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from: Adam Moya, 1522, MS0557

subject: Ganged Heliostat Modal Memo

1 INTRODUCTION

This memo documents the methodology and results from the modal tests conducted on the ganged heliostat prototype in April of 2016. Modal tests were conducted on the ganged heliostat prototype constructed at the National Solar Thermal Test Facility (NSTTF) to describe the structures dynamics and examine how the first few modes of vibration may be excited during wind events. This memo documents the experimental test setup and results including natural frequencies and damping estimates for each test conducted along with some preliminary wind excitation analysis.

2 EXECUTIVE SUMMARY

A total of six standard modal tests were conducted on the ganged heliostat. The heliostat is designed to operate in a number of orientations, and thus six scenarios were selected to be representative of an operational heliostat. The heliostat was oriented at a 0 degree (face up), 45 degree, and 90 degree orientations for the modal test configurations. The ganged heliostat design features a number of mirrors resting on two guide wires which can be tensioned and rotated to align with any given target. The prototype was tensioned to two different levels at the 3 orientations for the modal tests discussed in this memo. In addition to the modal tests, output only acceleration data was taken during wind events. These tests will be described in detail throughout this memo.

3 TEST ITEM DESCRIPTION

The ganged heliostat consists of 22 individual mirror facets fixed to small sections of PVC pipe. Two guide wires are strung through these individual pipe sections and allow for manipulation of the facets by controlling the tension and rotation of the wires at a support structure. These support structures consist of a wood and uni-strut assembly which are each weighed down with concrete and sandbags. Two linear actuators on either end of the heliostat control the rotation of the wires, while two different linear actuators control the tension in the wires. There is no measurement for the tension in the wires, and thus the low and high tension configuration mentioned in this memo are qualitative and kept constant by arbitrary marks on the linear actuator. The ganged heliostat is shown in Figure 1.

Figure 1: Ganged Heliostat Prototype

4 TEST SETUP

4.1 Boundary Conditions and Fixtures

The ganged heliostat does not have a traditional free-free nor a fixed base boundary condition as the installed prototype is not a final design thus the boundary condition can be considered “pseudo-fixed”. The supports on either ends are weighed down by concrete and sand bags which allow for a relatively accurate assumption that the ground is fixed. While this assumption is good for the purposes of this test, it is noted that it is very difficult if not theoretically impossible to obtain a true infinite stiffness “fixed” boundary condition as any structure or base will have some small compliance. Fixed base modal testing could be accomplished through specialized sub-structuring routines, however this is beyond the scope of this test.

The experimental test setup for acquiring the first fundamental modes of the structure includes a total of 20 PCB 356A33 100mV/g accelerometers glued to strategic mirror facets and on the wood support structures on either end. The accelerometers were glued to the mirror facets with super glue while using an intermediary layer of Kapton tape for protection of the mirror surface. Excitation for the stand-alone modal tests were performed using an instrumented modal hammer with a nominal sensitivity of 100 mV/lbf. It was found that the hammer was having trouble exciting the lower frequency modes of interest, so a square section of foam was taped to the hammer head. This “modal trick” helps to provide lower frequency energy needed to excite the modes of interest. The hammer and accelerometers used can be seen in Figure 2.

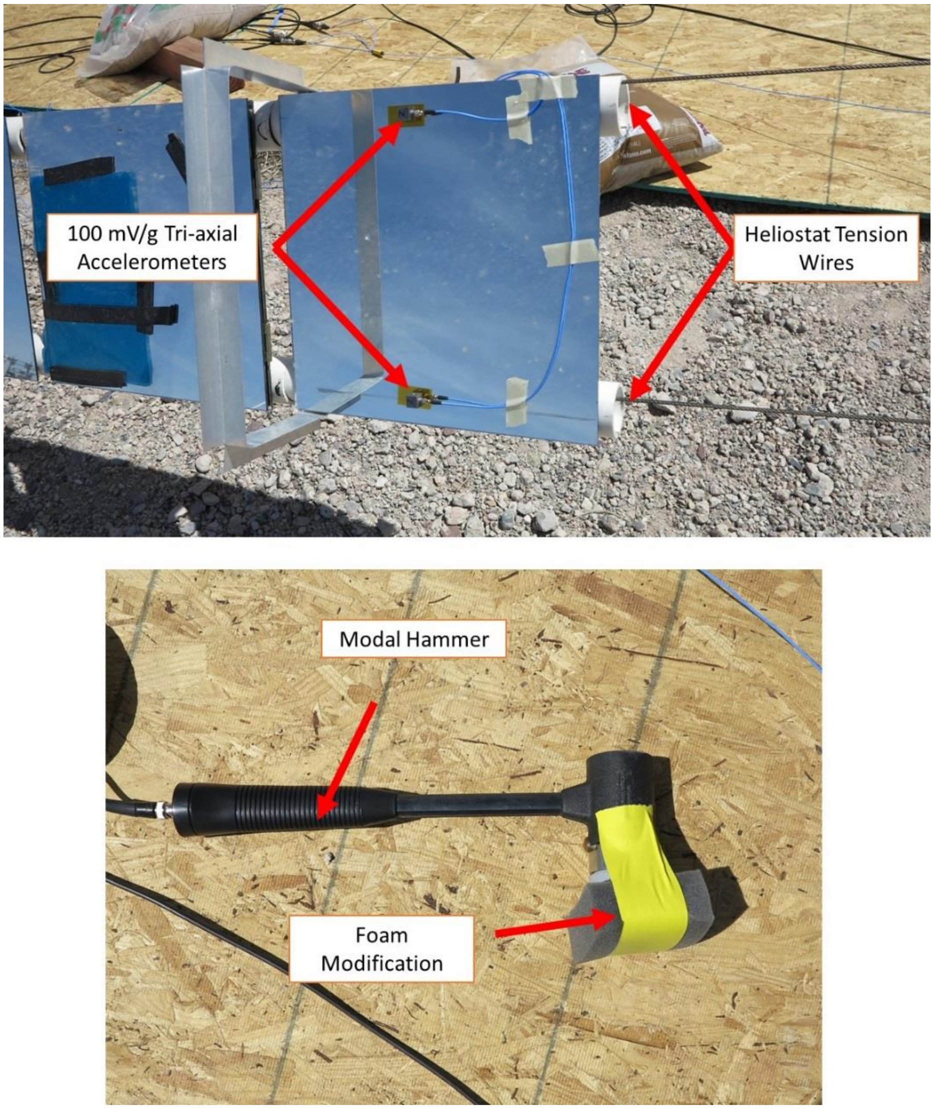

Figure 2: Experimental Setup

4.2 Coordinate System and Measurement Locations

As stated in the section above, the heliostat was instrumented with 20 total tri-axial accelerometers. 19 accelerometers were glued to the center top and bottom portion of the mirrors and labeled as nodes 101-109 and 201-209 as seen in Figure 3. In addition to these mirror locations, a single tri-axial accelerometer was glued to the wood supports on either end of the heliostat, i.e. nodes 301 and 302. It was found that force inputs on either side of the wood support provided good controllable excitation of the low frequency modes of interest and thus node 302 was used for a drive-point.

The number of channels recorded during wind events was down selected to include nodes of interest. The blue boxes around nodes 101, 201, 104, 204, 105, 205, 109, 209 represent the gauges recorded during the wind events presented in section 5.2. These locations were selected as the each node represent locations which have the largest acceleration during the low frequency modes found in the modal tests, and offer good spatial resolution for capturing wind excitation data.

The experimental geometry discussed here was recreated in Matlab for mode shape animation purposes. The modal geometry as seen in Figure 4 was created using cylindrical coordinates. The red lines represent the connections between instrumented mirror facets and the blue triangles are stationary supports used for visualization. The modal geometry is rotated using a simple transformation matrix for the 45 degree and 90 degree orientation and can be seen in the mode shapes shown in Appendix 1.

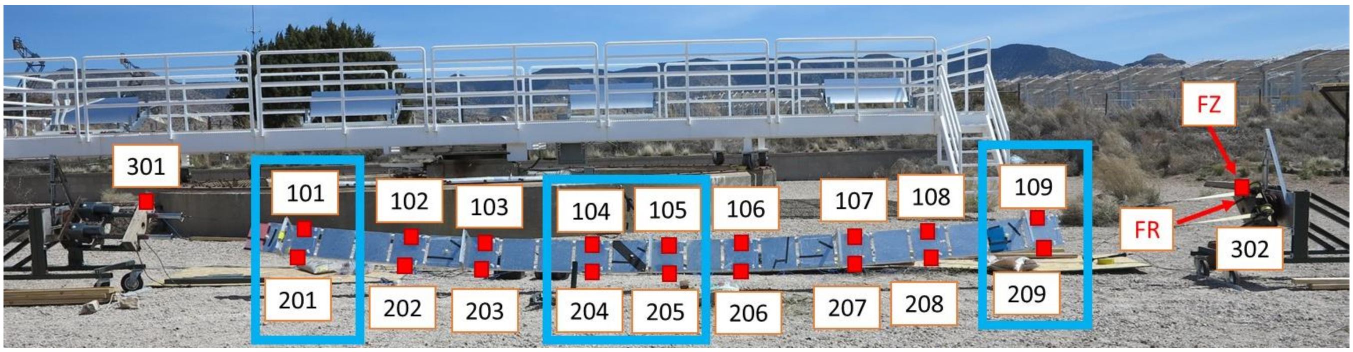

Figure 3: Accelerometer and Force Input Locations

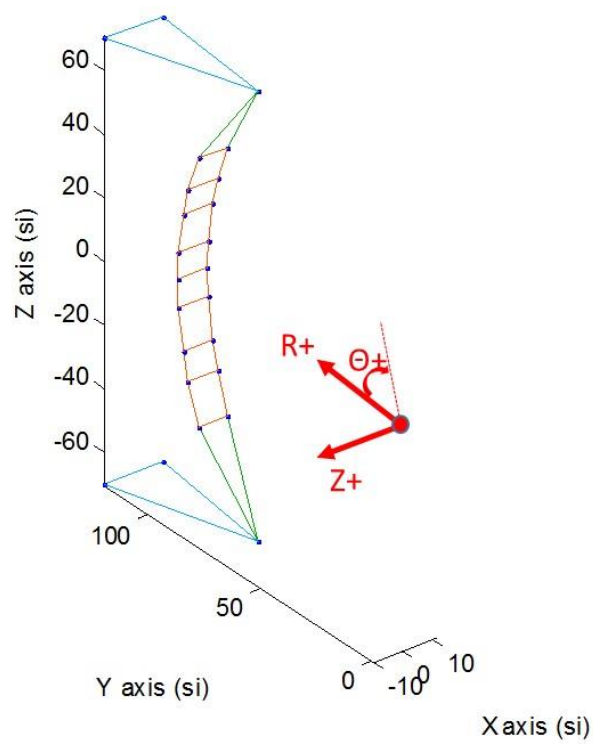

Figure 4: 0 Degree Orientation Modal Geometry

4.3 Hammer Inputs

Excitation was provided in both the radial and Z+ axis located at node 302. The force input was repeated five times in each orientation and averaged for the results presented. Further information and the data acquisition settings and uncertainties can be found in section 4.4. The force autospectra shown in Figure 5, Figure 6, and Figure 7 shows the hammer input properly excites the structure beyond the recorded bandwidth or 50 Hz, however the modes reported in this memo are all below 5 Hz. It is important to note the input autospectra dips at low frequencies which could cause erroneous peaks in the FRF. This is discussed further in section 7.

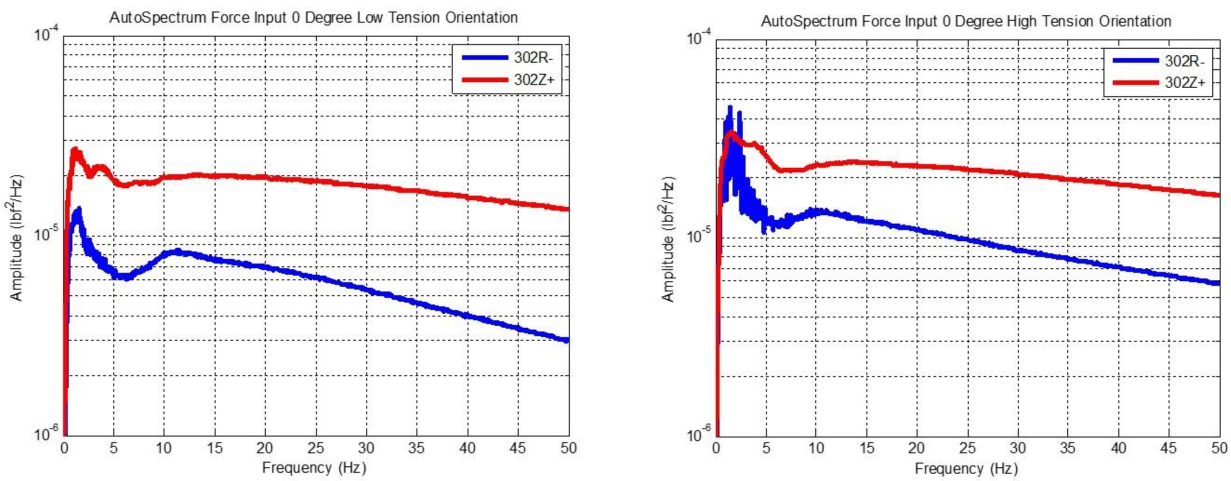

Figure 5: 0 Degree Orientation Low and High Tension Force AutoSpectra

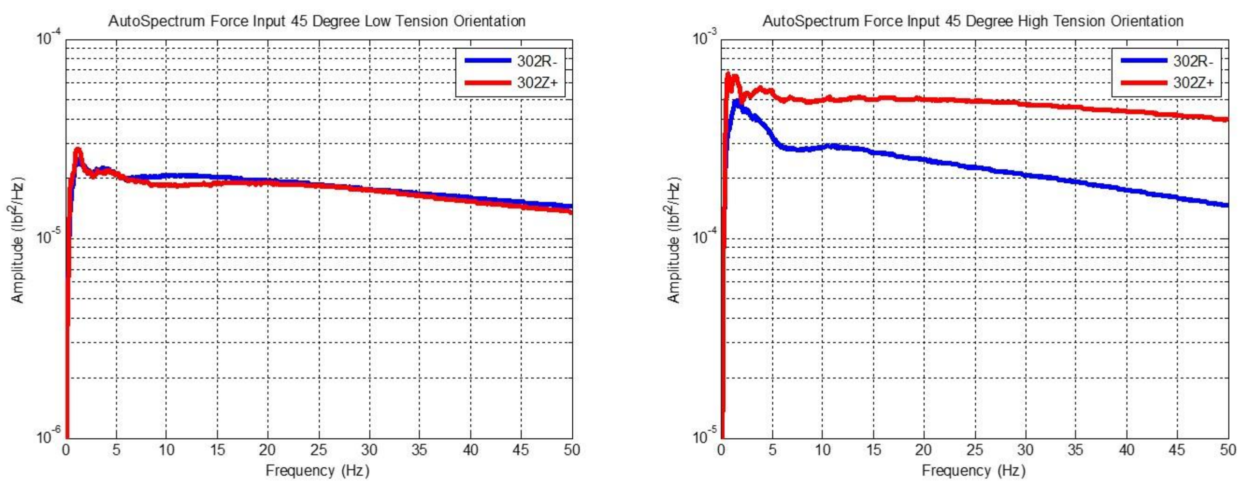

Figure 6: 45 Degree Orientation Low and High Tension Force AutoSpectra

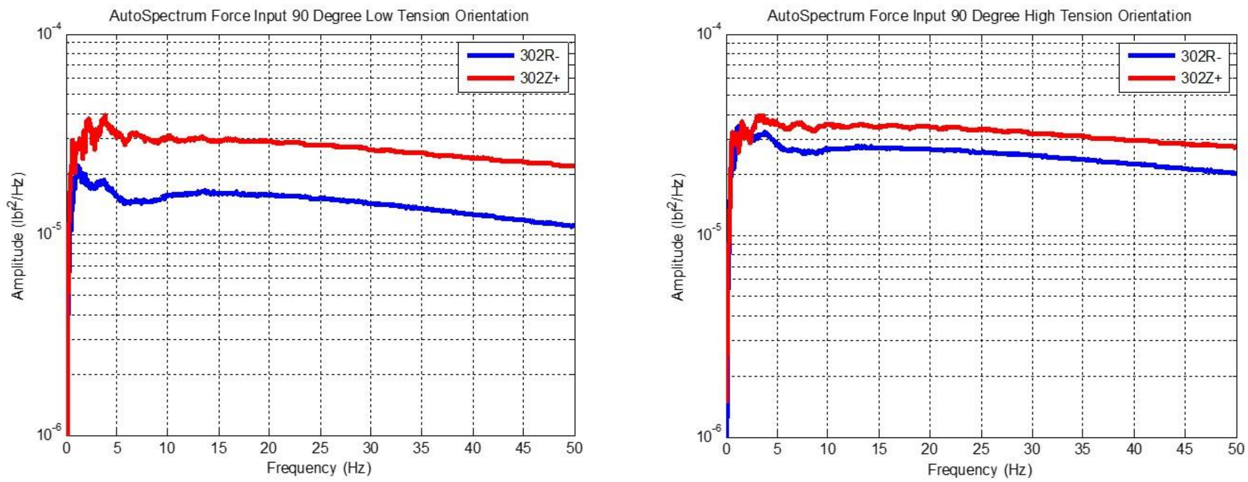

Figure 7: 90 Degree Orientation Low and High Tension Force AutoSpectra

4.4 DAQ Setup & Uncertainties

The B&K data acquisition system (DAQ) used for this test was set up to measure data between zero and 50 Hz with a frequency resolution of 0.0625 Hz and a frame length of 16 seconds. No windows were applied to either the data from the reference excitation or the accelerometers as the response of the unit completely decayed within the time frame. Data was averaged over five different impacts at each node location described in the geometry.

End to end system uncertainty is estimated by recording the data acquisition system's response to a 1V sine source signal on all channels used in a test described by Mayes [1]. All channels were within a standard deviation of 1.9%, well below the 5% standard reported for accelerometer calibrations.

