the mean of average deviations for the 10" hose is less than the radius of hose as per the
one-sample t-test. Figure 124 shows the boxplot of 95% CI of the mean and hypothesized population mean value of 5.15mm for average deviations of 10” hose.

\[
\begin{align*}
H_0 & : \mu = 5.15 \text{mm} \\
H_1 & : \mu < 5.15 \text{mm} \\
\text{Test of } & \mu = 5.15 \text{ vs } < 5.15
\end{align*}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Bound</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Deviation 10&quot;</td>
<td>20</td>
<td>2.811</td>
<td>0.828</td>
<td>0.185</td>
<td>3.131</td>
<td>-12.64</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Figure 123. One-Sample T-Test for Average Deviations of 10” Hose from Minitab® Software.

Figure 124. Boxplot of Comparison of 95% CI of Mean of Average Deviations for 10” Hose and Hypothesized Population Mean of 5.15mm.

**One-Sample T-Test Results for Average Deviations of 13” Hose**

It can be concluded from the one-sample t-test for average deviations for the 13” hose that the mean of average deviations is less than 5.15mm at significance level of 0.05. The p-value for the null hypothesis test is shown in Figure 125. Figure 126 shows the boxplot for 95% CI of the mean and hypothesized population mean value of 5.15mm for average deviations of the 13” hose.
Figure 125. One-Sample T-Test for Average Deviations of 13” Hose.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Bound</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Deviation</td>
<td>20</td>
<td>3.835</td>
<td>0.947</td>
<td>0.212</td>
<td>4.201</td>
<td>-6.21</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Figure 126. Boxplot of Comparison of 95% CI of Mean and Hypothesized Population Mean of 5.15mm.

ANOVA Analysis Using General Linear Model for Average Deviations

Analysis of Variance (ANOVA) analysis using Minitab® statistical software’s general linear model was conducted with length and twist angle as the factors and average deviation as the response. ANOVA results are presented in Table 12. The results of the post hoc analysis using Tukey Test (at 5% significance level) are reported in the form of homogeneous subsets. Hose length is significant in effecting the average deviations. The average deviation increases with increase in length. The average
deviation for a 15° twist angle was significantly less than for a 25° using Tukey 95% simultaneous CIs. There is no significant interaction between length and twist angle factors as per the ANOVA results.

Table 12

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2</td>
<td>233.530</td>
<td>116.765</td>
<td>85.930</td>
<td>0.000</td>
</tr>
<tr>
<td>TwistAngle</td>
<td>1</td>
<td>12.094</td>
<td>12.094</td>
<td>8.900</td>
<td>0.004</td>
</tr>
<tr>
<td>Length*TwistAngle</td>
<td>2</td>
<td>1.204</td>
<td>0.602</td>
<td>0.400</td>
<td>0.645</td>
</tr>
<tr>
<td>Error</td>
<td>54</td>
<td>73.378</td>
<td>1.359</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
<td>320.206</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Means: 10” = 2.8101
13” = 3.835
16” = 7.413

Tukey Homogeneous Subsets: (10”) (13”) (16”)

Means: 15° = 4.237
25° = 5.135

Tukey Homogeneous Subsets: (15°) (25°)

The mean of the average deviation increases slightly with an increase in twist angle, whereas it increases significantly from a 13” to 16” increase in length as per the main effects plot shown in Figure 127. This is due to an increase in spread of hose shapes for the 16”.
Chapter Summary

Description of the experiment conducted to obtain scans for ten samples each of 10”, 13”, and 16” hose lengths between attachment points at 15° and 25° twist angles was presented. The 10” hose was not used in development of the torsion stiffness curve. However, the mean of the average deviation (3.443mm) for ten samples of the 10” hose at a 25° twist angle was within the 95% CI of the mean of average deviations (1.894mm, 3.713mm) for an 11” hose (N = 1). Thus the torsional stiffness curve used in the torsion spring model is robust to changes in hose length and is general enough to be used for any hose length in the 10”-13” range with the resulting mean of average deviations not exceeding 5.150mm (hose radius) for twist angles of 15° and 25°. This is based on the one-sample t-test result for 10” and 13” hoses which rejected the null hypothesis of the mean of the average deviation being equal to 5.150mm in favor of it being less than 5.150mm.
The mean of the average deviation for the ten samples of 13” hose for a twist angle of 15° was 3.547mm and for 25° was 4.123mm. This is comparable to 3.478mm and 3.779mm for 20° and 30° twist angles for one-sample of 13” hose in the previous chapter. Thus the torsional stiffness curve obtained from regression adequately captures the variability due to difference in initial orientations.

