Using Stiffeners for Improved Geometric Fidelity of Flexible Elements

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USING STIFFENERS FOR IMPROVED GEOMETRIC
FIDELITY OF FLEXIBLE ELEMENTS

by

Ankit Kapoor

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

Western Michigan University
Kalamazoo, Michigan
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Flexible hoses play an important role in safe operation of a transportation vehicle in automotive and aerospace field. Due to lack of accurate and efficient modeling techniques for such flexible elements with large deformation, most Computer Aided Engineering system do not address the problem in their solution methods.

In this thesis a method is presented to improve the geometric fidelity of flexible element models by using off-axis bi-linear stiffeners (spring) into a discrete linear beam model. Resulting deflection of a hose were compared with the digital scans of an actual deflection of the hose. Though the method is computationally expensive, resulting deflection of the hose accurately matches with the actual deflection, presenting a clear improvement over existing methods.
ACKNOWLEDGMENTS

It is my great pleasure to have this opportunity to thank the people who have helped me during my thesis and my study at Western Michigan University.

I would like to express my deepest gratitude to Dr. Mitchel J. Keil, my advisor, for helping, guiding and encouraging me to complete this thesis. Without his numerous suggestions and immense knowledge this work would have never been completed.

I would like to thank Dr. Jorge Rodriguez and Dr. Alamgir Choudhury for their expertise and many discussions that greatly inspired this work.

I am thankful to the donors of the Center of Integrated Design Lab for providing the equipment that was necessary for increasing the scope of this thesis. I am also thankful to Jai Thomas and Asif Paranjpe as my other team members who were very supportive and passionate to productively complete the hose modeling and routing project funded by DaimlerChrysler, which served as the basis for this thesis.

Finally, I want to devote this work to my parents. It is their endless love that made me what I am today. Thank you, Mom and Dad.

Ankit Kapoor
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CHAPTER I

INTRODUCTION

Problems in designing flexible components

Flexible components such as hoses are necessary for safe operation of any vehicle in the automotive or aerospace industry. These components are subject to large elastic deformation and potential collisions with other components in a mechanical system. However, flexible component geometry is difficult to model in solids. Because of this difficulty flexible elements are often designed late in a vehicle development cycle. This can delay shipment.

Design problems center around modeling in solids, physical data, and validation.

Modeling in solids

Various commercial computer aided design (CAD) and computer aided engineering (CAE) packages are available for design of these flexible models. For example, SDRC offers an I-DEAS module for design of a wire harness, cables and hoses called I-DEAS Harness Design™, and Parametric Technology provides a Pro/Engineer module called Pro/Piping. CATIA V4 3D Tubing Design (TU3) also provides a route in the CAD environment. However, none of the above CAD packages provide the actual configuration developed by flexible models on the basis of their actual properties.

Automotive designers rely primarily on physical mock-ups to finalize the
hose placement, an extremely costly process due to the time and material involved in making the prototype. Placing a hose into a suspension system, then observing what the hose may interfere with as the suspension is moved. If interference is detected between the hose and its environment, the brake system designers remove the hose and fabricate a new hose to avoid the interfering area. This process is repeated until all areas of interference are eliminated, a time consuming and costly method.

**Physical property data**

Keil (2002) and Chipperfield (2002) discuss the problem of getting the actual test data for the flexural properties of flexible components, especially hoses. Previous work done at Western Michigan University on the mechanical properties (Keil 2002) found the torsional stiffness and effective bending modulus. The author tested the torsional stiffness of a hose by passing a thin wire of low torsional stiffness though the hose to relieve any axial load, and a plate that was subjected to oscillation on its natural frequency. The effective bending modulus was found in the same study by mounting a length of actual model on a cantilever and measuring its deflection under its own weight. This testing gave an estimate of torsional and bending stiffness for beams using linear theory.

**Validation technique**

In a previous effort to compare the results from the beam model measurements were taken on a hose mounted in a vehicle (Keil & Rodríguez, 2002). Keil & Rodríguez, (2002) pointed out that deviations from the test could be due to various sources: the usage of a contact measurement device, and the difficulty in accessing points being measured. In another attempt a non-contact measurement
device was used to take digital scans of the actual hose (Kapoor et al., 2003). This
digital scan provided a point cloud of the hose surface, which could be qualitatively
compared to the model. A method was needed to find the actual center of the hose
with greater precision.

Previous modeling techniques

Various approaches have been identified in the past for modeling flexible
elements, such as the usage of beam elements and virtual reality.

Beam modeling

Sugiyama and Otaki (1992) of Yamaha Motor Company proposed a
mathematical model for brake hose layout. The model used small beams with point
masses to model a discrete approximation of the entire brake hose. Sugiyama and
Otaki (1992) have assumed that a brake hose can be modeled as a series of particles
that are connected by small elastic beams. The final shape of the brake hose is
determined by solving equations of static force equilibrium. The authors have based
the equilibrium condition to be dependent on the initial conditions, such that a good
initial condition tends to give a rapid solution. Linear beam theory uses the heuristic
of limiting beam deflection to 10% of an individual beam’s length. It has been noted
that the number of beam elements must increase as deflection of a beam structure
becomes large, in order to maintain local linearity.