5 ANALYSIS AND RESULTS

5.1 Modal Results

The following section outlines the experimental modal results from each of ganged heliostat modal tests. Analysis was conducted using the SMAC program developed by Hensley and Mayes [2]. The experimental data was fit using a real modes approximation. The following sections contain a list of natural frequencies, damping estimates and mode shape descriptions in tabular form. Also plotted in each subsequent section is the complex mode indicator function (CMIF) calculated from measured data and its corresponding curve fit synthesized from the extracted modal parameters. These plots provide a measure of how well the extracted data represents the actual data. Note that the modal extraction for this structure was difficult due to data acquisition limitations restricting the frequency resolution.

The self-MACs (modal assurance criterion) are also included. These figures illustrate the similarity between all mode shapes for each test configuration and has values between 0 and 1 (0 representing completely unique modes and 1 signifying identical shapes). For a complete set of unique modes, the MACs should be close to the identity matrix. Mode shapes can be found in Appendix 1. Note that not all mode shapes are included as higher frequency modes are difficult to decipher. Some modes were also difficult to decipher due to limited instrumentation and / or limited input possibilities.

5.1.1 0 Degree Orientation

Table 1: Experimental Modal Results for Low Tension 0 Degree Orientation

Low Tension 0 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	1.18	1.02%	302Z+	In-Plane Sway Rigid Body Mode
2	1.73	0.03%	302Z+	1st Free Bending
3	2.13	1.59%	302Z+	1st Pinned Bending
4	2.36	0.12%	302Z+	1st In-Plane Torsion / Twist Mode
5	2.74	0.12%	302Z+	2nd Free Bending
6	3.36	2.19%	302X-	Rigid Body Rotation
7	3.62	0.49%	302X-	3rd Free Bending
8	4.63	4.22%	302X-	2nd In-Plane Torsion / Twist Mode

Table 2: Experimental Modal Results for High Tension 0 Degree Orientation

High Tension 0 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	1.19	1.02%	302Z+	In-Plane Sway Rigid Body Mode
2	1.82	0.92%	302X-	1st Pinned Bending
3	2.06	0.68%	302X-	1st Free Bending
4	2.55	0.46%	302Z+	1st In-Plane Torsion / Bending Mode
5	2.89	1.87%	302Z+	Rigid Body Rotation
6	3.00	1.74%	302Z+	2nd Free Bending
7	3.71	3.62%	302Z+	2nd In-Plane Torsion / Twist Mode
8	4.07	0.17%	302X-	3rd Free Bending
9	4.43	1.54%	302X-	1st Torsion Mode
10	5.06	0.29%	302X-	4th Free Bending

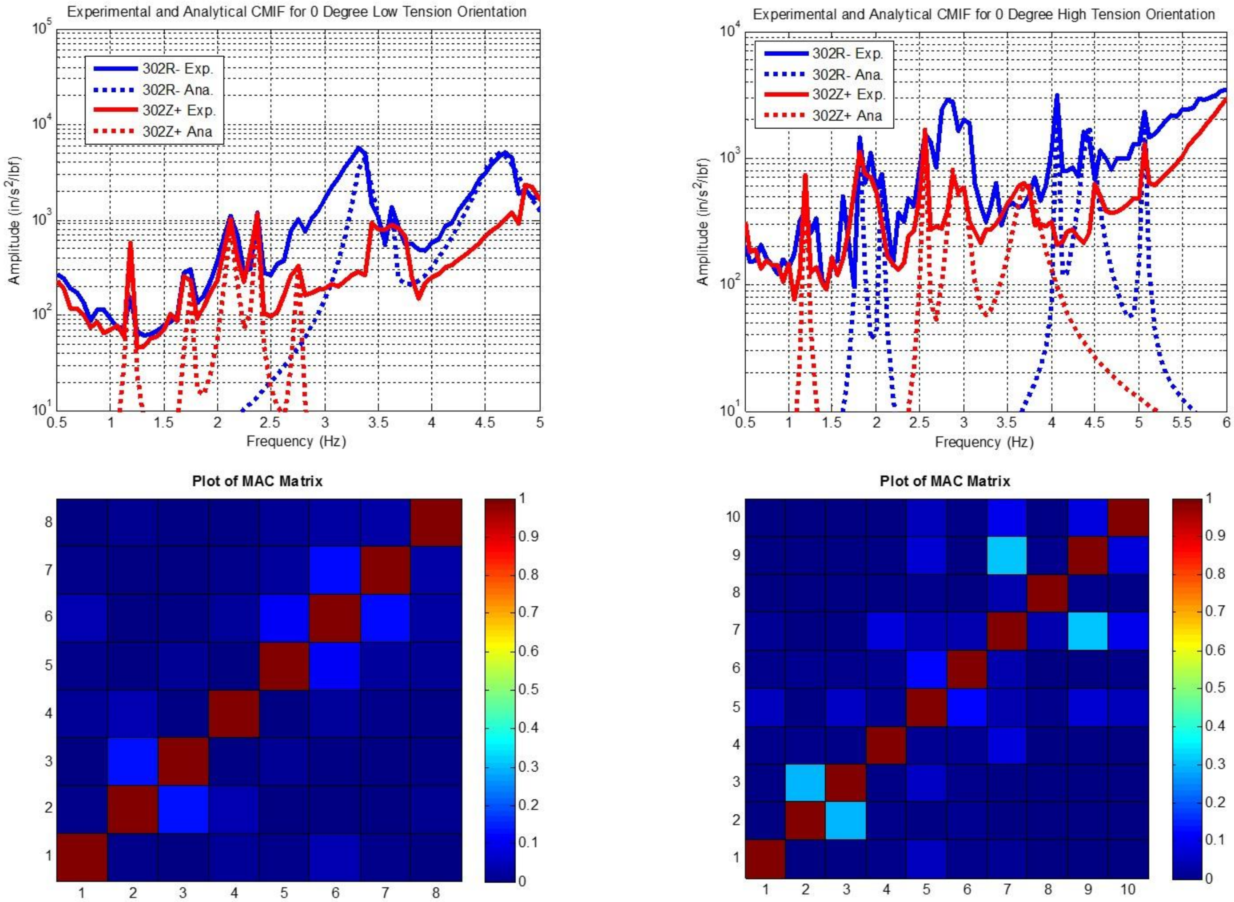

Figure 8: (Top) Experimental and Analytical CMIF for 0 Degree Low and High Tension Configurations. (Bottom) Self MAC for Low and High Tension Configurations

5.1.2 45 Degree Orientation

Table 3: Experimental Modal Results for Low Tension 45 Degree Orientation

Low Tension 45 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	1.12	0.46%	302Z+	RB Sway / 1st Bending
2	1.75	0.49%	302X-	1st Free Bending
3	2.19	2.02%	302X-	1st Pinned Bending
4	2.48	0.03%	302X-	2nd Free Bending / 1st Torsion
5	2.86	1.25%	302X-	3rd Free Bending
6	3.55	1.08%	302X-	4th Free Bending
7	4.23	1.71%	302X-	2nd Torsion
8	4.59	0.53%	302X-	5th Free Bending

Table 4: Experimental Modal Results for High Tension 45 Degree Orientation

High Tension 45 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	0.93	1.35%	302Z+	RB Sway / 1st Bending
2	1.85	0.94%	302X-	2nd Free Bending
3	1.94	0.31%	302Z+	1st Torsion / Twist
4	2.07	1.54%	302Z+	RB Sway / Twist
5	2.75	0.69%	302X-	2nd Torsion / Twist
6	2.86	0.24%	302X-	2nd Free Bending
7	3.55	2.11%	302Z+	3rd Free Bending / Twist
8	3.81	1.25%	302Z+	3rd Torsion Twist
9	4.92	0.39%	302Z+	4th Free Bending

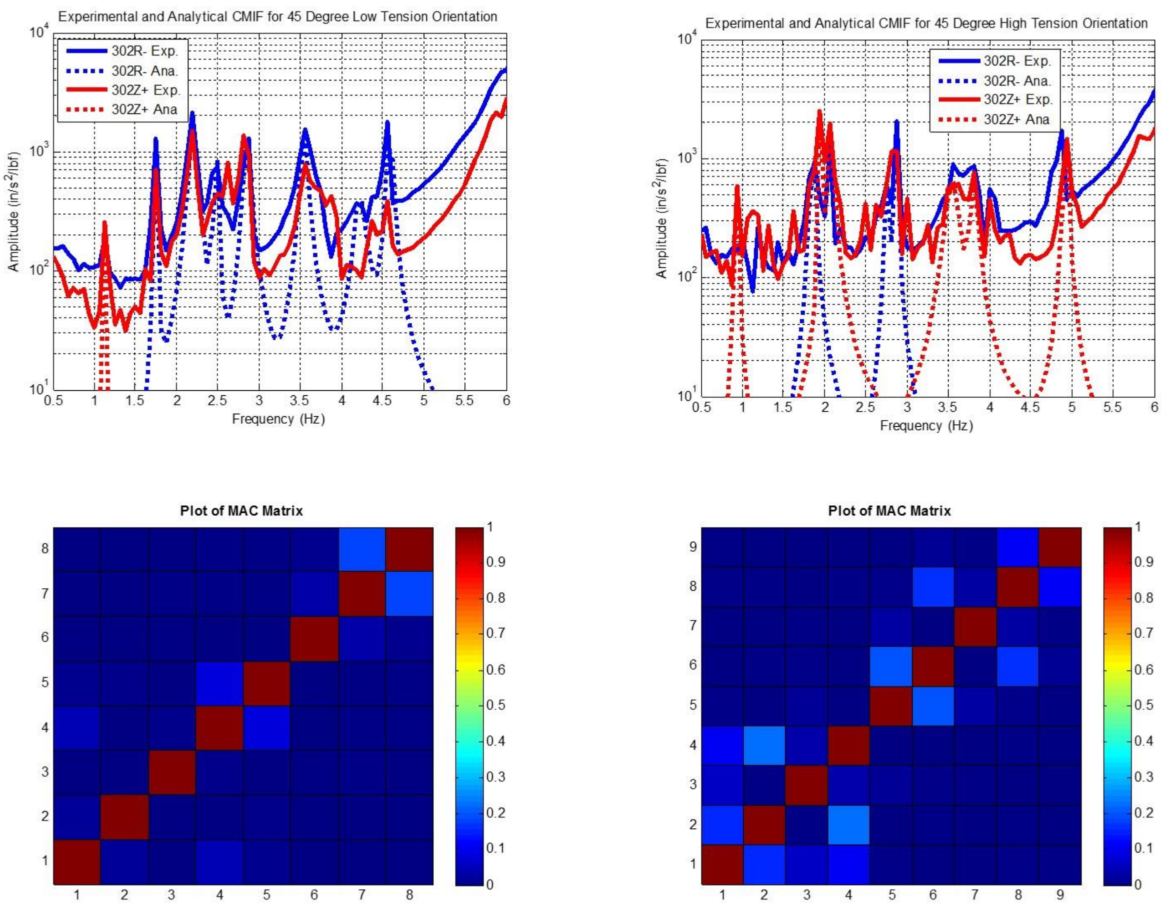

Figure 9: (Top) Experimental and Analytical CMIF for 45 Degree Low and High Tension Configurations. (Bottom) Self MAC for Low and High Tension Configurations

5.1.3 90 Degree Orientation

Table 5: Experimental Modal Results for Low Tension 90 Degree Orientation

Low Tension 90 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	0.9627	0.02%	302Z+	RB Rotation
2	1.6446	1.59%	302Z+	2nd Free Bending
3	1.9043	2.34%	302X-	RB Sway in Plane / Bending
4	2.1973	1.95%	302X-	In Plane Bending / Torsion
5	2.3596	1.58%	302Z+	2nd In Plane Bending / Torsion
6	2.5574	1.35%	302X-	3rd Free Bending
7	2.8981	6.09%	302Z+	In Plane Bending / Axial Translation
8	3.375	1.71%	302Z+	4th Free Bending
9	3.8144	7.00%	302Z+	3rd Torsion
10	4.3406	2.19%	302X-	5th Free Bending
11	4.757	8.20%	302Z+	6th Free Bending

Table 6: Experimental Modal Results for High Tension 90 Degree Orientation

High Tension 90 Degree Orientation

Mode #	Frequency (Hz)	Damping	Reference	Mode Description
1	0.9436	0.85%	302X-	RB Bottom Sway
2	1.6841	0.30%	302Z+	2nd Free Bending
3	1.8976	1.56%	302Z+	RB Sway in Plane / Bending
4	2.1049	3.16%	302Z+	RB Twist
5	2.4755	0.20%	302X-	3rd Free Bending
6	2.6848	0.85%	302X-	2nd In-Plane Bending
7	3.216	2.63%	302X-	1st Torsion
8	3.8392	1.48%	302Z+	4th Free Bending
9	3.9335	0.49%	302Z+	2nd Torsion
10	4.5991	1.56%	302Z+	Bending / Torsion

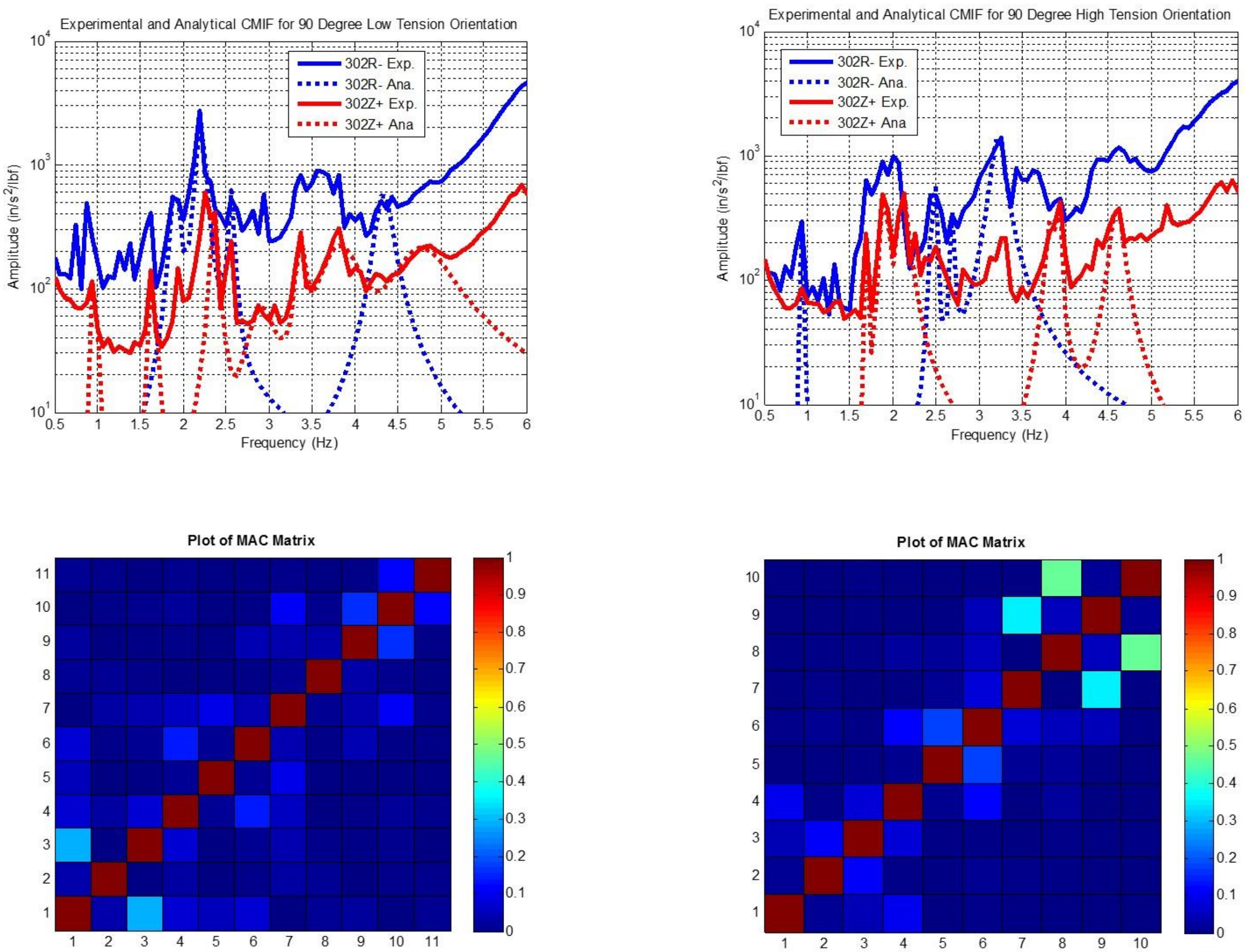

Figure 10: (Top) Experimental and Analytical CMIF for 90 Degree Low and High Tension Configurations. (Bottom) Self MAC for Low and High Tension Configurations

5.2 Wind Excitation Results

An effort was made to capture wind excitation in the three orientations, however the timing proved somewhat difficult. There was no available method of recording wind speed along with the data, and thus a hand held anemometer was used to approximate wind speed for each data set. Data was recorded during a low wind speed and a higher wind speed to examine the amplification of the low frequency modes presented in the above section. The low wind speed data was taken during 3-6 mph gusts while the higher wind speed contained 10-18 mph gusts. Figure 11 below displays the time histories for the maximum responses in the three orientations for the low wind speed (blue), and the high wind speed (red). The spikes in each acceleration time history represents the individual wind gusts. Note that the low wind speed data in the 45 degree orientation is initially higher than the higher wind speed. This was found to average out during the frequency analysis and thus the red data asset was labeled as the high wind speed.