ANOVA analysis results based on the general linear model showed that average deviations increased with an increase in 3” of hose length (10”, 13”, and 16”) and 10° of twist angle (15° and 25°). The longer lengths of hoses deflect more when attached between the same attachment points used for shorter hoses. The hysteresis effect is also more pronounced in such cases.
CHAPTER VII

CONCLUSIONS, FINDINGS, AND FUTURE WORK

Summary

A simulation model for brake hoses using beams and torsion springs was developed for the first time. The hysteresis of the rubber was found to have a significant effect on the hose shape. Also for the first time, the hysteresis bias was reduced during the experimental procedure for data collection, which has been documented in Chapter III. The preset in the hose was also found to have an effect on the hose shape when twisted at various angles. For example, the difference in the hose shapes when twisted at one end by 10° and 180° from four different initial orientations is shown in Figures 37 (a) and (b) and Figures 44 (a) and (b) respectively in Chapter III. The procedure for finding the best-fit torsional stiffness curve for torsion springs that would center the model in the scanned point cloud data has been described in Chapter IV. This reduced the error between the model and an actual hose shape from any initial orientation of the hose for a particular twist angle. A digitizer and its post-processing software was used to obtain scanned point cloud data of the hose when twisted through angles between and including 0° and 180° in increments of 10°. The slope of the torsional stiffness curve that centered the hose model in the point cloud data for every 10° of twist angle from 0° to 180° was found. The torsional stiffness curves for 11”, 13”, and 16” hoses were approximated by a cubic curve using polynomial regression analysis. This method is general enough to be used for finding torsional stiffness curves for other brake hose materials and flexible elements like wiring harnesses and robotic dresses.
A method for determining the accuracy of a brake hose model in terms of its deviation from the actual shape at various angles of twist was presented. The deviations between the centers of the circular cross-section of the model and the scanned point cloud of an actual hose were measured at 25%, 50%, and 75% of the length of the hose. The mean of the average deviations of the torsion spring model at the three locations for ten samples of a hose length typically used in mid-size cars and SUVs when twisted to the maximum angle possible in these vehicles was 3.443mm (standard deviation = 0.505mm). The model was also found to be robust to changes in hose length and is general enough to be used for any hose length in the 10”-13” range. A one-sample t-test result for 10” and 13” hoses showed that the population mean of average deviations would not exceed 5.150mm (hose radius) for twist angles of 15° and 25°.

The generality of the torsional stiffness curve was proved by comparable accuracy of a 10” hose to the 11” and 13” lengths that were used in the development of the torsional stiffness curve. The torsional stiffness curve obtained from regression analysis adequately captured the process variability in the manufacturing of hoses. The mean of the average deviation (3.443mm) for 10 samples of 10” hose at a 25° twist angle was within the 95% CI of the mean of average deviations (1.894mm,3.713mm) for an 11” hose (N = 1). The mean of the average deviation for the larger sample size (N = 10) of a 13” hose for a twist angle of 15° was 3.547mm and for 25° was 4.123mm.

The hose model with torsion springs and beams can be incorporated into a dynamic simulation of front suspension as shown in Figure 128. Different lengths of hoses in a range of 10”-13” (for compact to mid-size cars and SUVs) can be modeled between attachment points using the cubic torsional stiffness curve for the torsion
springs. The generality of the cubic torsional stiffness curve increases confidence in hose shape predicted by the model for different lengths. Thus an appropriate length that does not touch adjacent components on the chassis can be identified in the design phase, which eliminates the need for polymer bumpers to be fused to the brake hose.

Figure 128. Hose Model in a Dynamic Simulation Model of Front Suspension.

**Key Findings**

It was visually observed that the motion of the translational spring model was not smooth for twist angles between $0^\circ$ and $180^\circ$. The translational spring model had been a significant improvement over a simple linear beam model (Thomas, 2004). The torsion spring model was an improvement over the translational spring model. The motion of the torsion spring model was much smoother for twist angles between $0^\circ$ and $180^\circ$. The torsion spring model matched the shape of digital scans of actual hoses more closely than the translational spring model for twists of $10^\circ$, $20^\circ$, and $30^\circ$. The comparison of
maximum deviations of the two models is shown in Table 7 in Chapter V. The torsion spring model was also found to be more scalable than the one with translational springs. A paired t-test was conducted between average deviations of translational and torsion springs to evaluate if there was a statistically significant difference. The results of the paired t-test showed that average deviations of the torsion spring model are statistically less than that of the translational spring. Experimentally it was observed that the time required to build and simulate the translational spring model was three times greater than that for the torsion spring model for longer hoses.