Michael Bell created a website in 1998 which outlined an immersive virtual
environment tool that could be used for hose modeling. The website can be navigated
to research the potential concepts in defining and manipulating hose, such as the use
of point masses and springs.
Beam elements were used to establish elasticity, and short cylinders were used to establish discrete mass properties to study the effects of pressure and temperature of bend, twist, and buckling response for one type of hydraulic hose. Combined stiffness properties were developed to control elastic response of elements (Elliot, 1996).

Rodriguez and Keil (2001) have identified the usage of three-dimensional cubic Spline in combination with discrete flexible links for an adequate solid representation of these flexible elements in a CAD environment. The authors have identified that the software tool should be able to predict the position and motion of these flexible components as connection and mounting points are moved and accelerated.

Chipperfield and Vance (2002) proposed a method to model hydraulic hose paths. The tests were verified for pure bending. Moreover, the authors indicate that an initial guess needs to be given for the path the hose might take when assembled.

In 2002, Keil and Rodriguez gave a modeling methodology with the usage of linear beams to aid in routing and predicting movement of brake hoses with the objective of having an adequate representation in a CAD system for virtual prototyping. Once the mount points and orientation were identified, material properties and length were used to determine the path of the hose. However, the authors have pointed out that more research needs to be done for actual prediction of the hose paths.

Virtual reality approach for modeling

Research at Iowa State University (Chipperfield, Fischer & Vance 2002) has shown a hose routing method in the virtual reality environment called VRHOSE. The
system uses a head mounted display along with position sensitive wands and gloves to create hose models in an immersive three-dimensional virtual environment. Hose geometry is generated through the use of B-Spline curves. Chipperfield et al., 2002 state a need to include information on the physical properties of hoses, as well as a need for collision detection. The authors used a human factors software package for placing digital humans, after which a particular type and size of hose and connectors are selected from a directory. Hose route paths are then defined by specifying a series of points in space.

**Scope and objective of the research**

This work builds on the technique, which used beam elements to connect discrete masses. Figure 1 shows the comparison of the beam model with the digital scan of the actual hose.

![Figure 1 A flexible model using beam elements](image)
The usage of beam elements along with discrete elements was not sufficient for adding fidelity to flexible elements modeling. Due to which there is much left to do in achieving a satisfactory modeling technique, finding a proper validation technique, and identifying the properties of flexible elements.

This thesis describes a method to improve the geometric fidelity of flexible element models. Off-axis bi-linear stiffeners were incorporated into discrete linear beams model (developed by Rodriguez and Keil in 2002).

The objectives of this work were as follows:

1. Augment the previous beam flexible elements model with off-axis stiffeners (springs).
2. Validate the Off-Axis Spring Model.
3. Refine the Off-Axis Spring Model by changing the stiffness properties of the stiffeners, the angle at which stiffeners are placed, the stiffness ratio of beams used to connect 2 adjacent discrete elements, and the number of discrete elements.
CHAPTER II

PROCEDURE

Modeling of flexible elements

The model presented in this thesis was an improvement to the linear beam model developed by Keil and Rodriguez (2002). A brief outline to how the linear beam model was modeled has been outlined in Appendix.

Augmentation of Off-Axis Spring Elements to the beam model

Incorporating stiffeners to the model developed by Keil and Rodriguez (2002), which consisted of linear beam elements, was used as a means of improving the fidelity. A spring represents forces acting between two parts over a distance and along a particular direction. It applies the action force to the first part selected, called the action body, and applies an equal and opposite reaction force along the line of sight to the second part selected, called the reaction body (MSC Software 2003).

The end points of the spring on two parts were specified so as to model the strands in the inner core of the hose, which were approximately 33% less than the hose radius. The end points of the springs were made at this reduced radius, and lying on the center of mass plane of the discrete element (Figure 2). Figure 3 shows this setup in the top view.
Figure 2 A typical spring setup

Figure 3 Top view of the connection of one spring between two adjacent elements
The definition of the off-axis spring model begins by finding the discrete element length. Because of this the length of the flexible model (L) and the number of equally sized discrete elements (N) need to be defined in the Off-Axis Spring Model. The size of each discrete element (Ld) is calculated by dividing the length of the flexible model and the number of discrete elements being used, after which the angle at which the springs need to be placed on the center of mass plane of each element is defined (θ). Springs are placed at a radius about 33% less than the hose radius (Rh). This radius is defined as (Rs). The true length of the spring is seen in the side view along the axis of the spring. The length of spring as seen from its top view (Lt) was calculated from the size of each discrete element (Ld).

16 springs were modeled to form a circular pattern (Figure 4). Therefore the objective was to define the uniform positioning of 16 springs. Thus if 16 end points of springs were to be defined uniformly on the periphery of a circle, each sector of 45
degrees could have 2 markers. This would result in 8 equal sectors of 45 degrees. This enlarged view of one of the sectors can also be seen in Figure 5. Distance between “O” and marker “1” location is the radius at which the springs are placed (Rs). Thus, by knowing the spring placement distance and the length of the spring as seen in the top view angle, β can be calculated (Equation 8), after which the angle (α) between one of the edges of the sector and the line joining “O” and marker “1” location is calculated (Equation 9). This angle α is used to find the X and Y coordinates for all the marker locations (Equations 10-17).