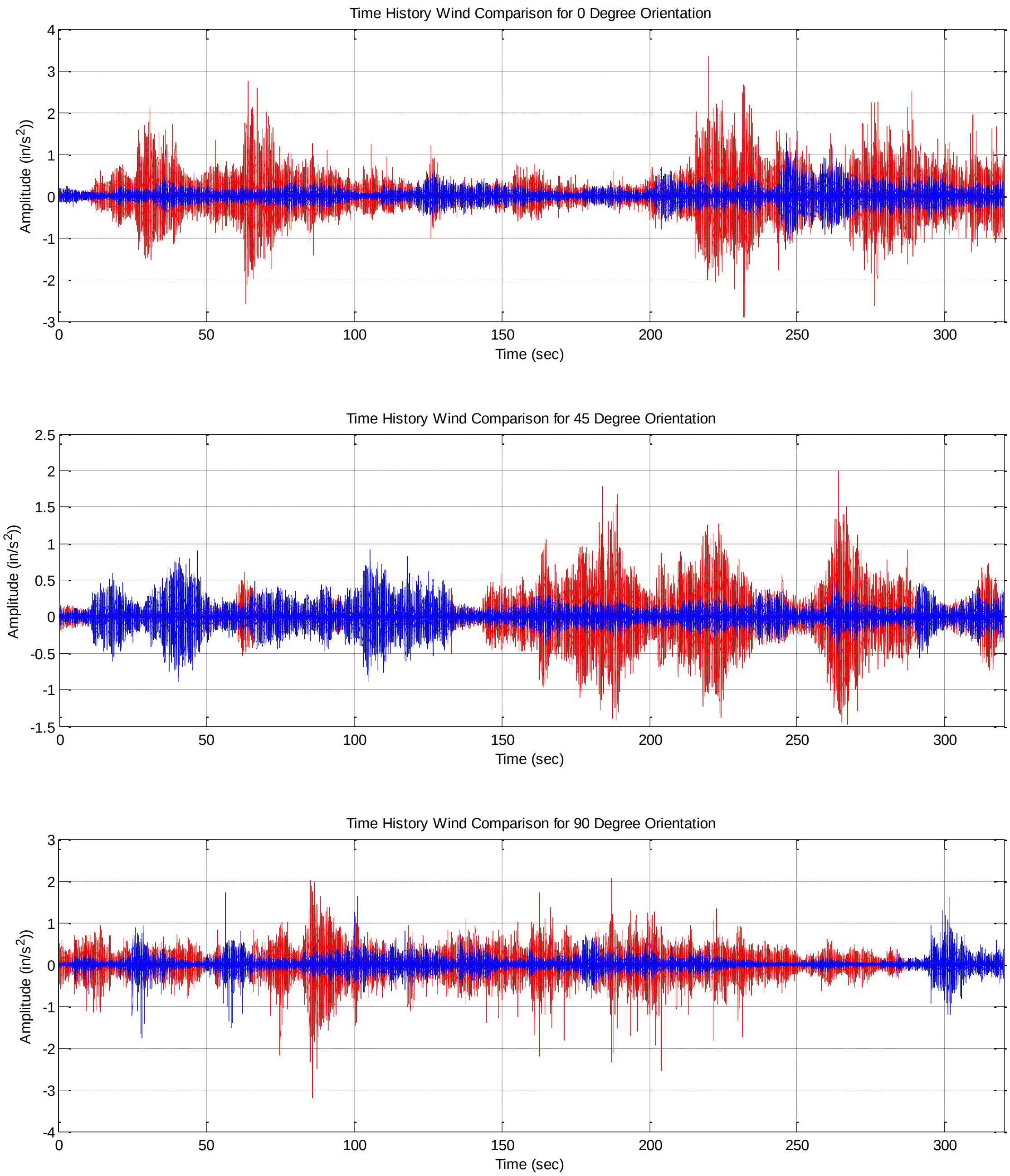

Figure 11: Time Histories for Low Vs. High Wind Excitation

Figure 12 displays the averaged autospectra for the low vs high wind speed data showed in Figure 11. These plots show that the higher wind speed correlates to a higher amplitude in low and high frequency responses as well as a shift in the lower modes to a higher frequency. This is intuitively true as the static load of the wind on the mirror facets would increase the tension in the wires which leads to a higher natural frequency. For this case, the modes of interest are below 5 Hz and show a significant response to the wind. The higher frequency data is also excited, but these modes have smaller displacements and are not as important in the heliostats performance.

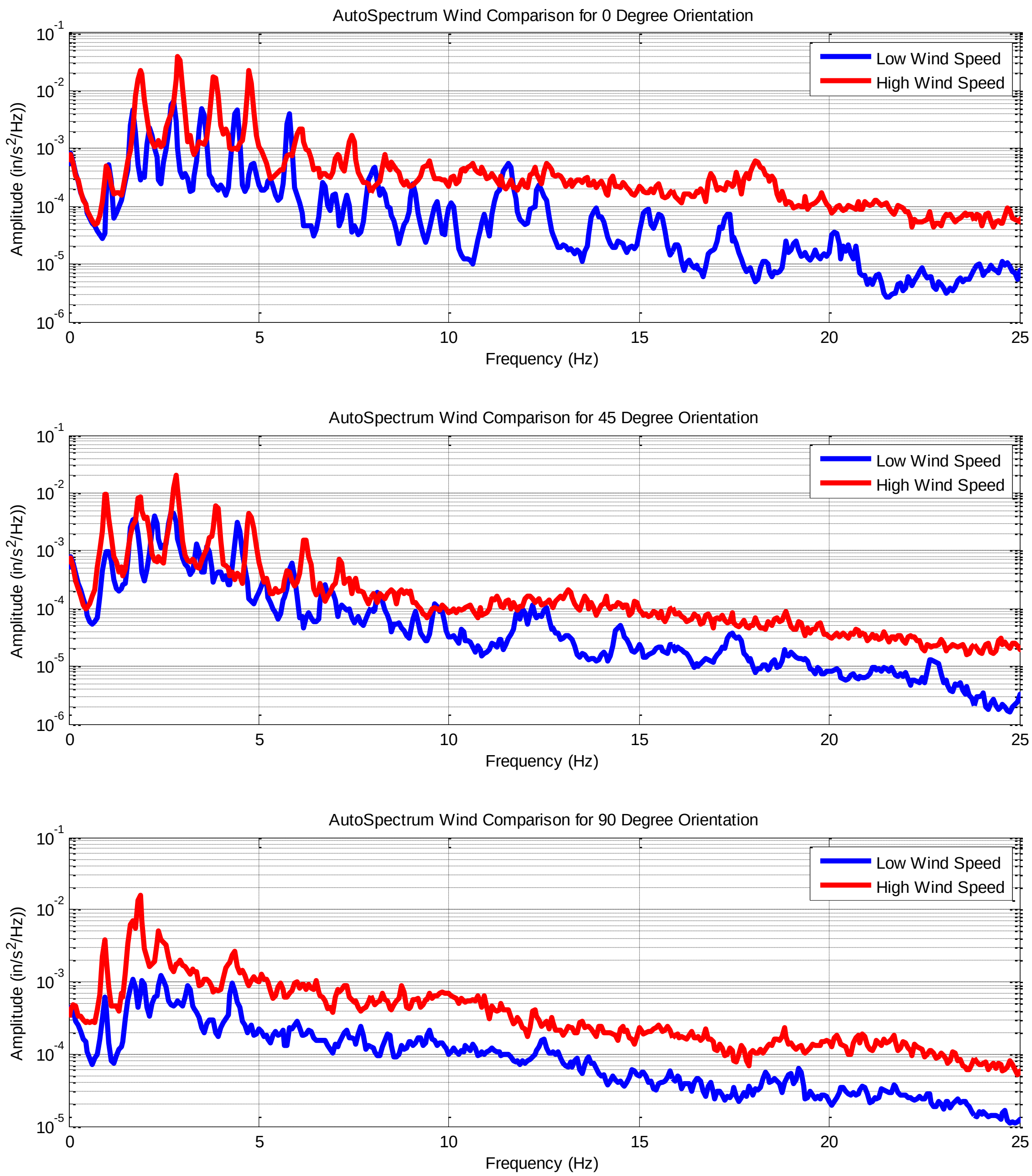

Figure 12: AutoSpectra for Low Vs. High Wind Excitation

6 WIND FENCE COMPARISON

To mitigate the excitation due to the wind shown in section 5, a makeshift wind fence was constructed out of wood and canvas as seen in Figure 13 below. The wind fence was placed approximately three feet south of the heliostat prototype. Data was acquired in the same 0, 45, and 90 degree orientations presented in previous sections. It was immediately noticeable that the wind changes directions enough to hit either side of the wind fence making direct correlation of wind blockage to decreased dynamic excitation difficulty. The results obtained in this leads one to believe the wind fence makes no difference in wind excitation.

Figure 13: Wind Fence Adjacent to Heliostat

Figure 14 displays the averaged autospectra response across the heliostat for a fence vs no fence comparison. These results show that the wind fence has no effect on the excitation, and in some cases makes it worse. This could be due to a possible increase in vortex shedding introduced by the fence. Figure 15 shows the time histories (Blue = Fence, Red = No Fence) and displays a similar trend of increased excitation with the wind fence. Despite these results being indicative of a wind fence not providing any benefit, further experimentation would be need to make this conclusive. Future testing would benefit from wind speed and direction measurements, and multiple orientations of the wind fence with respect to the heliostat.

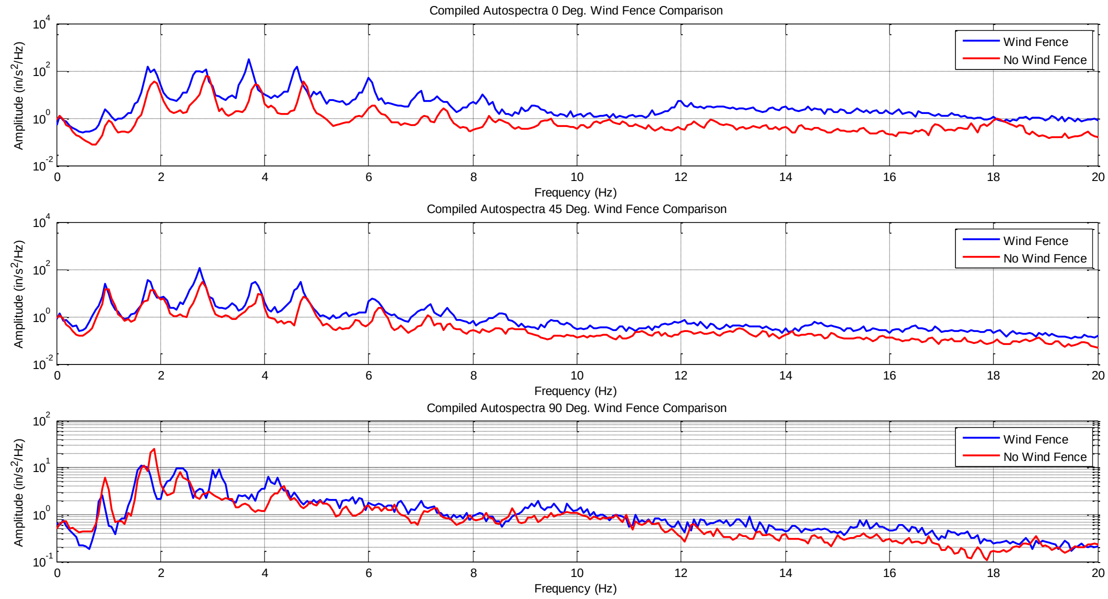

Figure 14: Compiled Wind Excited AutoSpectra Responses for Fence Vs. No Fence Configurations

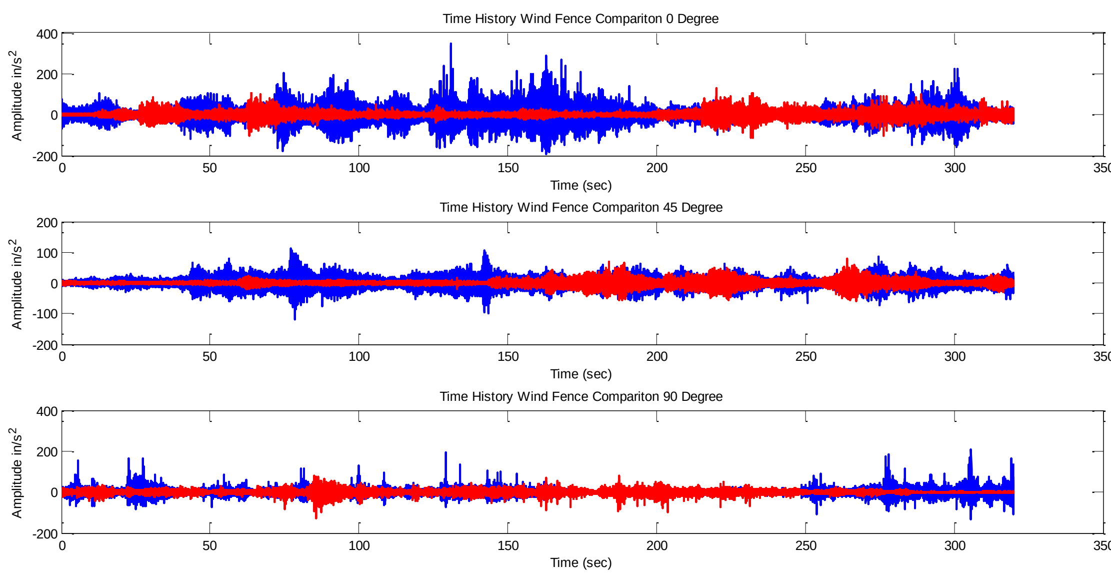

Figure 15: Time Histories from Wind Fence Vs. No Wind Fence Comparison

7 DATA QUALITY ISSUES AND LESSONS LEARNED

Due to the highly non-linear nature and low frequency response of the ganged heliostat, the modal extraction was quite difficult with the instrumentation and data acquisition system used. In some cases, the hammer input dips at low frequencies causing questionable frequency response functions and modal fits. This can lead to erroneous mode shapes being reported. Different forms of excitation such as step relaxation, natural excitation or electrodynamic shaker excitation may aid with this problem. The data presented above is still useful as the collective modes align with what's expected and show similar frequencies to what was seen in the wind excited data. The modes were also found to be repeatable in the different orientations giving confidence in the modal fits. It is important to note this low frequency error if the data is to be used for FEM model correlation as some of the modes may not exist and be an artifact of the noisy hammer input at low frequencies. The objective of the test was still met as mode shapes of interest were isolated and shown to be excited in a windy environment at low frequencies which could present a problem for future ganged heliostat designs.

* Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8 REFERENCES

[1] Memo to T.J. Baca, 1525, dated September 30, 2005, from: R.L. Mayes, 1525, subject: Data Acquisition Uncertainty Procedure
[2] Hensley, Daniel P., Mayes, Randy L., "Extending SMAC to Multiple References", Proceedings of the 24th International Modal Analysis Conference, pp 220-230, January 2006

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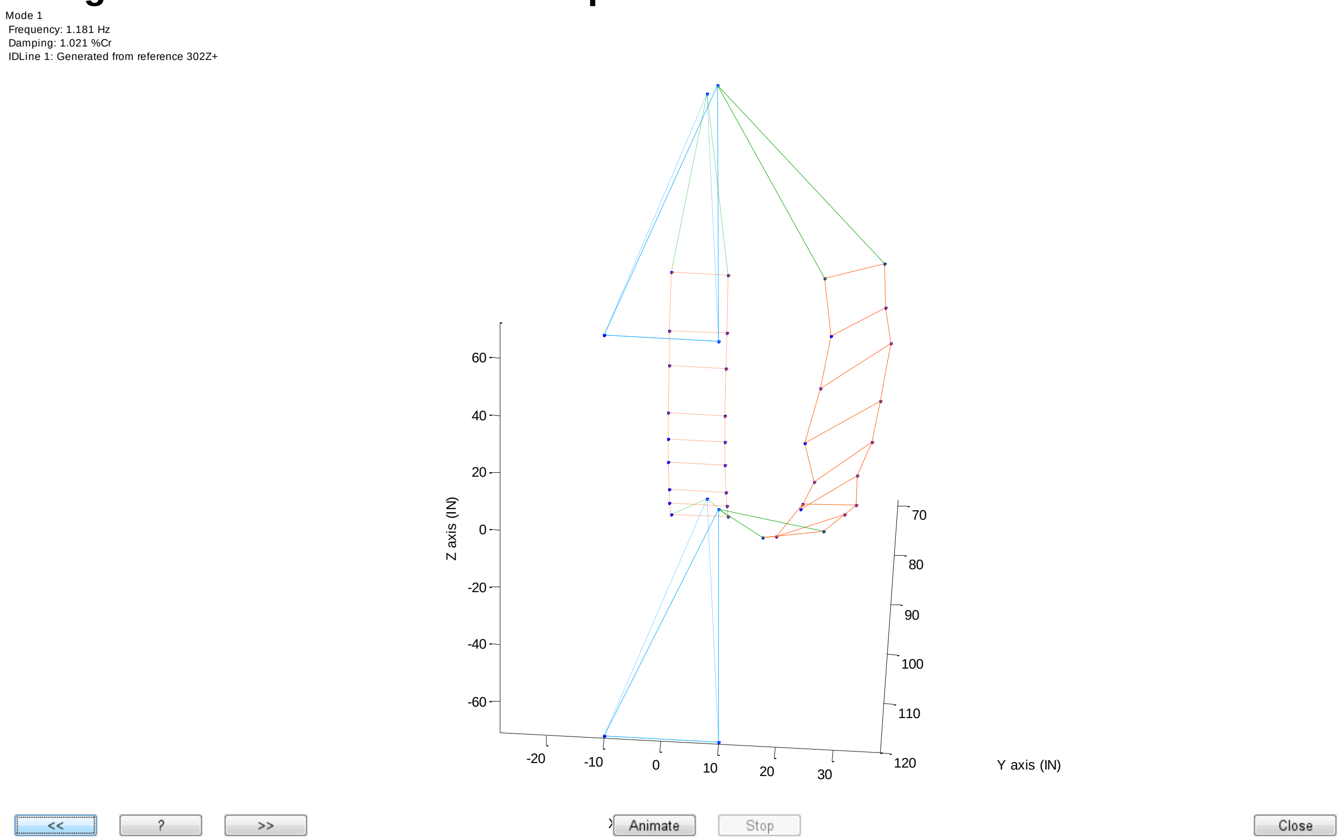
9 APPENDIX 1 – MODE SHAPES FROM ANALYTICAL FITS TO EXPERIMENTAL DATA