Axial force in the beam at the end being twisted increases with an increase in twist angle. This causes the angular deformation of springs to decrease with an increase in twist angle beyond approximately 80°. The torque values for the angular deformation beyond 80° have already been defined for twist angles below it. Thus, the torsional stiffness curve could not be optimized for twist angles beyond 80° for matching the model with the center of the scans. Similar characteristics were also observed for 13” and 16” hoses.

The axial force characteristics of the beams in the non-coplanar position were high in the no-twist position. Thus it is advisable to refrain from attaching the hose between non-coplanar attachment points to prevent high axial loads in initial assembly. The torsional stiffness curve for the hose with non-coplanar attachment points was different from coplanar points due to the difference in magnitude of axial forces in beams.

It was found that the initial assumption that hoses would assume approximately the same shape when twisted through the same angle from different initial orientations
was not valid. This was evident from the difference in the scanned point cloud data of hose shapes for the same angle of twist from four different initial orientations. The longer lengths of hoses deflect more when attached between the same attachment points used for shorter hoses. The hysteresis effect is also more pronounced in such cases.

**Future Work**

To contribute and continue this important work, further research could be conducted to address the following issues.

Currently this study has been limited to the GY5052 hose. It would be interesting to investigate if the torsional stiffness curve used in the torsion spring model presented in this research needs to be modified for other hose types. Though a brake hose shows less than 1% change in length at 1600 psi, the effect of pressurized hoses on shape should be studied. Further, a technique to automate adjustment of torque values based on changing angular deformations should be investigated. This would help in reducing the time needed in finding the best-fit torsional stiffness curve in case the one based on the cubic curve as per equation 12 causes the model to deviate significantly from the actual shape.

It is essential to model the contact forces between brake hose and the adjoining structures on the chassis in order to find the hose length that would not rub against them. It is difficult to model these forces in Adams™/View Simulation Software which was used in the current research. The simulation time also increases with contact forces in the dynamic simulation. Genetic-based algorithms (Sandurkar & Chen, 1997) and search and optimization algorithms (Costa, Monclar, & Zrikem, 2001), which are computationally faster, can be developed to propose a hose path that would avoid interference. This would eliminate the need for modeling contact forces in simulation software; however, such
algorithms do not incorporate the physical properties of the hose. Therefore a hose path proposed by the optimization algorithm can be verified with the hose shape from the torsion spring model without modeling the contact forces.

A hose model with torsion and translational springs needs to be investigated. The translational springs could be used to compensate for high axial forces in beams when the twist angle increases beyond 80°. This could increase the accuracy of the model for twist angles above 80°.

The difference in hose shapes from different initial orientations due to the preset increased when longer hoses were attached between points without adequate separation. The study of the effect of distance between attachment points on the hysteresis and the deflection of hose would be beneficial in the initial assembly of a brake hose.

The hysteresis and preset properties of brake hoses should be considered while reporting the accuracy of the virtual reality and finite element models for a brake hose, as mentioned in Chapter II. The deviation between the predicted hose shape from these modeling approaches and the actual one can be reported using the method presented in Chapter V. The hysteresis property of rubber should be experimentally negated using the procedure mentioned in Chapter III while collecting any data in the future to determine the effectiveness of brake hose modeling techniques. A comparison needs to be made between the accuracy of the above approaches and the torsion spring model in predicting hose shape for a hose length twisted through a specified angle. Simulation time required for finite element models for hose lengths and twist angles considered in this research needs to be compared with that of torsion spring model.
REFERENCES


Appendix A

Vector Direction at the Vector Points at Either End
Resulting in Different Geometries
Appendix B

CAD Drawings of Parts of the Fixture
Figure 1: CAD Model of the Fixture
Part 5: Angle Mount Plate 3