The formulas used for placing the markers on a particular discrete element are:

Length of flexible model = L

Number of discrete elements = N

Hose radius = Rh

Spring Angle = θ

Size of each discrete element (L_d) = \( \frac{L}{N} \)

Length of spring in top view (L_t) = \( \frac{L_d}{\tan[(180 \times θ) / Π]} \)

Radius of spring placement (Rs) = \( \frac{R_h}{1.5} \)

\[ \beta = \sin^{-1} \left[ \left( \frac{L_t}{2Rs} \right) \times \left( \frac{180}{Π} \right) \right] \]

\[ α = \frac{45 - 2β}{2} \]

Marker 1 X Coordinate = \( \sin \left( 360 - \frac{α \times Π}{180} \right) \times \frac{R_h}{1.5} \)

Marker 1 Y Coordinate = \( \cos \left( 360 - \frac{α \times Π}{180} \right) \times \frac{R_h}{1.5} \)

Marker 2 X Coordinate = \( \sin \left( 45 - \frac{α \times Π}{180} \right) \times \frac{R_h}{1.5} \)
Marker 3 X Coordinate = $\sin\left(45 + \frac{\alpha \times \pi}{180}\right) \times \frac{R_h}{1.5}$  \hspace{1cm} (1)

Marker 3 Y Coordinate = $\sin\left(45 + \frac{\alpha \times \pi}{180}\right) \times \frac{R_h}{1.5}$  \hspace{1cm} (2)

Marker 4 X Coordinate = $\sin\left(90 - \frac{\alpha \times \pi}{180}\right) \times \frac{R_h}{1.5}$  \hspace{1cm} (3)

Marker 4 Y Coordinate = $\sin\left(90 - \frac{\alpha \times \pi}{180}\right) \times \frac{R_h}{1.5}$  \hspace{1cm} (4)

This cyclic method is repeated to get the X and Y coordinates for the markers in the other sectors.

Figure 1 Marker positioning setup
Method used to validate the Off-Axis Spring Model

Digital scans were taken for two states (Figure 6): A $0^\circ$ twist state and a state where one end was twisted $180^\circ$.

![Digital scans for the $0^\circ$ and $180^\circ$ twist states](image)

Finding the center of the digital scan

The digital scan from this optical measuring system was seen to have geometric dropouts. However, this scan was complete enough to provide a reasonable comparison of resulting positions between the Off-Axis Spring Model and the scan for both the above states, i.e., initial no twist state and the $180^\circ$ twist state.

This scan provided data for the periphery of the actual hose, for which the ATOS software was used to find its center. Initially a visual inspection was performed to select sections for both the initial no twist state and the $180^\circ$ twist case,
such that they have the maximum deviation from the digital scan and the Off-Axis Spring Model. Small sections of the actual hose were selected in the digital scan to minimize distortion from the curvature. These sections can be seen in Figures 7 & 8.

A best-fit cylinder is made from the create primitives menu in the ATOS processing software. From these cylinders, the center point on the axis was found by taking the mid point of the two end points. These mid points provided the X, Y, and Z coordinates for each location used for validation purpose for the model developed in this thesis (Table 1). These mid points provided the center of mass location for the actual hose. This process was carried out for the three locations (1, 2, 3) that was seen to have the maximum deviation for the 0\(^0\) twist state (Figure 7), while for the 180\(^0\) twist at one end, the three locations (4, 5, 6) were identified having the maximum deviation (Figure 8).
Measuring the deviation from the digital scan and the Off-Axis Spring Model

Once the three locations used for validation for both the $180^0$ twist and $0^0$ twist state were identified, the Off-Axis Spring Model was checked for deviations from this digital scan. Center of mass positions of each discrete element at these static positions of $0^0$ and $180^0$ twist states were later exported to CAD software. These center of mass points were then connected with a cubic spline. The locations used for validation were then entered into this CAD file. The shortest distance was measured between the center of mass points of the scan (locations used of validation) and the Spline joining the center of mass locations of the Off-Axis Spring Model. An example for the deviations between the Off-Axis Spring Model and digital scan are
noted in Figures 9 and 10 for the $0^\circ$ twist state, and $180^\circ$ twist state respectively.
Refining the Off-Axis Spring Model.

The effect of several variables was studied in regard to their effect on the position of the model. They were:

A. Stiffness properties of beams used in the flexible model.
B. Combined response of number of discrete elements and spring angle.
C. Stiffness property of the stiffeners (springs) / Spline definition.

Stiffness properties of flexible models

In the model developed in this thesis, beams connect two adjacent discrete elements. The attachment points of these beams are the center of mass markers of each discrete element (Appendix). The beams transmit force and torque between the two connecting elements in accordance with Timoshenko beam theory. Torsional stiffness of beams ($K_t$) is related to the polar moment of inertia ($J$) and the shear modulus of elasticity ($G$). This is shown in Equation 18.

\[
K_t = \frac{GJ}{L}
\]  

The effect of changing the torsional stiffness ratio of beams was studied in the model developed by Rodriguez and Keil (2001).