9.1 0 Degree Low Tension Mode Shapes



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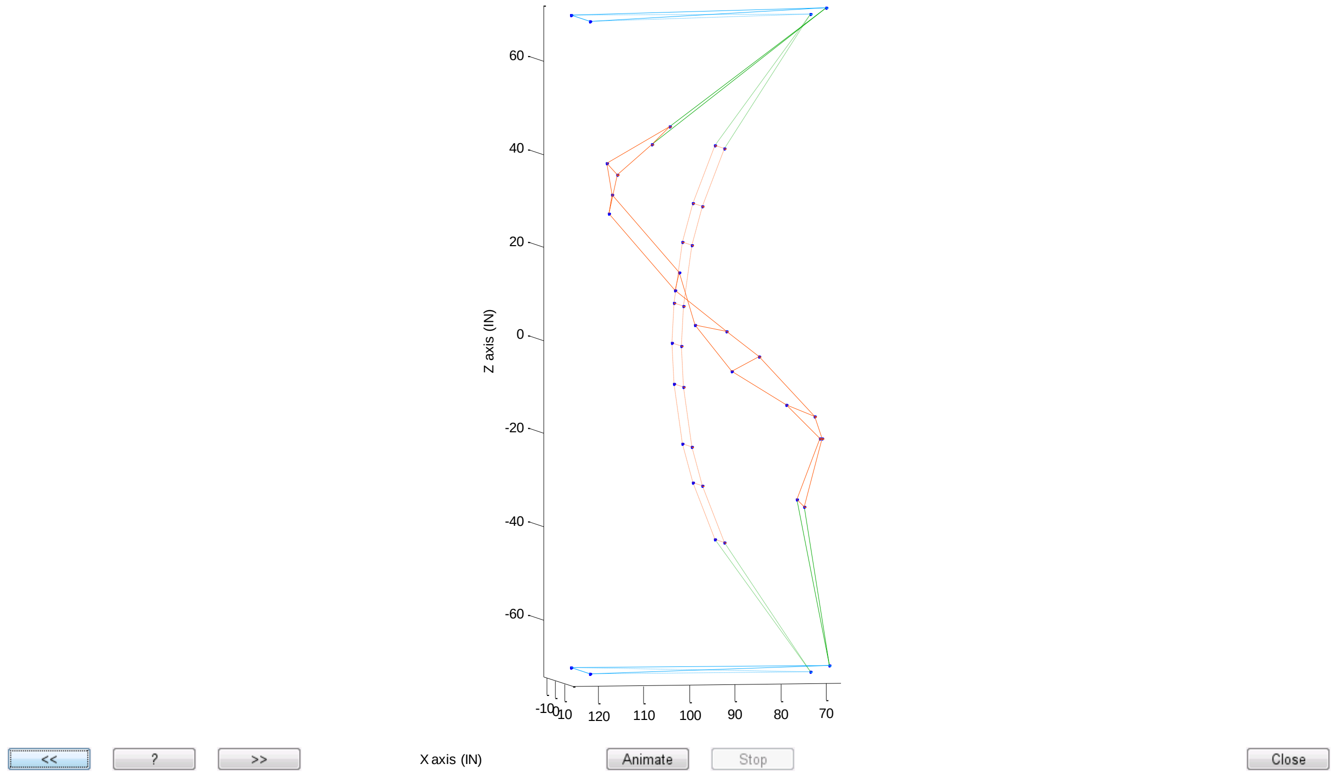
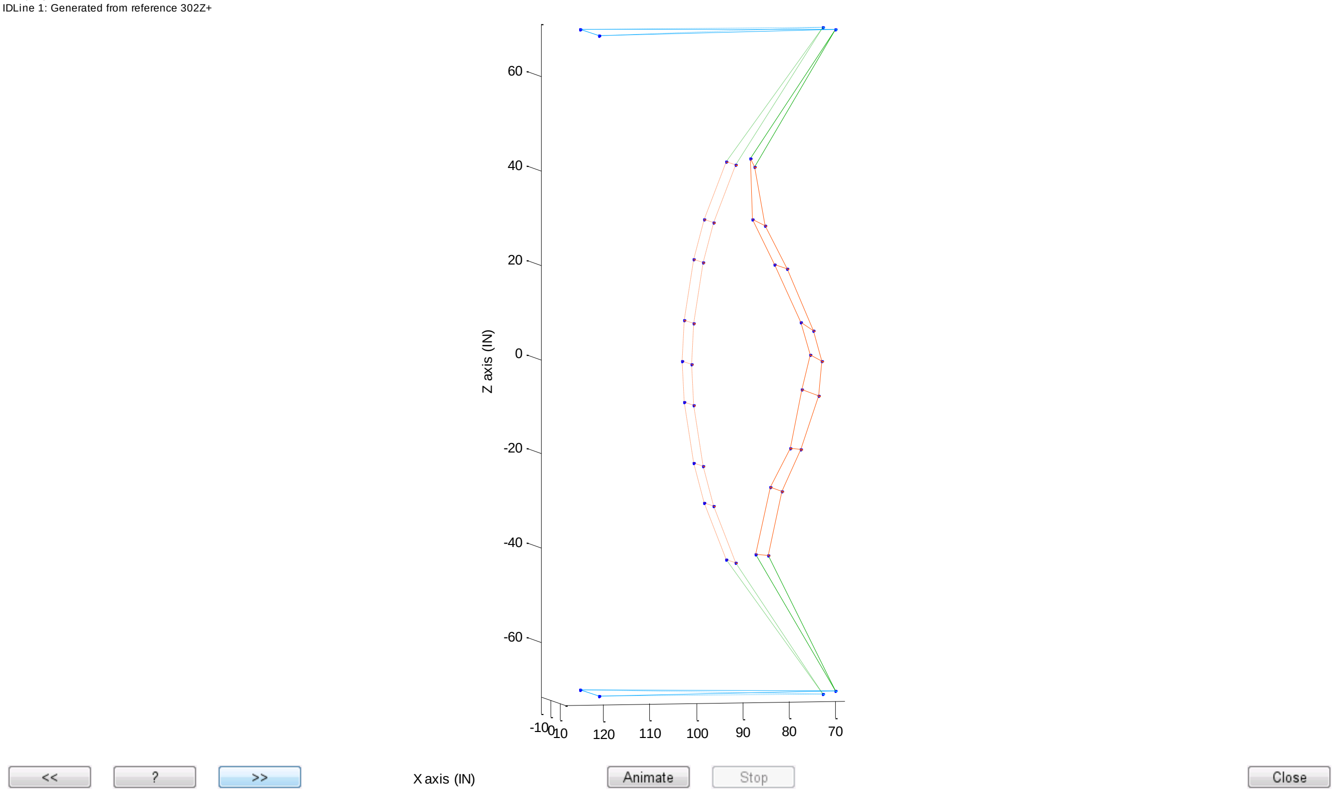
Mode 2
Frequency: 1.729 Hz
Damping: 0.032 %Cr
IDLine 1: Generated from reference 302Z+



Mode 3
Frequency: 2.125 Hz
Damping: 1.587 %Cr
IDLine 1: Generated from reference 302Z+



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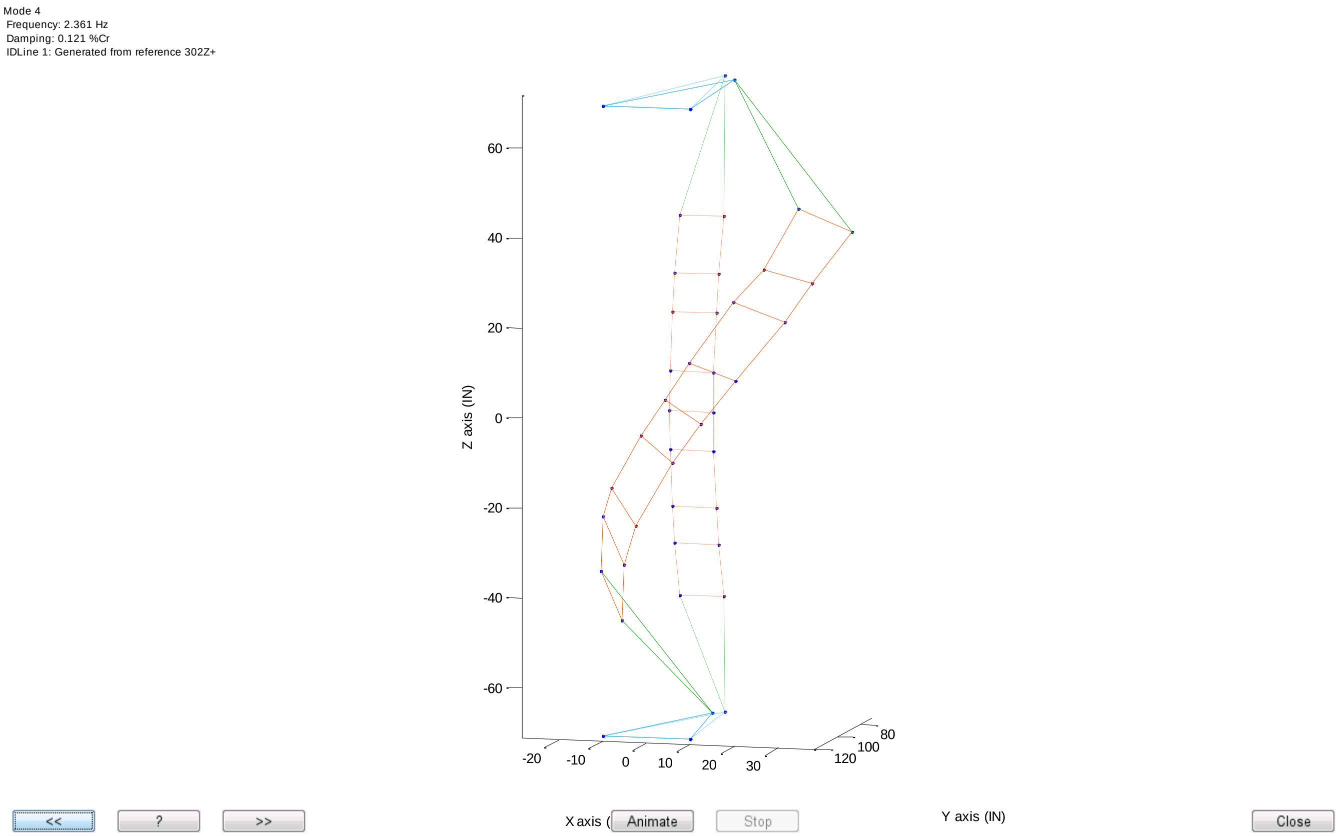
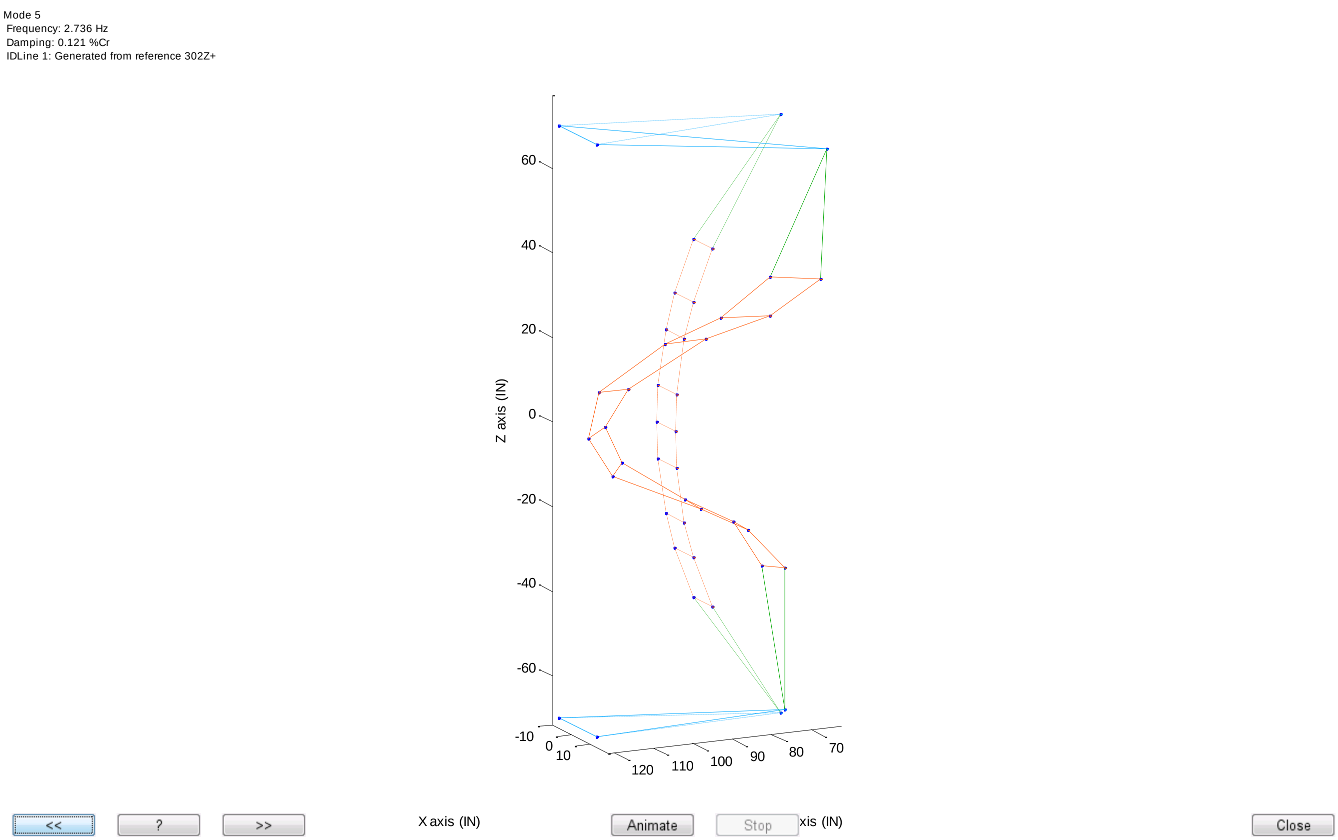

Mode 4
Frequency: 2.361 Hz
Damping: 0.121 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
-20
-10
0
10
20
30
120
100
80
<<
?
>>
X axis (
Animate
Stop
Y axis (IN)
Close


Mode 5
Frequency: 2.736 Hz
Damping: 0.121 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
-10
0
10
120
110
100
90
80
70
<<
?
>>
X axis (IN)
Animate
Stop
xis (IN)
Close

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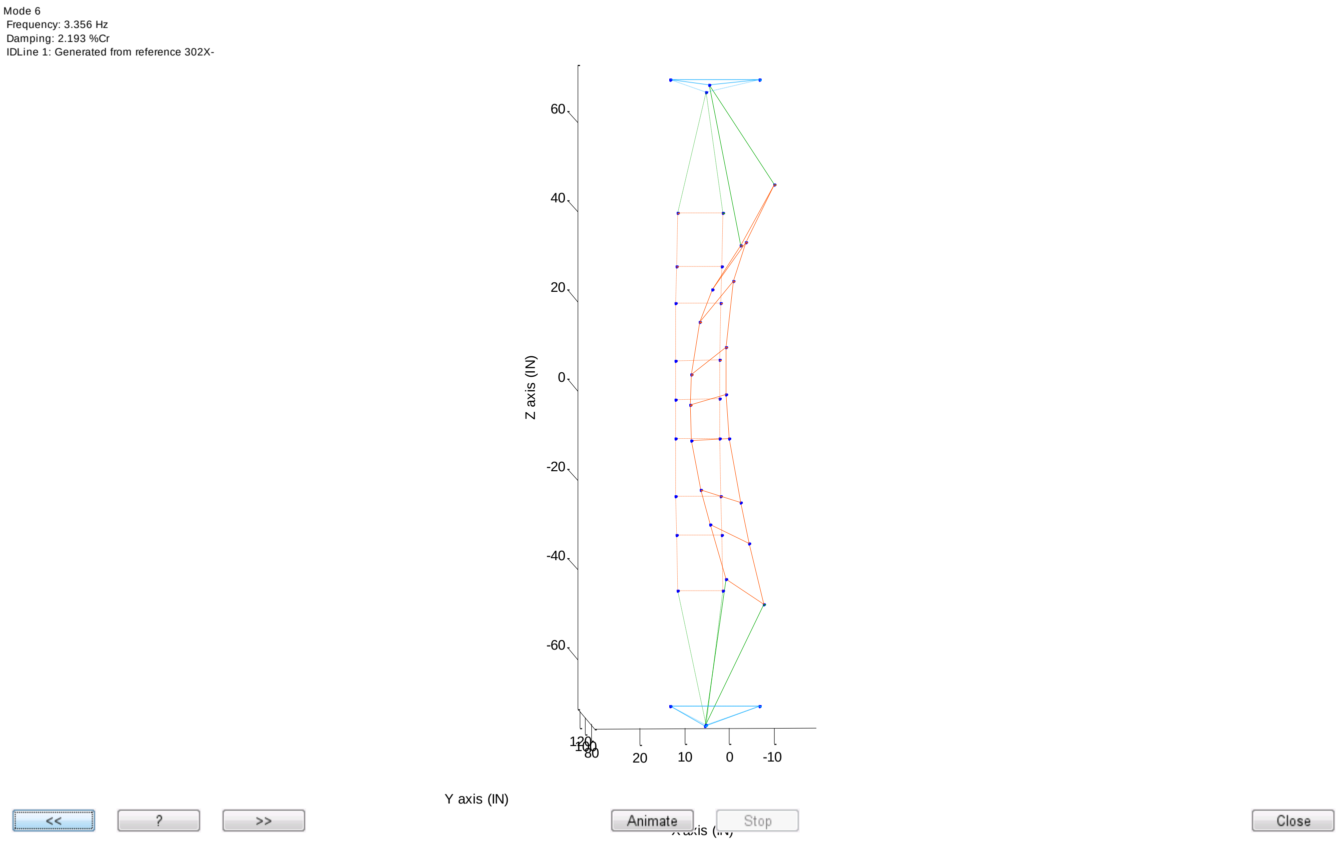