Part 6: Angle Plate 2
Part 7: Angle Plate 3

Part 8: Angle Toggle Clamp
Part 9: Bench Vise Plate

Part 10: Boss

Part 11: Weldable Shaft Collars One-Piece, 1/2" Bore, 1-1/8" OD, 13/32" Width
Part 12: Fixture Bottom Plate

Part 13: Flat Head 6

Part 14: Hose Holder
Part 15: Hose Holder Fixed

Part 16: Pipe Gear Cover
Part 17: Pipe Gear Cover

Part 18: Plate Fixed End
Part 19: Machinable-Face One-Piece Clamp-on Collar 1/2" Bore, 1-1/4" Outside Diameter, 3/4" Width
Part 20: Toggle Gear Assembly
Part 20-5: Socket Screw 18
Appendix C

The ANOVA Table for Polynomial Regression Analysis for 11”, 13”, and 16” Hoses
Polynomial Regression Analysis: Torque versus Ang_Def

The regression equation is
Torque = -47.30 + 4383 Ang_Def - 3741 Ang_Def**2 + 1498 Ang_Def**3

S = 63.3173  R-Sq = 99.0%  R-Sq(adj) = 98.9%

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>242416832</td>
<td>80805611</td>
<td>20155.62</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>641</td>
<td>2569824</td>
<td>4009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>644</td>
<td>244986656</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

Deviations of Torsion Spring Model from Four Scans (N = 1)
<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Scan Number</th>
<th>Deviation (mm) along % length of hose</th>
<th>25% length</th>
<th>50% length</th>
<th>75% length</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>1</td>
<td>3.349</td>
<td>2.461</td>
<td>3.156</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.462</td>
<td>1.328</td>
<td>1.971</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.386</td>
<td>1.334</td>
<td>0.763</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.212</td>
<td>2.339</td>
<td>1.325</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>3.281</td>
<td>2.249</td>
<td>3.645</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.355</td>
<td>1.535</td>
<td>2.257</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.397</td>
<td>0.889</td>
<td>1.115</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.375</td>
<td>2.818</td>
<td>1.674</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>3.653</td>
<td>2.328</td>
<td>1.282</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.861</td>
<td>2.964</td>
<td>1.885</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.327</td>
<td>2.904</td>
<td>4.132</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.567</td>
<td>3.833</td>
<td>2.905</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>1</td>
<td>4.621</td>
<td>3.314</td>
<td>1.194</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.972</td>
<td>3.116</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.826</td>
<td>4.393</td>
<td>3.317</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.571</td>
<td>4.975</td>
<td>5.173</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>5.687</td>
<td>4.669</td>
<td>2.258</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4.902</td>
<td>3.529</td>
<td>2.733</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.488</td>
<td>4.518</td>
<td>2.280</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.972</td>
<td>2.387</td>
<td>4.315</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>5.839</td>
<td>5.884</td>
<td>3.359</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.961</td>
<td>4.415</td>
<td>2.116</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>6.045</td>
<td>4.704</td>
<td>3.042</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.213</td>
<td>1.852</td>
<td>3.904</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>1</td>
<td>9.785</td>
<td>5.383</td>
<td>4.140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.905</td>
<td>1.629</td>
<td>6.621</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.074</td>
<td>4.512</td>
<td>1.519</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.024</td>
<td>2.108</td>
<td>6.401</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>9.791</td>
<td>5.637</td>
<td>3.672</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.900</td>
<td>3.014</td>
<td>5.763</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.122</td>
<td>3.714</td>
<td>4.178</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.553</td>
<td>3.534</td>
<td>6.146</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>9.219</td>
<td>5.722</td>
<td>3.383</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.958</td>
<td>3.050</td>
<td>5.286</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.930</td>
<td>2.797</td>
<td>3.390</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>5.271</td>
<td>5.003</td>
<td>6.899</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E