Combined response of number of discrete elements and spring angle

The size of discrete elements and the angle at which stiffeners are placed between adjacent discrete elements was studied. The size of each discrete element can
change by changing the number of discrete elements required to model, and keeping the length of flexible model constant. For example if flexible model length of 330.824 was divided into 55 elements, the size of each discrete element would be 330.824/55 = 6.01498mm, whereas if it was divided into 40 elements, the size of each discrete element would be 8.2706 mm.

Initially 100 numbers of elements or element size of 3.30824mm was chosen, but the model would not run. Due to which it was reduced to a little less than 50% in its size to 40 elements. Also the spring angle was changed from 55°. It was seen when this spring angle was changed to 70° from 55° the deviation from the digital scan and the Off-Axis Spring Model reduced considerably. After which the effect of changing the element size and the spring angle, individually and in a combination, was studied to see their effect on the deviation from the digital scan.

Properties of the stiffeners (springs) / Spline function definition

Springs (MSC Software) are defined by a spring constant \( k \) and a preload \( F_o \) at installed length \( L_i \), or a free length \( L_i = L_o \) where the preload \( F_o = 0 \). In this case the force would be \( F = -k * (L - L_i) + F_o \).

After defining the spring placements, the objective was to define the stiffness properties of the springs. A Spline function was used to model this stiffness property of springs. Splining (MSC Software) is a method of interpolation that allows derivation of intermediate locations on a curve or surface between known points. The independent variable is the deformation, while the dependent variable is the force value being defined for the springs (Table 2).
<table>
<thead>
<tr>
<th>Deformation in mm (Independent variable)</th>
<th>Force in N (Dependent variable)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-140</td>
</tr>
<tr>
<td>-0.5</td>
<td>-130</td>
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<td>-0.4</td>
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</tr>
<tr>
<td>0.4</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 2 A typical Spline definition

Initially when defining the deformation and force column as seen in Table 2, four steps were taken in defining the Spline function controlling the stiffness of springs for 40 discrete elements.

Step 1: Identify the elements on the Off-Axis Spring Model that has the highest bend curvature at the simulated position.

Elements that had the highest bend curvature were identified. This was done by connecting the center of mass positions of the Off-Axis Spring Model at the simulated positions for both the cases $0^0$ and $180^0$ twist state by a Spline curve and using a curvature magnitude plot and curvature along length plot (where length was
normalized to 1) to identify this region using a CAD software. This is more clearly shown in Figures 11 and 12.

Elements having the highest bend curvature were identified from these curvature plots. They were 39\textsuperscript{th} and 40\textsuperscript{th} element for the 0\textdegree twist state, while for the 180\textdegree state they were the 36\textsuperscript{th}, 37\textsuperscript{th} and 38\textsuperscript{th} elements. These elements on the Off-Axis Spring Model for both the states are in Figure 13 and 14.
Figure 8 Identification of the highest curvature elements for the $0^\circ$ twist state

Figure 9 Identification of the highest curvature elements for the $180^\circ$ twist state

Step 2: Export the deformation values from ADAMS Postprocessor to a
spreadsheet for the springs attached with the identified elements having the highest bend curvature.

Once the elements associated with the highest curvature were identified, the deformation values of the springs attached with these elements were exported from ADAMS Postprocessor to a spreadsheet. This can be done using the file menu of the Postprocessor, which prompts to a dialog box for exporting results from the simulation to a spreadsheet. A typical dialog box can be seen in Figure 15. ADAMS tends to export this file in another extension (.tab), so in order to open this file in Windows Excel one has to change this extension to “.xls”.

![Dialog box for exporting deformation values](image)

**Figure 10** Dialog box used for exporting the deformation values of springs

**Step 3: Analyze the deformation values of the springs during the simulation.**

The deformations for these springs were later plotted in groups of 16, as 16 springs were used to connect between two adjacent discrete elements. Figures 16 through 18 show the deformation of the springs associated with each corresponding element with respect to time of the simulation. It can be seen from these figures that...
during the simulation, the springs on the top surface of the Off-Axis Spring Model, (the springs under tension) were seen to have a deformation in the range of 0mm to 0.4mm, while springs at the bottom surface (the springs under compression) were seen to have a deformation in the range of 0mm to –1.0mm. This led to defining the deformation column when defining the Spline function for 40 elements.

![Figure 11 Deformation of springs connecting between element 35 and 36](image1)

![Figure 12 Deformation of springs connecting between element 36 and 37](image2)
Step 4: Analyze the force column of the Spline function.

The initial values defined in the force column were adjusted for deformations ranging from –0.6mm to 0.35mm to minimize deviations between the model and the scan for the 0° twist position.

The end values defined in the force column for its tension was important to minimize the deviations between the model and the scan for the 180° twist position. The significance of defining this end point can be seen in Figure 20.