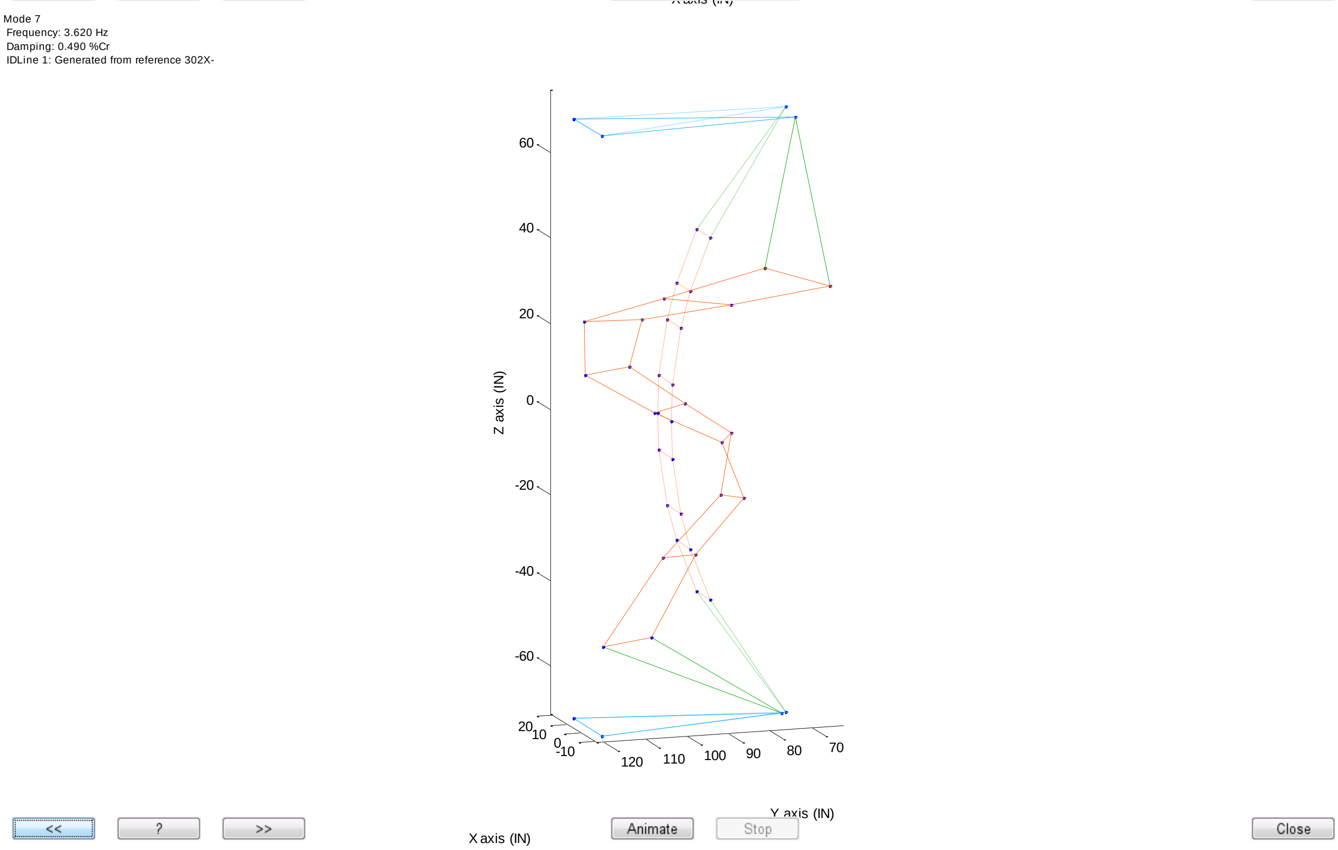

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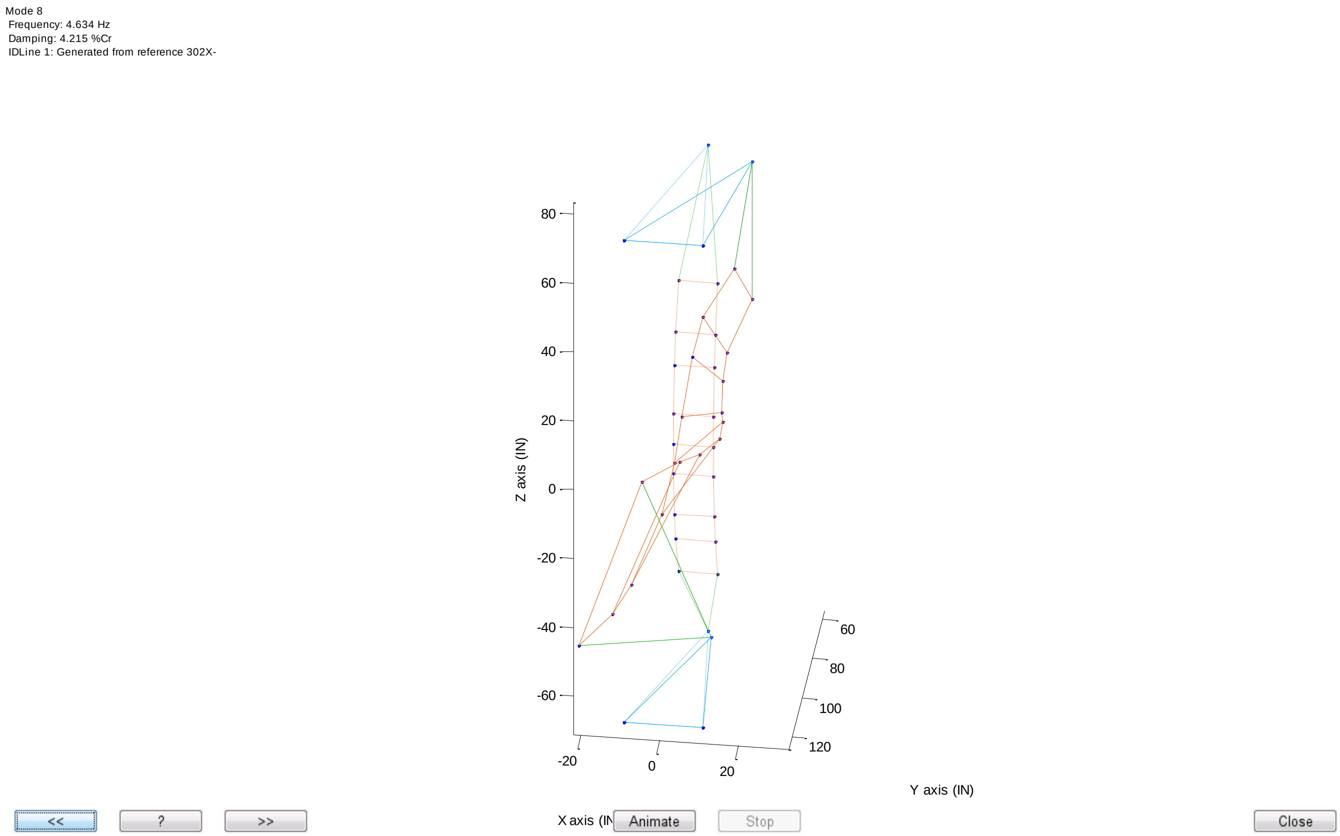
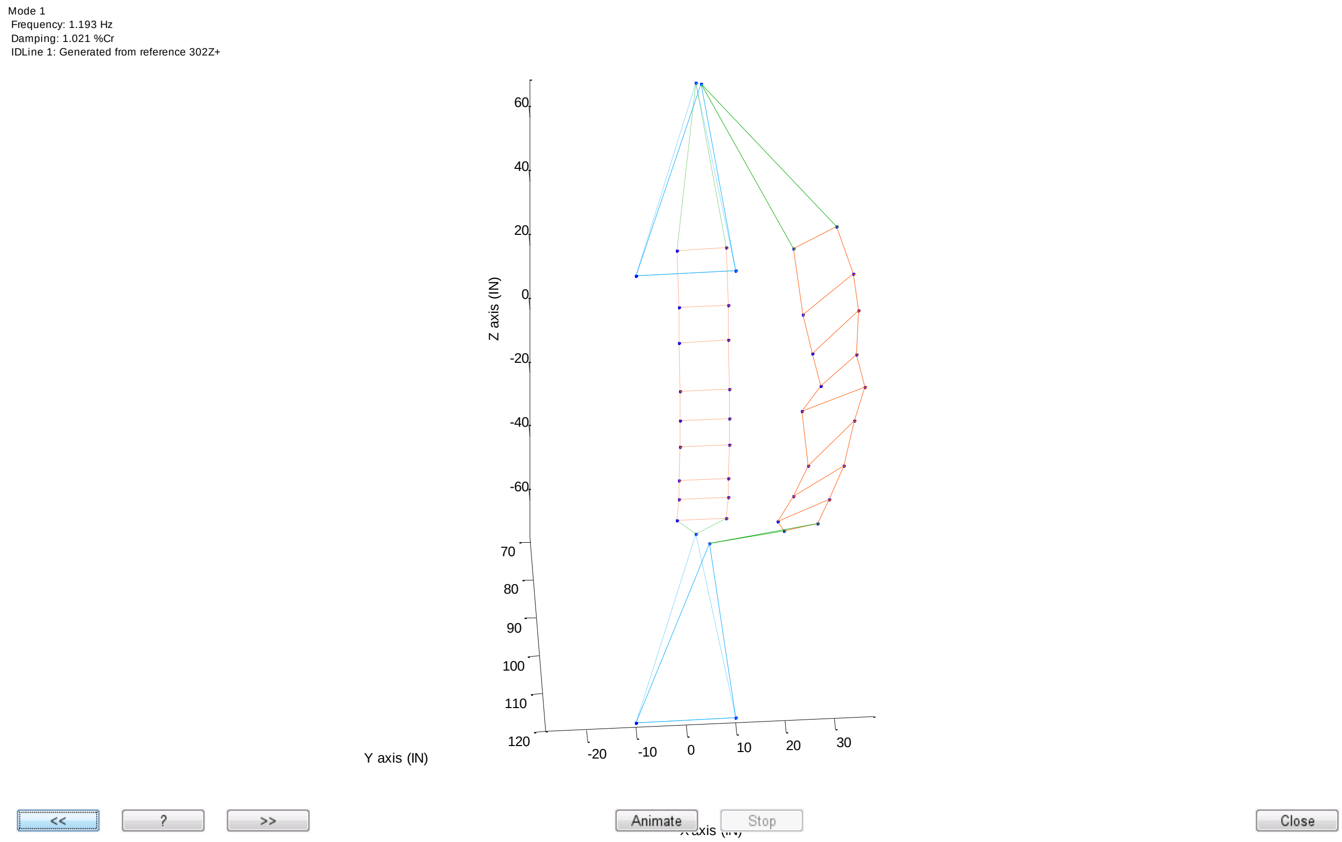
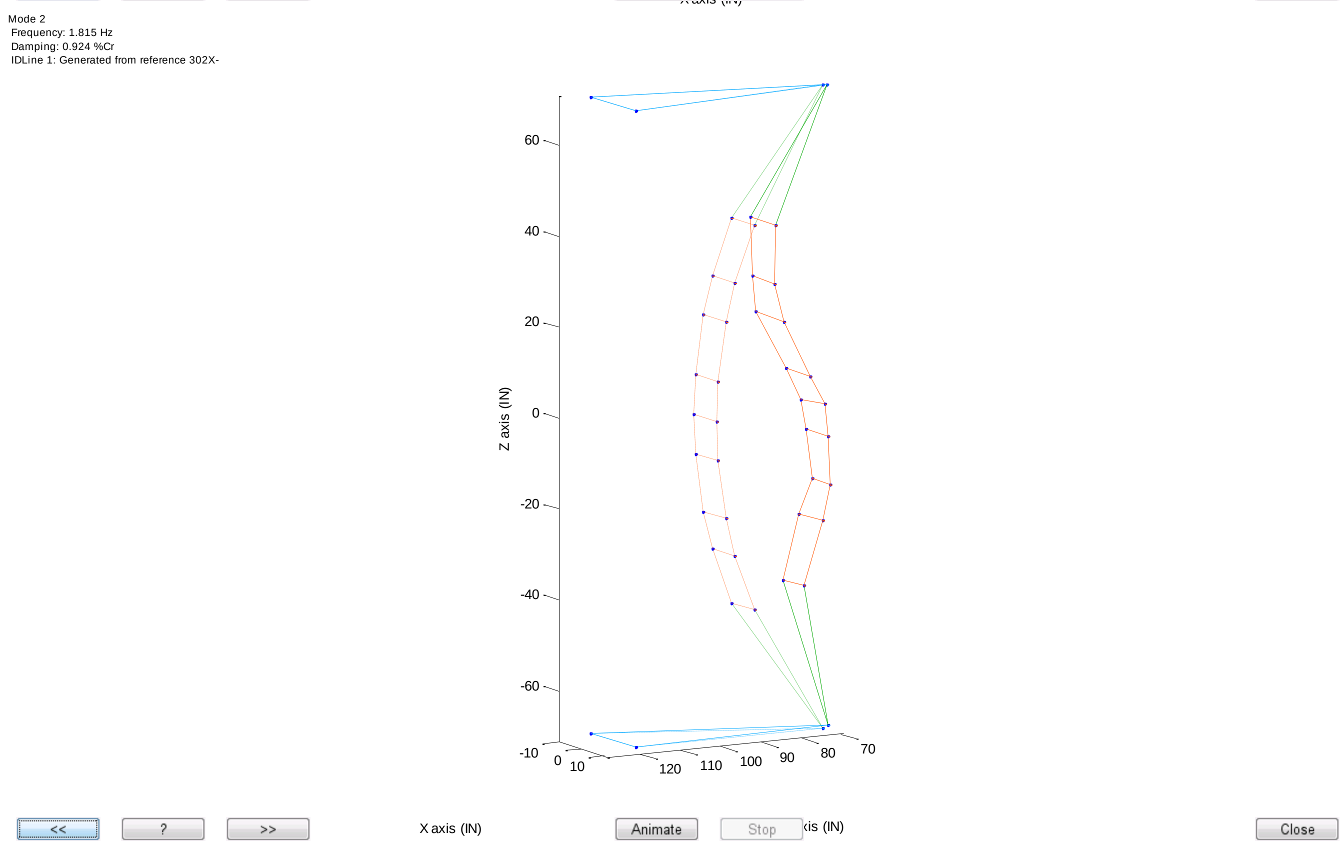


9.2 0 Degree High Tension Mode Shapes


Mode 1
Frequency: 1.193 Hz
Damping: 1.021 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
70
80
90
100
110
120
Y axis (IN)
-20
-10
0
10
20
30
<<
?
>>
Animate
Stop
Close


Mode 2
Frequency: 1.815 Hz
Damping: 0.924 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
-10
0
10
120
110
100
90
80
70
X axis (IN)
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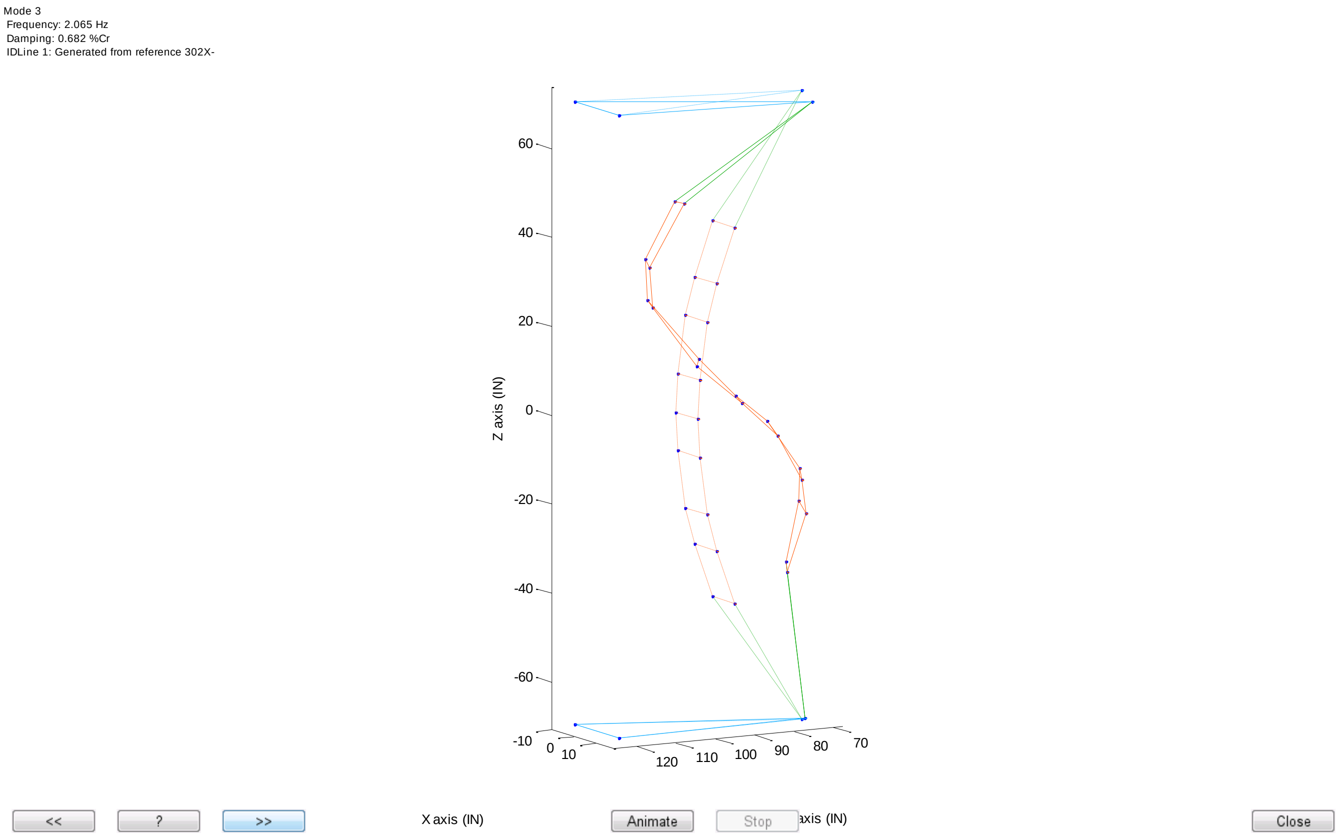
Animate
Stop
Close