Deviations of Translational Spring Model from Scans of One Sample from Different Initial Orientations (N=1)
<table>
<thead>
<tr>
<th>Length</th>
<th>Twist Angle (deg)</th>
<th>Scans</th>
<th>25% length</th>
<th>50% length</th>
<th>75% length</th>
</tr>
</thead>
<tbody>
<tr>
<td>11&quot;</td>
<td>10</td>
<td>1</td>
<td>3.308</td>
<td>0.681</td>
<td>3.480</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.475</td>
<td>3.147</td>
<td>2.346</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.894</td>
<td>2.873</td>
<td>0.739</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.781</td>
<td>3.470</td>
<td>3.341</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>3.875</td>
<td>2.096</td>
<td>3.479</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.476</td>
<td>3.136</td>
<td>2.346</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.483</td>
<td>1.663</td>
<td>0.739</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.147</td>
<td>2.377</td>
<td>0.935</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>4.594</td>
<td>4.499</td>
<td>1.266</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.381</td>
<td>1.855</td>
<td>1.598</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.606</td>
<td>3.755</td>
<td>4.222</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.723</td>
<td>4.467</td>
<td>3.336</td>
</tr>
<tr>
<td>13&quot;</td>
<td>10</td>
<td>1</td>
<td>6.639</td>
<td>6.103</td>
<td>2.621</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.960</td>
<td>2.208</td>
<td>2.443</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.735</td>
<td>1.005</td>
<td>0.753</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.291</td>
<td>5.782</td>
<td>3.548</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>7.366</td>
<td>9.111</td>
<td>4.977</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.214</td>
<td>4.086</td>
<td>3.506</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.777</td>
<td>4.705</td>
<td>2.192</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.239</td>
<td>4.283</td>
<td>3.661</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>9.580</td>
<td>14.274</td>
<td>7.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4.868</td>
<td>6.659</td>
<td>5.363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.818</td>
<td>9.600</td>
<td>5.274</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>2.761</td>
<td>7.621</td>
<td>5.605</td>
</tr>
<tr>
<td>16&quot;</td>
<td>10</td>
<td>1</td>
<td>10.099</td>
<td>6.071</td>
<td>6.745</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7.431</td>
<td>0.800</td>
<td>9.284</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.494</td>
<td>4.579</td>
<td>4.184</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.554</td>
<td>2.927</td>
<td>9.065</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>11.249</td>
<td>8.209</td>
<td>7.402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.939</td>
<td>3.827</td>
<td>9.184</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>6.899</td>
<td>0.816</td>
<td>7.507</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.984</td>
<td>3.456</td>
<td>4.061</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1</td>
<td>11.957</td>
<td>10.087</td>
<td>3.780</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6.829</td>
<td>5.288</td>
<td>7.235</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.304</td>
<td>4.677</td>
<td>7.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.543</td>
<td>2.241</td>
<td>8.545</td>
</tr>
</tbody>
</table>
Appendix F

Deviations of Torsion Spring Model from Scans of Ten Samples
<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Twist Angle (deg)</th>
<th>Sample</th>
<th>25% length</th>
<th>50% length</th>
<th>75% length</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15</td>
<td>1</td>
<td>2.100</td>
<td>1.481</td>
<td>2.190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.054</td>
<td>2.965</td>
<td>0.762</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.432</td>
<td>2.839</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.040</td>
<td>2.439</td>
<td>3.480</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>1.939</td>
<td>2.014</td>
<td>1.980</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>1.028</td>
<td>2.194</td>
<td>1.950</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>2.753</td>
<td>3.702</td>
<td>2.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.867</td>
<td>2.255</td>
<td>1.560</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>1.834</td>
<td>2.399</td>
<td>0.570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.573</td>
<td>2.221</td>
<td>1.520</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1</td>
<td>2.540</td>
<td>4.050</td>
<td>2.580</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.340</td>
<td>3.630</td>
<td>1.970</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.190</td>
<td>4.770</td>
<td>2.240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>3.330</td>
<td>5.530</td>
<td>3.770</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>1.770</td>
<td>4.950</td>
<td>3.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.870</td>
<td>5.280</td>
<td>2.660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>4.990</td>
<td>4.250</td>
<td>2.220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>3.030</td>
<td>5.760</td>
<td>2.610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>4.450</td>
<td>4.790</td>
<td>0.760</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3.180</td>
<td>3.360</td>
<td>1.620</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td>1</td>
<td>5.450</td>
<td>4.500</td>
<td>4.130</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.420</td>
<td>3.050</td>
<td>3.170</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4.660</td>
<td>5.260</td>
<td>4.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.330</td>
<td>2.940</td>
<td>5.550</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>5.600</td>
<td>3.820</td>
<td>2.840</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>3.300</td>
<td>2.260</td>
<td>2.640</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>4.820</td>
<td>3.900</td>
<td>2.630</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>3.940</td>
<td>2.640</td>
<td>3.180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>4.800</td>
<td>4.790</td>
<td>2.050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.020</td>
<td>2.710</td>
<td>0.870</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1</td>
<td>6.858</td>
<td>4.600</td>
<td>3.850</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.900</td>
<td>3.850</td>
<td>2.300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.800</td>
<td>7.400</td>
<td>3.560</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.830</td>
<td>4.410</td>
<td>4.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>6.160</td>
<td>5.410</td>
<td>1.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>4.400</td>
<td>3.250</td>
<td>2.700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5.370</td>
<td>4.990</td>
<td>1.760</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>4.320</td>
<td>4.050</td>
<td>2.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>4.200</td>
<td>4.710</td>
<td>1.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>2.910</td>
<td>5.160</td>
<td>1.110</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>1</td>
<td>8.636</td>
<td>11.684</td>
<td>1.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7.910</td>
<td>7.880</td>
<td>3.590</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>14.840</td>
<td>11.810</td>
<td>6.570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.020</td>
<td>9.850</td>
<td>2.890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>7.180</td>
<td>7.430</td>
<td>3.140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>9.470</td>
<td>5.560</td>
<td>6.860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>10.190</td>
<td>9.640</td>
<td>3.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>9.410</td>
<td>8.620</td>
<td>3.880</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>6.760</td>
<td>3.150</td>
<td>5.340</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>4.530</td>
<td>6.020</td>
<td>4.500</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1</td>
<td>10.922</td>
<td>12.420</td>
<td>2.190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9.770</td>
<td>8.400</td>
<td>4.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>9.710</td>
<td>9.490</td>
<td>4.290</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8.690</td>
<td>8.200</td>
<td>4.860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>10.950</td>
<td>5.720</td>
<td>6.130</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>11.780</td>
<td>10.890</td>
<td>4.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>10.560</td>
<td>9.780</td>
<td>3.050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>7.390</td>
<td>3.850</td>
<td>6.320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>7.060</td>
<td>5.250</td>
<td>4.610</td>
</tr>
</tbody>
</table>
Appendix G