A typical Spline curve, which is applied to control the stiffness properties of the springs for 40 elements, is shown in Figure 19. The Spline curve was later generalized for different sizes of discrete elements.
Figure 14 A typical Spline curve

Figure 15 Importance of the critical point
CHAPTER III
RESULTS AND DISCUSSIONS

Off-axis springs were introduced to the beam model and various variables were studied regarding their effect on the fidelity of the flexible model. The results and analysis for these identified variables are given below:

Stiffness properties of the stiffeners (springs)

The Spline function was generalized for different elements sizes by keeping the other variable, such as length of hose (330.824mm) and angle of spring (70\(^0\)) placement constant at their specified values. The dependent variable (force) was kept constant while the independent variable (deformation) was changed for tension and compression.

This process provided a restriction on the size of each discrete element used to generalize the Spline function for defining the stiffness. The size of the element varied between 5.90757 mm and 8.2706 mm, or a range of 40 to 56 for the number of elements. Table 3 shows the equations that the Spline function follows for changes made to the number and size of elements. This Spline generalization resulted in a deviation of less than 6mm when compared to the digital scan of the actual model for the 180\(^0\) twist state for any element size or number of elements in the range provided above.
<table>
<thead>
<tr>
<th>Deformation in mm</th>
<th>Force in N</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-140</td>
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<tr>
<td>(0.3*40/N)</td>
<td>200</td>
</tr>
<tr>
<td>(0.31*40/N)</td>
<td>201</td>
</tr>
<tr>
<td>(0.32*40/N)</td>
<td>202</td>
</tr>
<tr>
<td>(0.35*40/N)</td>
<td>203</td>
</tr>
<tr>
<td>(0.4*40/N)</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 3 Generalized Spline definition

Where:

N is the range of discrete element that can be used (40 ≤ N ≤ 56).

Example: When number of discrete elements used is 55, the Spline function changes as shown in Table 4.

When the element size was increased or decreased in a particular proportion, the independent variable (deformation) defining the stiffness in the Spline also changed in the same proportion (Table 5).
\begin{align*}
\text{Deformation in mm} & \quad \text{Force in N} \\
-(0.6 \times 40/55) &= -0.43636 \\
-(0.5 \times 40/55) &= -0.36364 \\
-(0.4 \times 40/55) &= -0.29091 \\
-(0.3 \times 40/55) &= -0.21818 \\
-(0.2 \times 40/55) &= -0.14545 \\
0 &= 0 \\
(0.2 \times 40/55) &= 0.14545 \\
(0.3 \times 40/55) &= 0.21818 \\
(0.31 \times 40/55) &= 0.22545 \\
(0.32 \times 40/55) &= 0.23273 \\
(0.35 \times 40/55) &= 0.25455 \\
(0.4 \times 40/55) &= 0.29091 \\
\end{align*}

Table 4: Spline function for a hose length of 330.824 mm with 55 equal discrete elements

\begin{center}
\begin{tabular}{ccccccc}
40 & 43 & 45 & 50 & 55 & 56 & Number of elements \\
- & 0.93023 & 0.88889 & 0.80000 & 0.72727 & 0.71429 & Proportion \\
\end{tabular}
\end{center}

\begin{center}
\begin{tabular}{cccccccc}
Deformation in mm & Force in N \\
\hline
-0.60000 & -0.55814 & -0.53333 & -0.48000 & -0.43636 & -0.42857 & -140 \\
-0.50000 & -0.46512 & -0.44444 & -0.40000 & -0.36364 & -0.35714 & -130 \\
-0.40000 & -0.37209 & -0.35556 & -0.32000 & -0.29091 & -0.28571 & -120 \\
-0.30000 & -0.27907 & -0.26667 & -0.24000 & -0.21818 & -0.21429 & -110 \\
-0.20000 & -0.18605 & -0.17778 & -0.16000 & -0.14545 & -0.14286 & -100 \\
0.00000 & 0.00000 & 0.00000 & 0.00000 & 0.00000 & 0.00000 & 0 \\
0.20000 & 0.18605 & 0.17778 & 0.16000 & 0.14545 & 0.14286 & 50 \\
0.30000 & 0.27907 & 0.26667 & 0.24000 & 0.21818 & 0.21429 & 200 \\
0.31000 & 0.28837 & 0.27556 & 0.24800 & 0.22545 & 0.22143 & 201 \\
0.32000 & 0.29767 & 0.28444 & 0.25600 & 0.23273 & 0.22857 & 202 \\
0.35000 & 0.32558 & 0.31111 & 0.28000 & 0.25455 & 0.25000 & 203 \\
0.40000 & 0.37209 & 0.35556 & 0.32000 & 0.29091 & 0.28571 & 3000 \\
\end{tabular}
\end{center}

Table 5: Proportion for change in stiffness with discrete element size

It can be calculated from the Table 5 above that for change in element size, when 45 elements are used instead of 40, the proportional change = 7.35164/8.27060 = 0.88889. This proportional change is the same as change in deformation in the Spline function, i.e. = -0.5333/-0.6 = 0.88889.
Size and number of discrete elements

The larger the number of discrete elements, the smoother the motion of the simulated part appeared. However, a balance needs to be established between the number of these elements and the smoothness desired. This balance is necessary because by using more elements, the simulation time increases drastically, and will reach a stage when the software cannot simulate for more segments of discrete elements.