Mode 3
Frequency: 2.065 Hz
Damping: 0.682 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
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0
10
120
110
100
90
80
70
X axis (IN)
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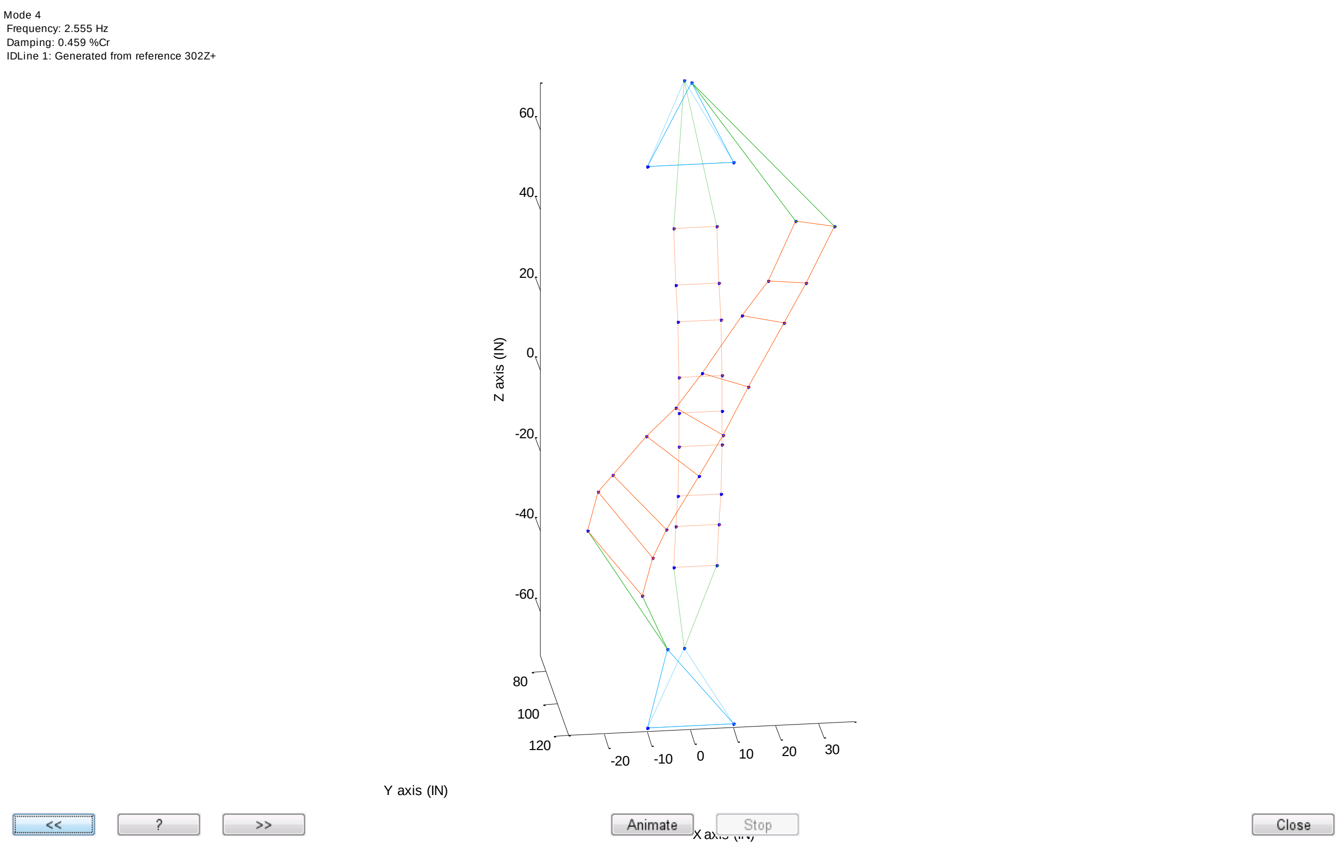
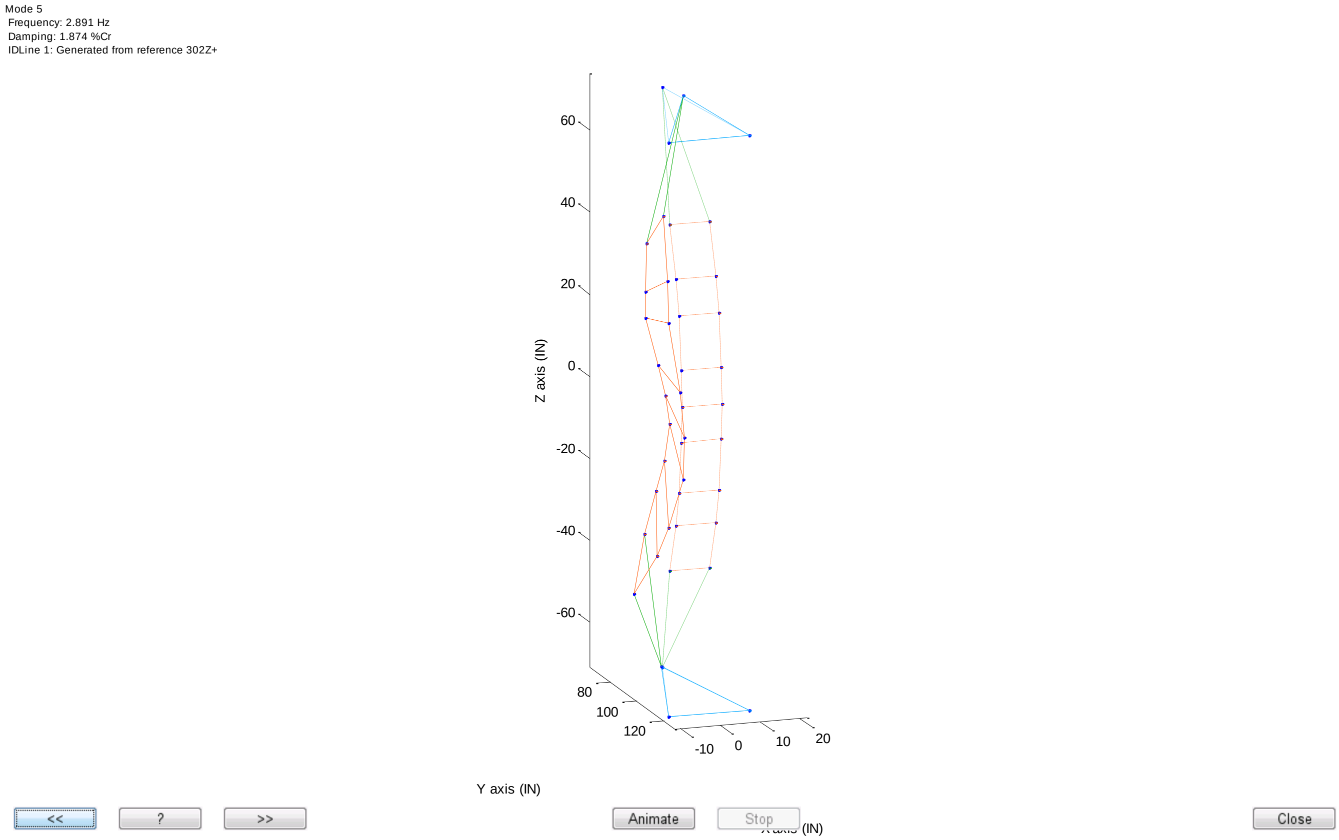
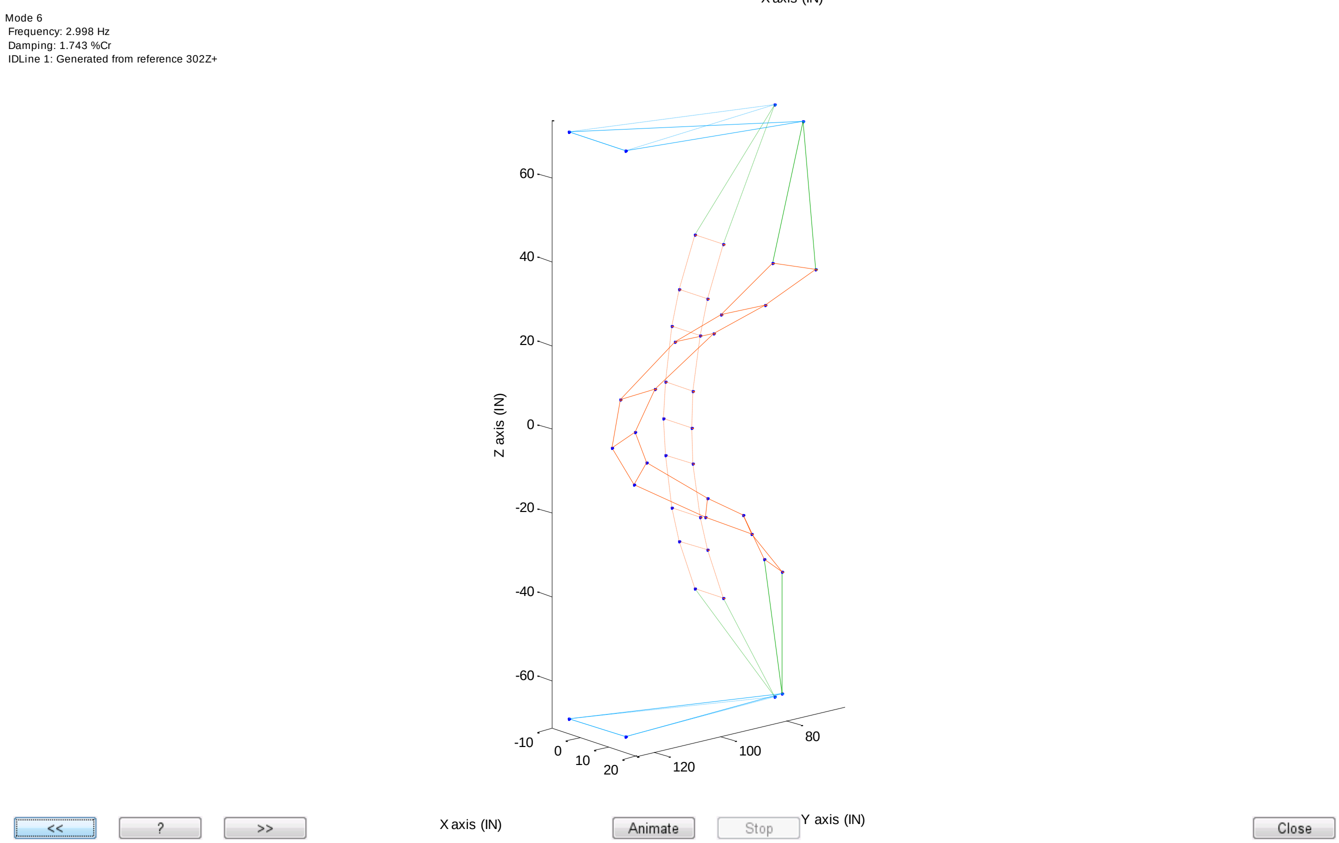
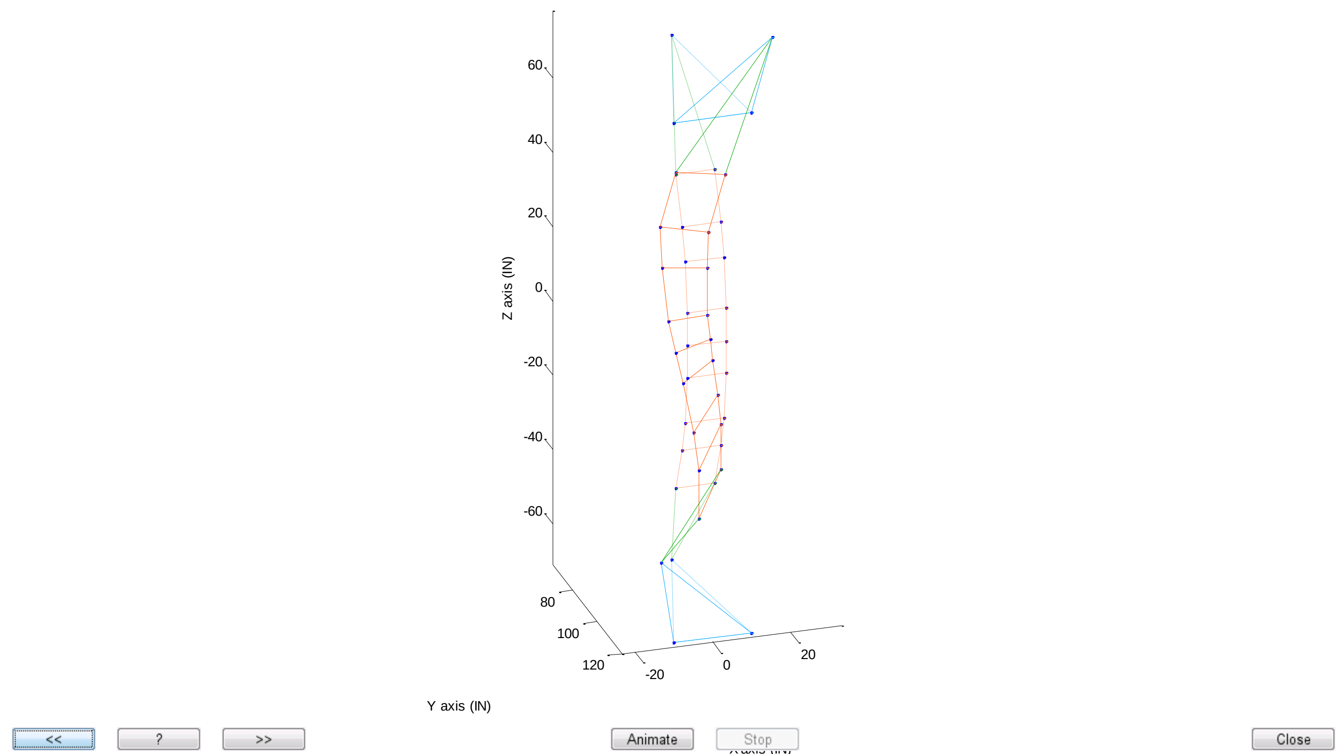
?
>>
Animate
Stop
Close


Mode 4
Frequency: 2.555 Hz
Damping: 0.459 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
80
100
120
-20
-10
0
10
20
30
Y axis (IN)
<<
?
>>
Animate
Stop
Close

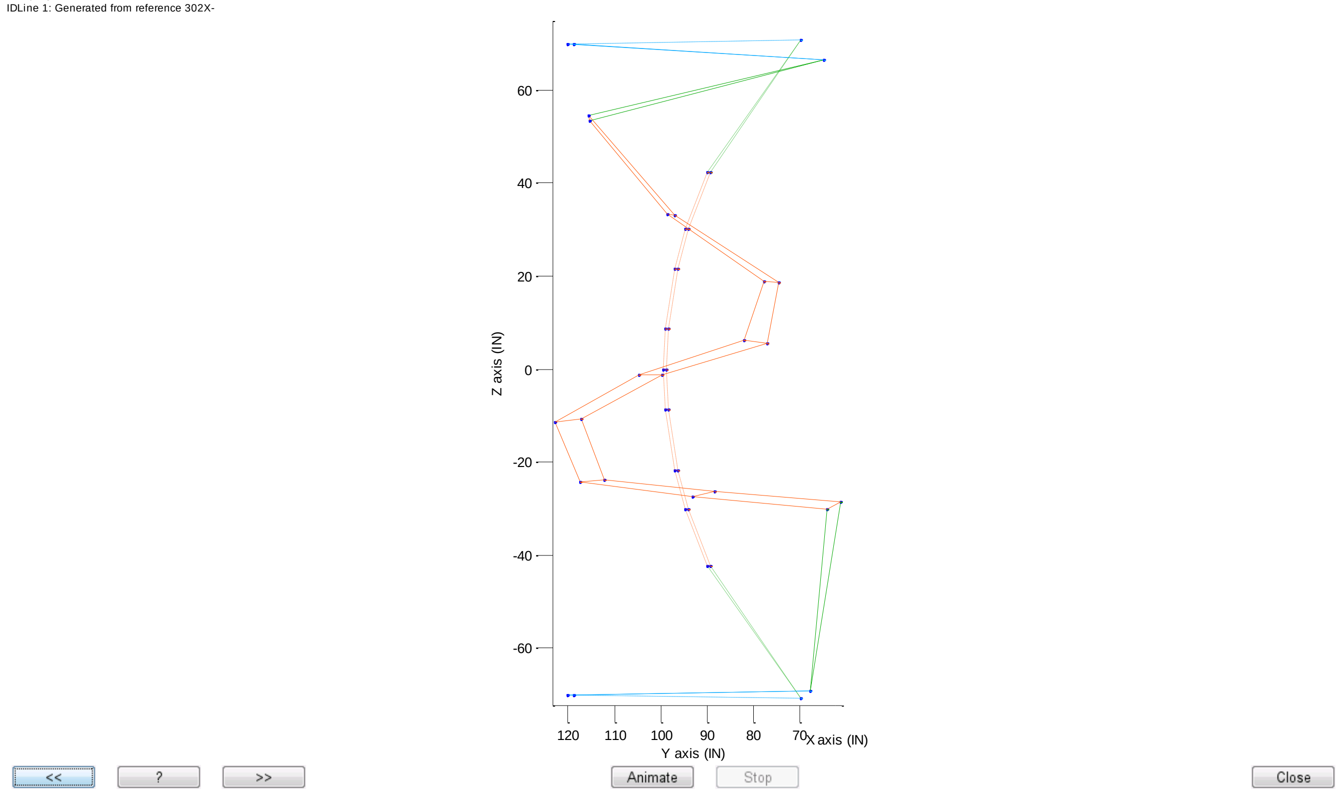

Mode 5
Frequency: 2.891 Hz
Damping: 1.874 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
Y axis (IN)
X axis (IN)
60
40
20
0
-20
-40
-60
80
100
120
-10
0
10
20
<<
?
>>
Animate
Stop
Close