Summary of Average Deviations for 10", 13", and 16" Hoses
Summary for Average Deviations
Length = 10

Anderson-Darling Normality Test
A-Squared  0.49
P-Value  0.202

Mean  2.8107
StDev  0.8280
Variance  0.6855
Skewness  0.03746
Kurtosis  -1.42525
N  20

Minimum  1.6010
1st Quartile  1.9933
Median  2.8308
3rd Quartile  3.5792
Maximum  4.2100

95% Confidence Interval for Mean
2.4232  3.1982
95% Confidence Interval for Median
2.0843  3.4659
95% Confidence Interval for StDev
0.6297  1.2093

Legend:
Length: Length in Inches
Deviation: Deviation in mm

Summary for Average Deviations
Length = 13

Anderson-Darling Normality Test
A-Squared  0.17
P-Value  0.925

Mean  3.8350
StDev  0.3468
Variance  0.8965
Skewness  -0.470182
Kurtosis  0.614998
N  20

Minimum  1.5333
1st Quartile  3.3758
Median  3.9483
3rd Quartile  4.6017
Maximum  5.5867

95% Confidence Interval for Mean
3.3918  4.2781
95% Confidence Interval for Median
3.3684  4.4143
95% Confidence Interval for StDev
0.7201  1.3829

Legend:
Length: Length in Inches
Deviation: Deviation in mm
Summary for Average Deviations
Length = 16

Anderson-Darling Normality Test
A-Squared 0.76
P-Value 0.041

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>7.4128</td>
</tr>
<tr>
<td>StDev</td>
<td>1.7262</td>
</tr>
<tr>
<td>Variance</td>
<td>2.9798</td>
</tr>
<tr>
<td>Skewness</td>
<td>1.10782</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1.63628</td>
</tr>
<tr>
<td>N</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>5.0167</td>
</tr>
<tr>
<td>1st Quartile</td>
<td>6.0525</td>
</tr>
<tr>
<td>Median</td>
<td>7.2767</td>
</tr>
<tr>
<td>3rd Quartile</td>
<td>7.8217</td>
</tr>
<tr>
<td>Maximum</td>
<td>11.7867</td>
</tr>
</tbody>
</table>

95% Confidence Interval for Mean
6.6049 - 8.2207
95% Confidence Interval for Median
6.5784 - 7.7622
95% Confidence Interval for StDev
1.3128 - 2.5213

Legend:
Length in Inches
Deviation in mm