There was a limitation of the software to simulate more than 68 elements when stiffeners are used. The effect of changing the number of elements was studied while keeping the other variables such as length of hose (330.824mm), and spring angle ($70^\circ$) constant. The spring angle was set at this value as in the range of spring angle variation (explained in next section) this angle had the highest deviation.

It was seen that, when springs were incorporated into the linear beam model developed Rodriguez & Keil (2002), the deviation from the scanned data decreased to a value of 5.26mm. This value was rounded to the next higher integer (6mm) and was used as the upper limit for accepting other configurations.

The Spline function controlling the stiffness properties of the springs was accordingly adjusted using equations in Table 4 when changing the number of elements between 40 and 68 elements. The highest deviation was recorded from the 3 locations used for validation for each configuration of the number of elements (Table 6). It can be seen from this Table 6 that when the number of elements was increased from 57 to 68 the deviation increased to a value greater than 6mm. As shown in Figure 21, for a range of number of elements 40 to 56, the deviation from the digital scan and the Off-Axis Spring Model is less than 6 mm. By dividing this range of number of elements by the length of the flexible model, a range for the size of each
A discrete element was found to be 5.90757 mm to 8.2706 mm. By knowing the upper limit of the size of discrete elements for deviations less than 6 mm and the upper limit of number of discrete elements that can simulate, the maximum length of flexible model that can be modeled is 562 mm.

<table>
<thead>
<tr>
<th>Nos. of elements</th>
<th>Location 4</th>
<th>Location 5</th>
<th>Location 6</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>4.218</td>
<td>3.784</td>
<td>5.269</td>
<td>5.269</td>
</tr>
<tr>
<td>43</td>
<td>4.61</td>
<td>4.017</td>
<td>5.345</td>
<td>5.345</td>
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<tr>
<td>45</td>
<td>4.855</td>
<td>4.17</td>
<td>5.422</td>
<td>5.422</td>
</tr>
<tr>
<td>50</td>
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<td>4.511</td>
<td>5.604</td>
<td>5.604</td>
</tr>
<tr>
<td>55</td>
<td>5.859</td>
<td>4.889</td>
<td>5.833</td>
<td>5.859</td>
</tr>
<tr>
<td>56</td>
<td>5.941</td>
<td>4.951</td>
<td>5.911</td>
<td>5.941</td>
</tr>
<tr>
<td>57</td>
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<td>5.016</td>
<td>5.946</td>
<td>6.022</td>
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<td>6.201</td>
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<td>6.263</td>
</tr>
<tr>
<td>65</td>
<td>6.303</td>
<td>5.479</td>
<td>6.613</td>
<td>6.613</td>
</tr>
<tr>
<td>68</td>
<td>6.41</td>
<td>5.633</td>
<td>6.807</td>
<td>6.807</td>
</tr>
</tbody>
</table>

Table 6 Deviation in mm from the center of mass of the digital scan and the Off-Axis Spring Model when changing the number of elements independently

![Variation of Number of Elements](image)

Figure 16 Number of elements variation
Spring angle

The use of stiffeners (springs) improves the fidelity of the Off-Axis Spring Model. The angle of these springs was found to be important.

The effect of changing this angle was studied while keeping the other variables such as length of hose (330.824mm), number of elements (56 elements), and stiffness properties of spring (for a specified element size of 56 elements) constant.

The deviation from the actual model was compared for each angle change studied. The Off-Axis Spring Model was validated using the 3 locations having the maximum deviations. Angle was varied from 55° to 90°. For each angle change the location having the highest deviation was recorded to get a deviation plot (Table 7). Figure 22 shows for a range of spring angle 70° to 83° the deviation of the digital scan and the Off-Axis Spring Model is less than 6 mm. It can also be seen that this deviation reduces considerably when the spring angle varies from 55° to 70°. The maximum deviation at spring angle (55°) was very high at 25.974mm because of which a lower value of spring angle was not considered for analysis.

<table>
<thead>
<tr>
<th>Spring Angle in degrees</th>
<th>Deviations from digital scan for the 180° twist state (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location 4</td>
</tr>
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<td>55°</td>
<td>7.965</td>
</tr>
<tr>
<td>65°</td>
<td>8.55</td>
</tr>
<tr>
<td>69°</td>
<td>6.302</td>
</tr>
<tr>
<td>70°</td>
<td>5.941</td>
</tr>
<tr>
<td>71°</td>
<td>5.846</td>
</tr>
<tr>
<td>72°</td>
<td>5.773</td>
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<td>73°</td>
<td>5.716</td>
</tr>
<tr>
<td>74°</td>
<td>5.678</td>
</tr>
<tr>
<td>75°</td>
<td>5.663</td>
</tr>
<tr>
<td>76°</td>
<td>3.895</td>
</tr>
<tr>
<td>80°</td>
<td>3.184</td>
</tr>
<tr>
<td>83°</td>
<td>2.749</td>
</tr>
<tr>
<td>84°</td>
<td>2.615</td>
</tr>
<tr>
<td>85°</td>
<td>2.493</td>
</tr>
<tr>
<td>90°</td>
<td>2.489</td>
</tr>
</tbody>
</table>

Table 7 Deviation in mm from the digital scan and Off-Axis Spring Model when changing spring angle independently
Simultaneous change of the number of discrete elements and spring angles

When the numbers of discrete elements were changed individually for a range of 40 to 56 elements the deviation from the Off-Axis Spring Model and the digital scan was less than 6mm. Similarly by individually changing the spring angle between $70^0$ and $83^0$ this deviation was less than 6mm. A response was studied when these 2 variables (number of elements and spring angle) were changed collectively.