Mode 6
Frequency: 2.998 Hz
Damping: 1.743 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
X axis (IN)
Y axis (IN)
60
40
20
0
-20
-40
-60
-10
0
10
20
120
100
80
<<
?
>>
Animate
Stop
Close

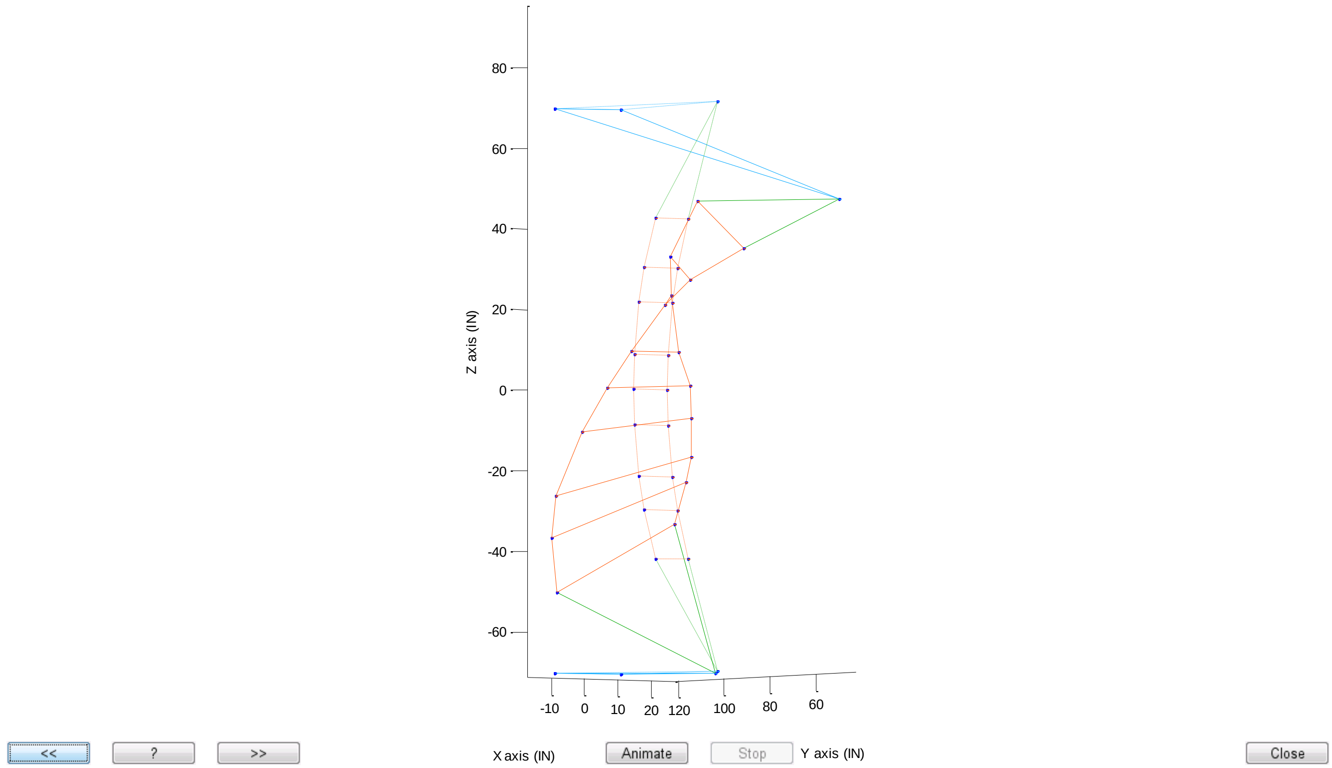
Mode 7
Frequency: 3.713 Hz
Damping: 3.619 %Cr
IDLine 1: Generated from reference 302Z+



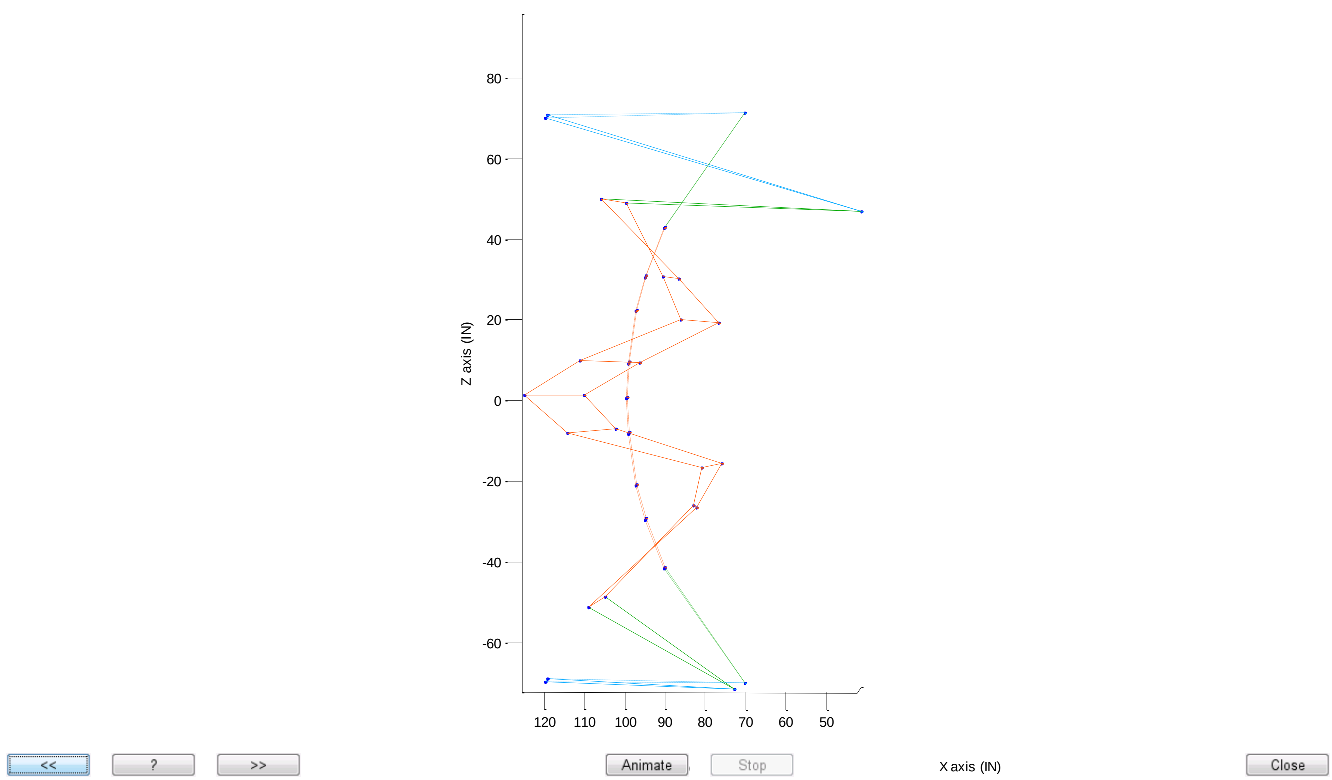
Mode 8
Frequency: 4.069 Hz
Damping: 0.170 %Cr
IDLine 1: Generated from reference 302X-



Mode 9
Frequency: 4.429 Hz
Damping: 1.545 %Cr
IDLine 1: Generated from reference 302X-

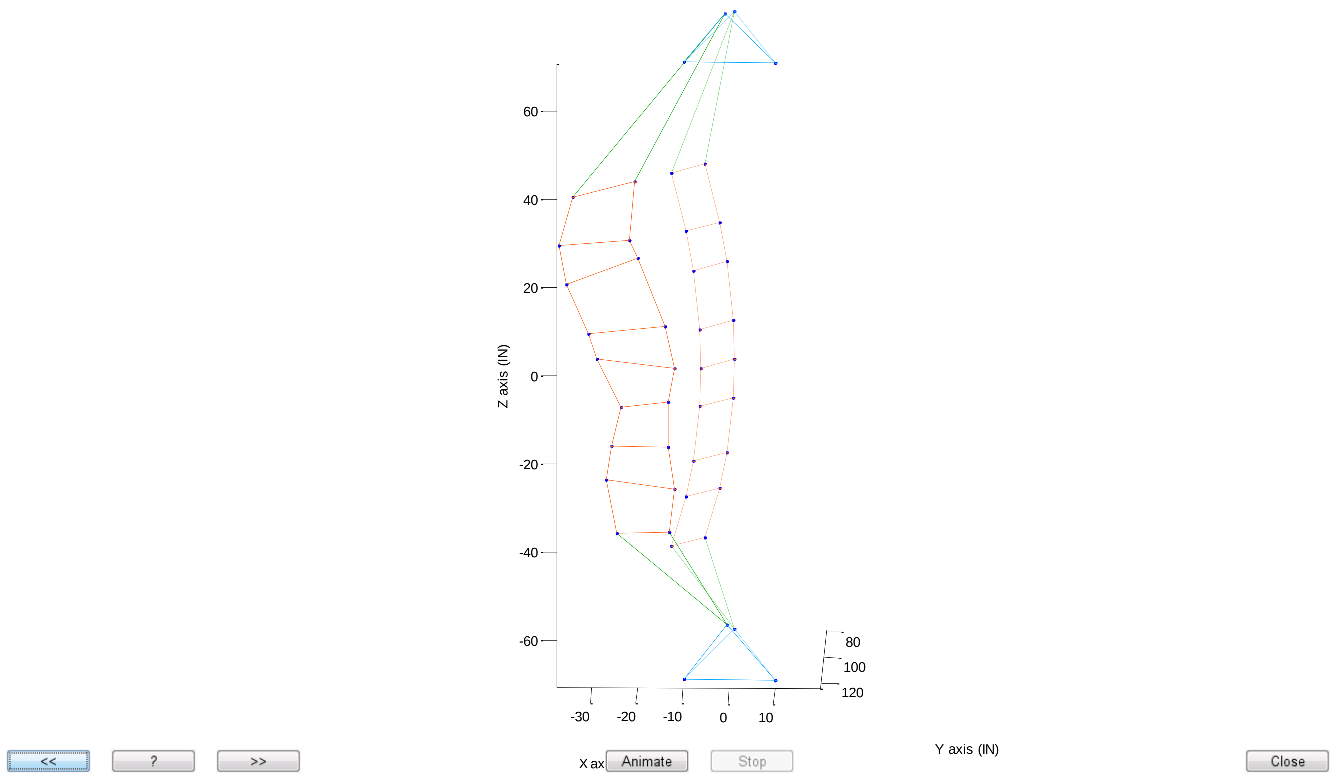


Mode 10
Frequency: 5.060 Hz
Damping: 0.288 %Cr
IDLine 1: Generated from reference 302X-

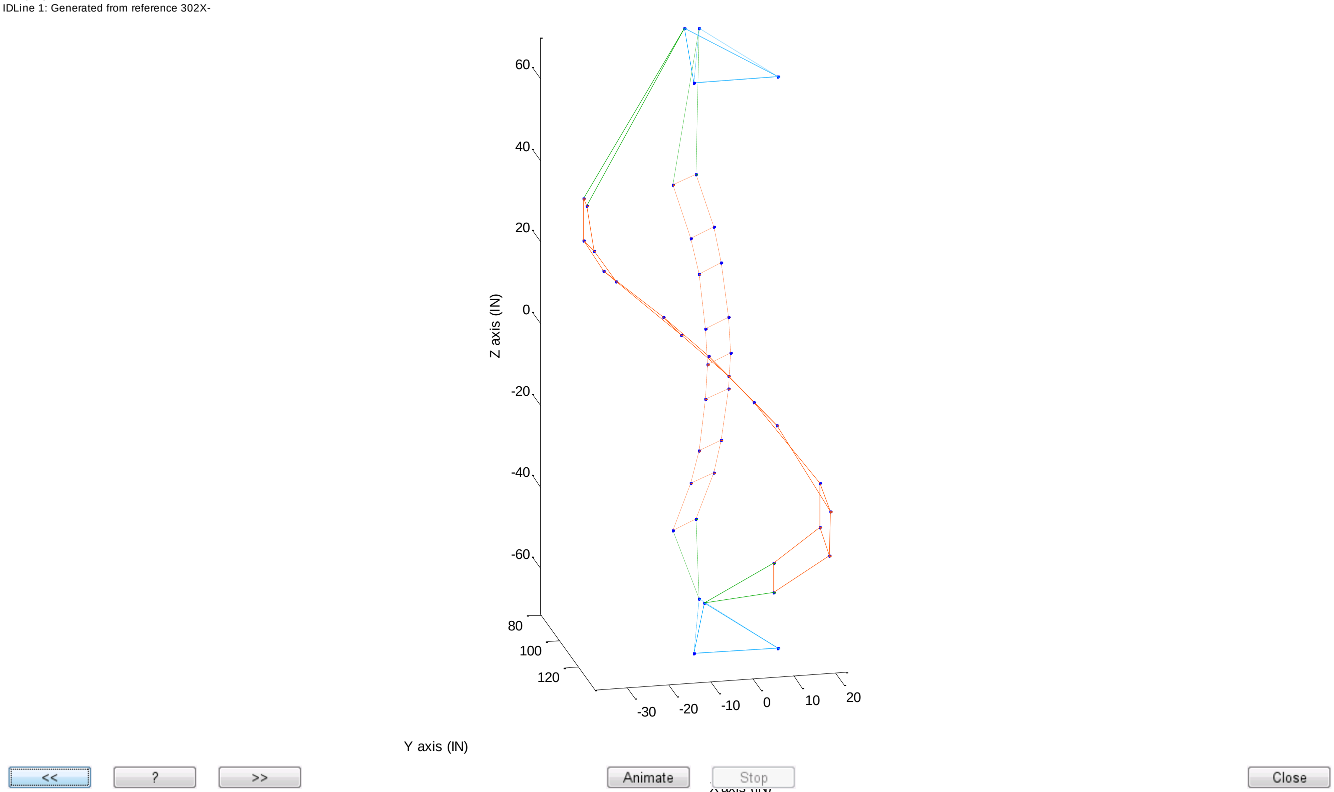


9.3 45 Degree Low Tension Mode Shapes

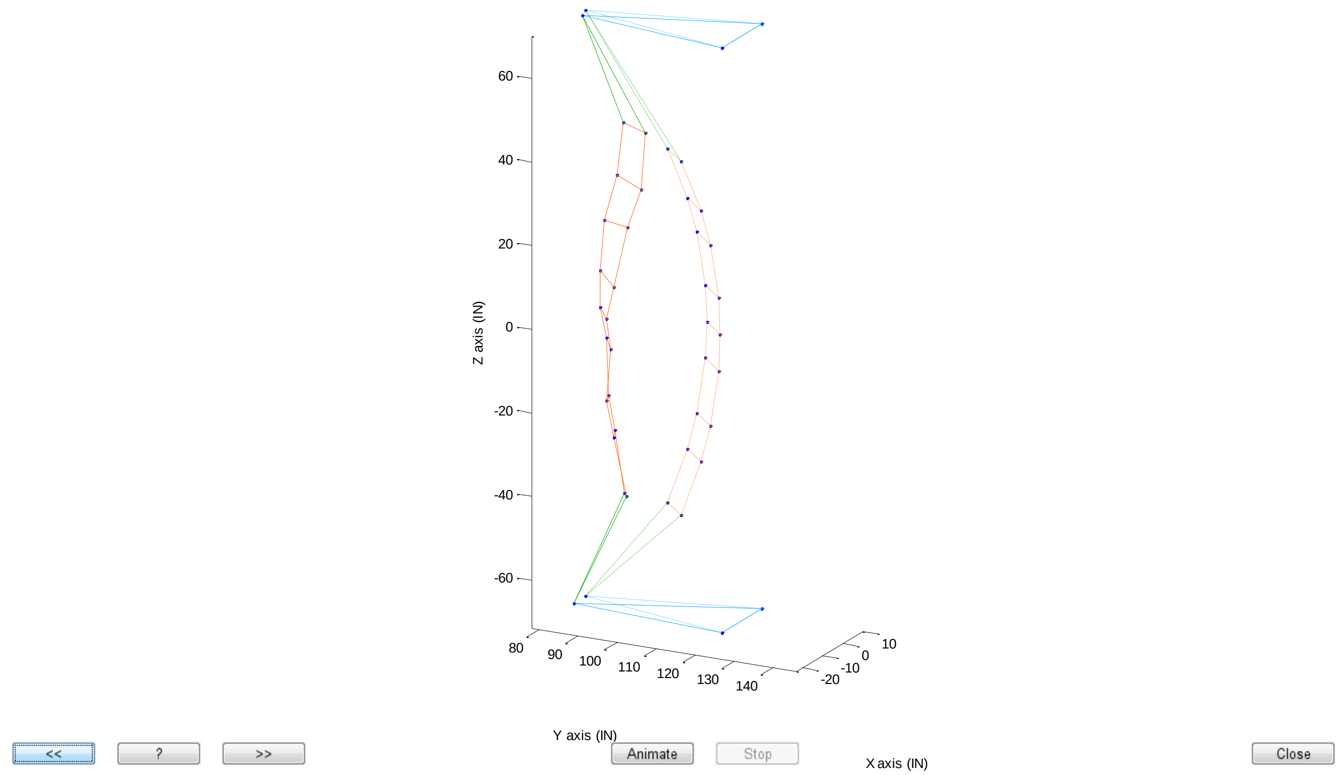
Mode 1
Frequency: 1.121 Hz
Damping: 0.456 %Cr
IDLine 1: Generated from reference 302Z+