The highest deviation was recorded from the Off-Axis Spring Model and the digital scan for each combination of change in spring angle and number of elements. This was done to create a response curve for both the states: $0^0$ and $180^0$ twist states. Figure 23 shows the response curve for the $180^0$ twist state, while Figure 24 shows the response curve for the $0^0$ twist state.

Table 8 shows for the $180^0$ twist state, as the number of elements reduces the
deviations reduce considerably. It can also be seen that when the number of elements is increased to 57 elements from 56 elements, there is a considerable increase in the deviations from the Off-Axis Spring Model and the digital scan. Also it can be seen from this table that when the spring angle defined is less than $69^0$ once again the deviations tend to increase.

Table 9 shows for the $0^0$ twist state, as the number of elements increases the deviations reduce considerably. It can also be seen that when the number of elements is reduced to 39 elements from 40 elements, there is a considerable increase in the deviations from the Off-Axis Spring Model and the digital scan. Also it can be seen from this table that when the spring angle is less than $70^0$ and greater than $83^0$, once again the deviations tend to increase.

![Deviation from the digital scan (in mm) for various combination of number of elements and spring angle.](image)

**Figure 18 Response curve for the 180° twist state**
Figure 19 Response curve for the 0° twist state

Table 8 Deviation from the digital scan and Off-Axis Spring Model for combination of number of elements and spring angle for the 180° twist state
Table 9 Deviation from the digital scan and Off-Axis Spring Model for the 0° twist state

<table>
<thead>
<tr>
<th>Number of elements</th>
<th>Location</th>
<th>Spring Angle (in degrees)</th>
<th>60°</th>
<th>70°</th>
<th>71°</th>
<th>72°</th>
<th>73°</th>
<th>74°</th>
<th>75°</th>
<th>80°</th>
<th>83°</th>
<th>84°</th>
<th>85°</th>
</tr>
</thead>
<tbody>
<tr>
<td>39 elements</td>
<td>1</td>
<td>0.21</td>
<td>0.178</td>
<td>0.221</td>
<td>0.248</td>
<td>0.249</td>
<td>0.221</td>
<td>0.116</td>
<td>0.118</td>
<td>0.115</td>
<td>0.127</td>
<td>0.218</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.341</td>
<td>0.349</td>
<td>0.461</td>
<td>0.478</td>
<td>0.498</td>
<td>0.512</td>
<td>0.521</td>
<td>0.531</td>
<td>0.601</td>
<td>0.621</td>
<td>0.628</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>1.589</td>
<td>1.523</td>
<td>1.512</td>
<td>1.535</td>
<td>1.539</td>
<td>1.542</td>
<td>1.546</td>
<td>1.567</td>
<td>1.578</td>
<td>1.601</td>
<td>1.612</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td>1.589</td>
<td>1.523</td>
<td>1.535</td>
<td>1.539</td>
<td>1.542</td>
<td>1.546</td>
<td>1.567</td>
<td>1.578</td>
<td>1.601</td>
<td>1.612</td>
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<td>40 elements</td>
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<td>0.154</td>
<td>0.154</td>
<td>0.992</td>
<td>-</td>
<td>-</td>
<td>0.103</td>
<td>1.049</td>
<td>0.96</td>
<td>0.929</td>
<td>0.898</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>0.922</td>
<td>0.339</td>
<td>0.339</td>
<td>0.361</td>
<td>-</td>
<td>-</td>
<td>0.457</td>
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<td>0.513</td>
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<td>-</td>
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<td>1.312</td>
<td>0.992</td>
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<td>-</td>
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<td>-</td>
<td>1.057</td>
<td>1.033</td>
<td>0.924</td>
<td>0.852</td>
<td>-</td>
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<tr>
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<td></td>
<td>1.485</td>
<td>1.136</td>
<td>1.125</td>
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<td>-</td>
<td>1.057</td>
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<td>0.943</td>
<td>-</td>
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<td>0.336</td>
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<td>-</td>
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<td>0.974</td>
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<td>0.504</td>
<td>0.506</td>
<td>0.511</td>
<td></td>
</tr>
</tbody>
</table>

Stiffness properties of flexible models

In the Off-Axis Spring Model, beams play a vital role in transmitting force and torque between the two center of mass positions of the connecting discrete elements. It can be seen from Equation 18 that torsional stiffness is directly proportional to the polar moment of inertia (J). It was seen that when the torsional stiffness ratio of beams were changed in a different proportion by increasing the polar moment of inertia, there was a significant reduction in the deviation from the digital scan and the Off-Axis Spring Model. The initial torsional stiffness ratio used for the beams was 7.24. There was a significant change made when springs were used, and this ratio was changed to about 15.
The highest deviation from the 3 locations for each configuration of the number of elements was recorded in order to plot the range of the number of elements that have a deviation of less than 6 mm. Table 10 shows the deviations from the digital scan for the $180^0$ twist state. It can be seen from this table that for the initial Off-Axis Spring Model developed by Rodriguez and Keil (shown as initial beam stiffness ratio at 7.24-without springs), the maximum deviation for the $180^0$ twist state from the digital scan was 15.837 mm when springs were not used. When springs were used in the same model, the deviation was 26.163 mm. However, without springs, when the proportion between the beam stiffness ratio was changed to 15 the deviations were still very high at 26.163 mm, but with the usage of springs and for a changed stiffness ratio model the deviation was considerably reduced to 3.938 mm. The springs used in this model are placed at spring angle $72^0$ and 40 discrete elements have been used. The effect of changing this stiffness ratio of the beams has on the deviation when springs are added to the Off-Axis Spring Model is shown in Figure 25 & 26. The effect of adding springs to the changes made in the stiffness ratio of then beams when the 2 models have been merged together is shown in Figure 27.

<table>
<thead>
<tr>
<th>Deviations from digital scan (in mm)</th>
<th>Location 4</th>
<th>Location 5</th>
<th>Location 6</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial beam stiffness ratio at 7.24 times (without springs)</td>
<td>4.974</td>
<td>10.152</td>
<td>15.837</td>
<td>15.837</td>
</tr>
<tr>
<td>Initial beam stiffness ratio at 7.24 times (with springs)</td>
<td>15.868</td>
<td>26.163</td>
<td>24.458</td>
<td>26.163</td>
</tr>
<tr>
<td>Changed beam stiffness ratio at 15 times (without springs)</td>
<td>22.941</td>
<td>17.189</td>
<td>15.933</td>
<td>22.941</td>
</tr>
<tr>
<td>Initial beam stiffness ratio at 15 times (with springs)</td>
<td>3.311</td>
<td>2.936</td>
<td>3.938</td>
<td>3.938</td>
</tr>
</tbody>
</table>

Table 10 Deviations for various cases of changes on stiffness properties of flexible model
Figure 20 Using initial beam stiffness ratio of 7.24 (without using springs)

Figure 21 Changing the beam stiffness ratio to 15 (using springs)
Figure 22 Merged model of the effect of adding springs to Off-Axis Spring Model with changes made in the stiffness ratio of beams
CHAPTER IV
CONCLUSIONS AND FUTURE RECOMMENDATIONS

The addition of stiffeners (springs) clearly improved the Off-Axis Spring Model performance. Currently the modeling and simulation process with these stiffeners is very slow and tedious, but this technique is a very promising technique that has proven to be very effective in predicting static positions of hydraulic hoses.

Using a generalized Spline function, a range of number of elements (between 40 and 56) and a range of spring angle (between 70° and 83°) can be obtained in order to achieve a deviation of less than 6mm from the digital scan used for validation for a hose length of 330.824mm. Also, the range of the size of each discrete element that can be used is between 5.9075mm and 8.2706mm. There was a limitation of 68 elements to how many discrete elements can be used to simulate in ADAMS. This limitation is due to the high computation involved when each of these 68 elements was connected by a set of 16 springs (which led to having a total of 1088 springs), after which the Off-Axis Spring Model would not simulate. Using this technique, the length of flexible models, which could be modeled, had the upper limit at 562mm with a lower limit at 330.824mm.

A designer interested in modeling a hose length of 400mm, for example, can divide the length into a size that lies within the range of the size of elements. Therefore, if a discrete element size of 8mm is to be used the number of elements that can be used are $\frac{400}{8} = 50$ elements. Caution should be exercised such that the number of elements doesn’t exceed 68 elements, as beyond that it will not simulate in ADAMS.

This Off-Axis Spring Model was tested for 180° deflection. The range of the
number of elements and spring angle variation was built up on the worst-case situation, i.e., if any of the deviations from a location used for validation exceeded 6mm, that particular configuration was rejected. This provided a consistency in deciding their respective ranges. However, this extreme test inspired confidence in the technique.

Future work will address the speed of setting up these models, improving the simulation times, as well as testing for various other hose lengths and intermediate deflections. The use of forces instead of springs would allow for building larger models in ADAMS. This can considerably improve the simulation time for the model allowing for more spring to be added on the inner radius so that it more closely forms a circular pattern in order to model the inner stands of the hose. Also, in the future, more experiments can be performed on different kinds of hoses having different characteristics such as different hose diameter.
BIBLIOGRAPHY


   http://www.capture3d.com/

   ASME: 28th Design Engineering Technical Conference and Computers and
   Information in Engineering Conference, Montreal, Canada.

   routing in Virtual Reality with Jack™*, American Institute of Aeronautics and
   Astronautics.

   ASME: 28th Design Engineering Technical Conference and Computers and
   Information in Engineering Conference, Montreal, Canada.


   Dynamics, Inc. internal document.

   Element models with stiffeners for improved geometry fidelity*, Proceedings of
   the 8th Annual International Conference on Industrial Engineers- Theory,
   Application, and Practice, Las Vegas, Nevada, USA.