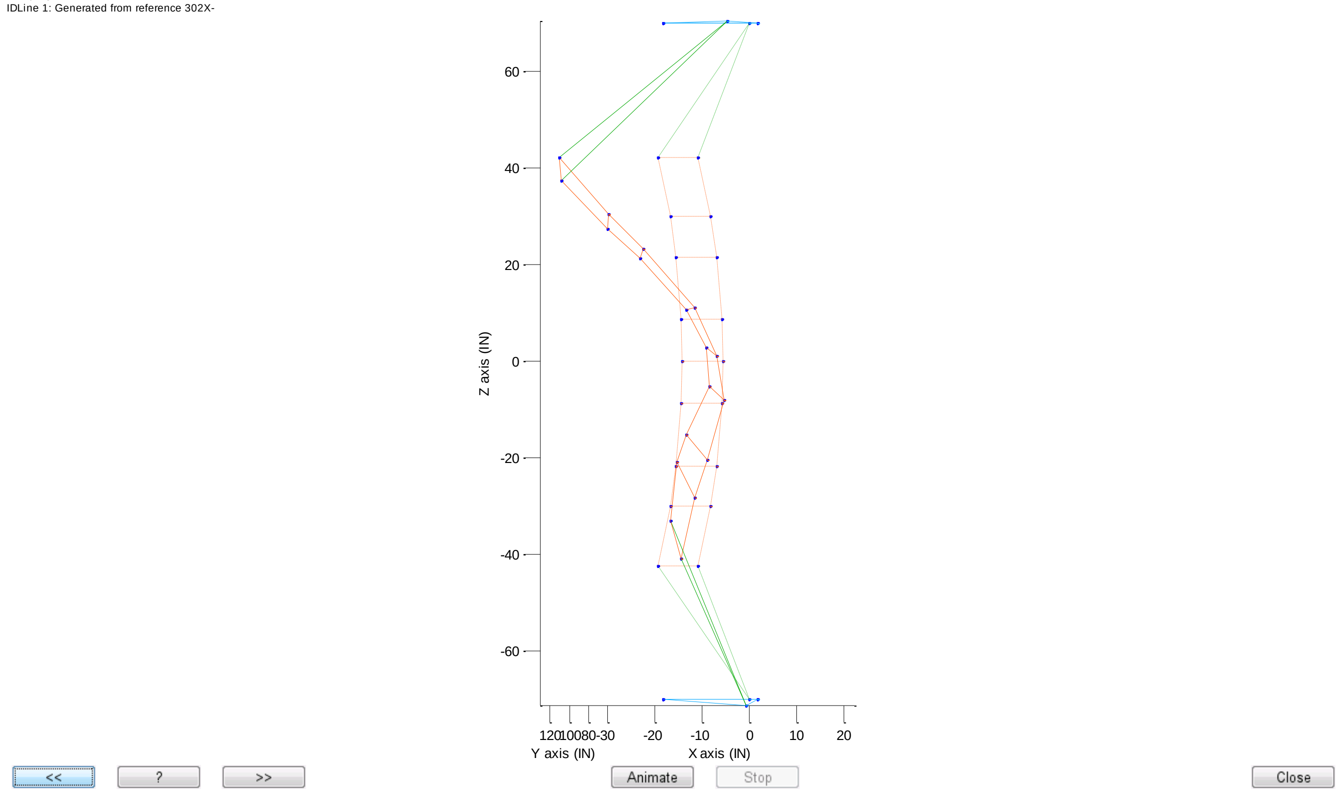
Mode 2
Frequency: 1.746 Hz
Damping: 0.488 %Cr
IDLine 1: Generated from reference 302X-

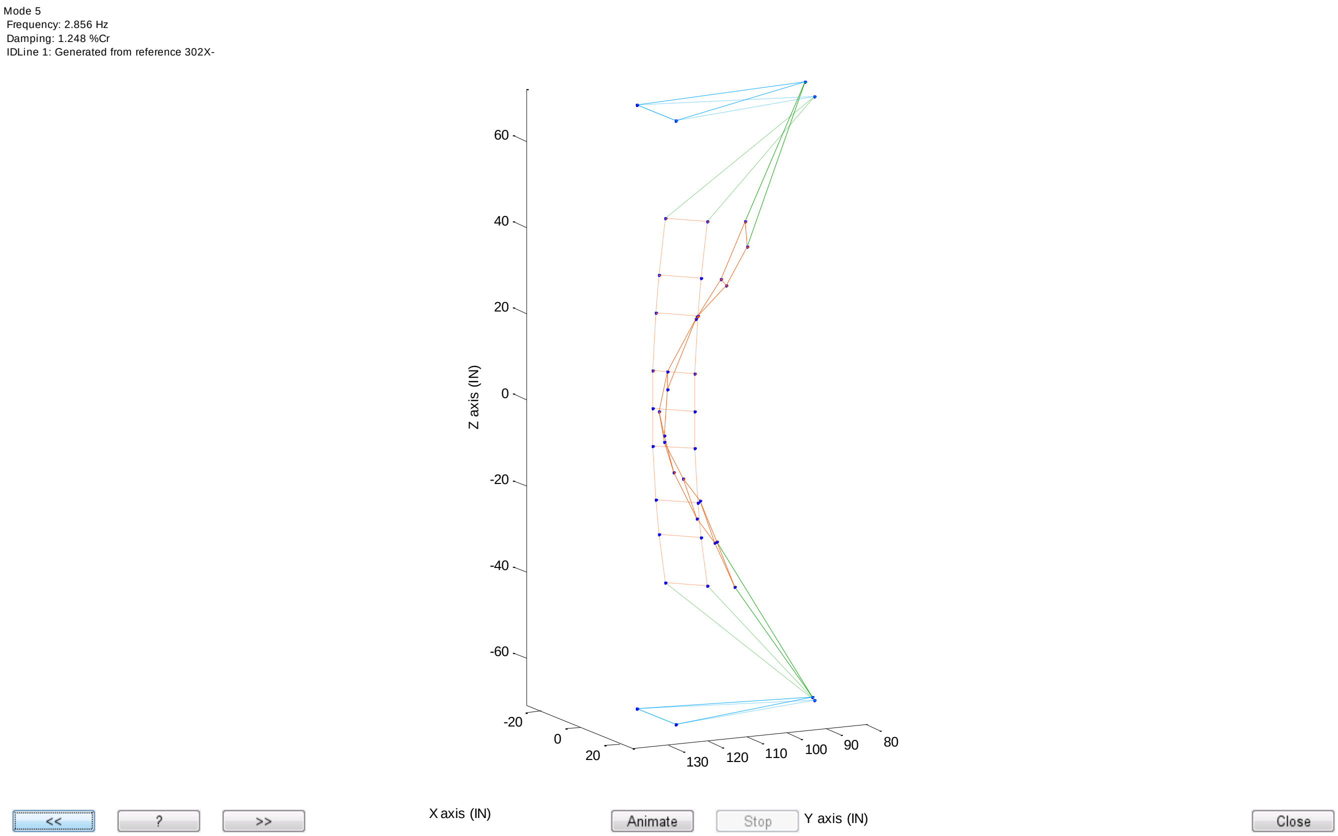


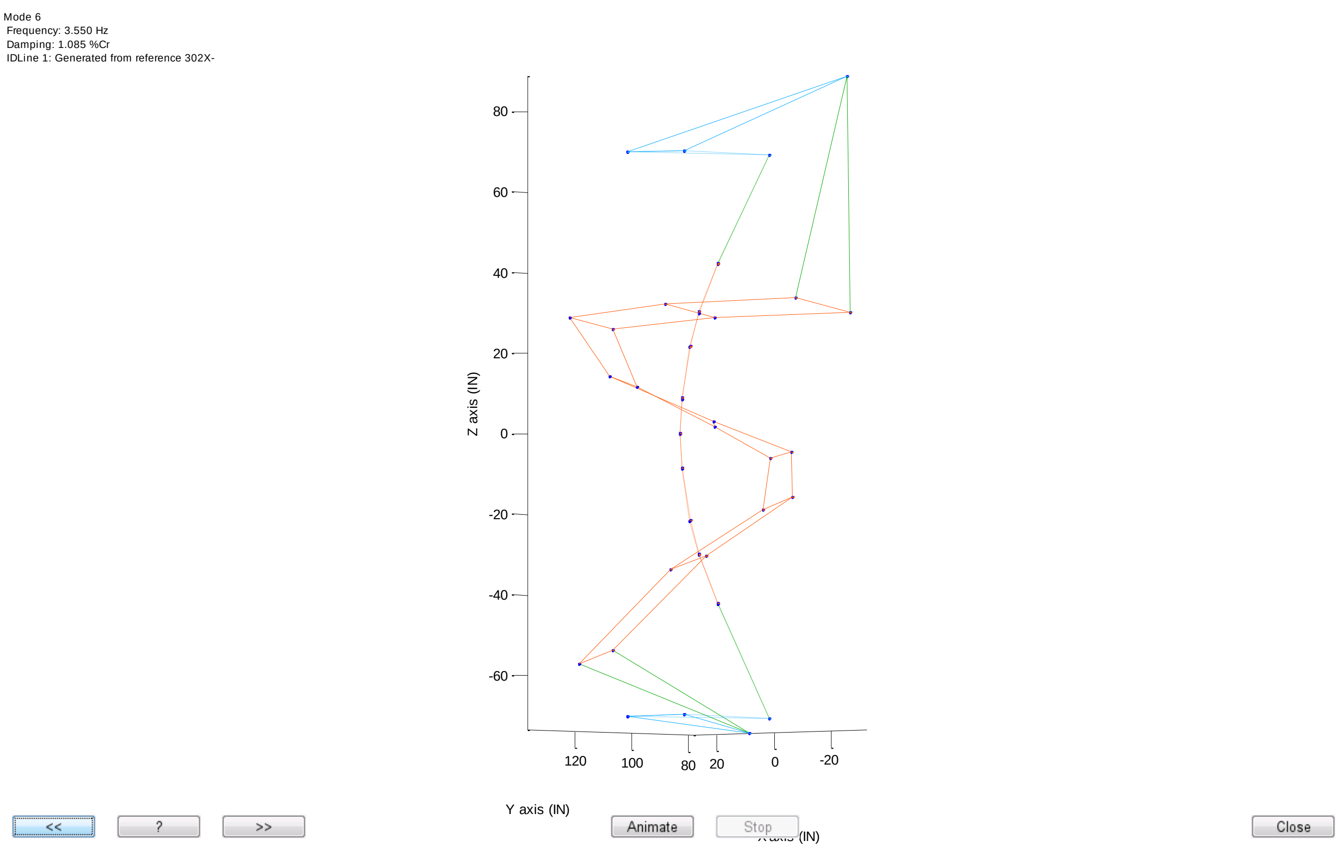
Mode 3
Frequency: 2.194 Hz
Damping: 2.024 %Cr
IDLine 1: Generated from reference 302X-

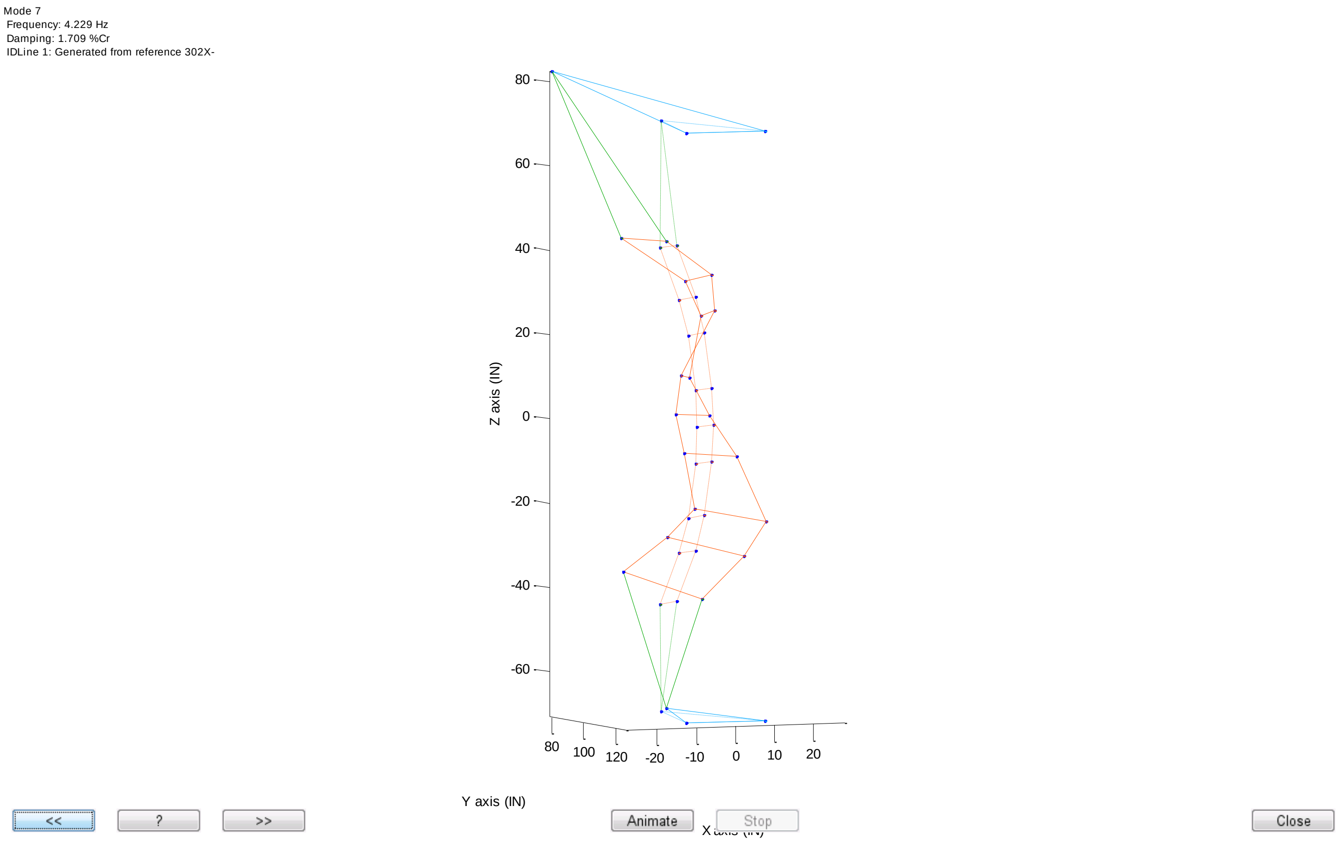


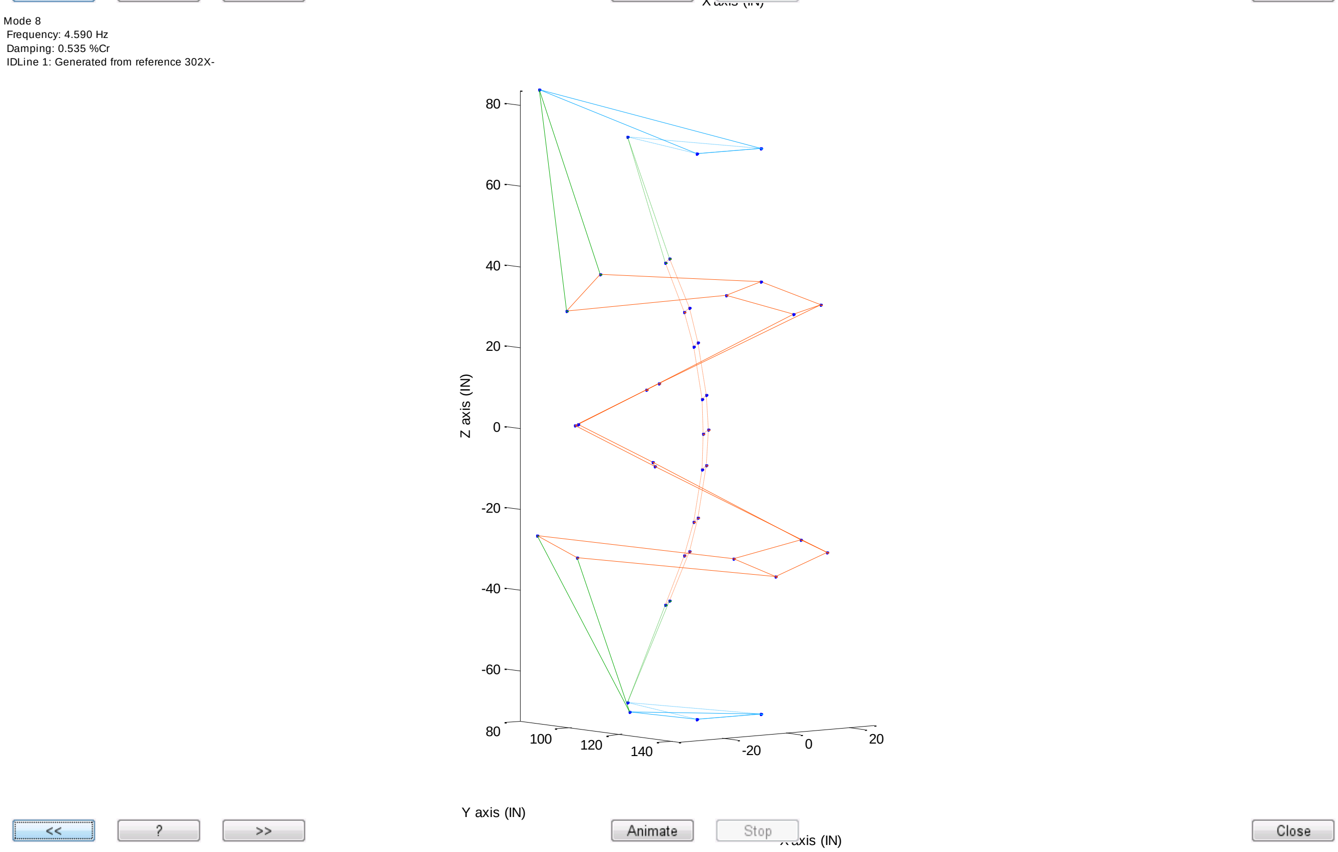
Mode 4
Frequency: 2.479 Hz
Damping: 0.026 %Cr
IDLine 1: Generated from reference 302X-




Mode 5
Frequency: 2.856 Hz
Damping: 1.248 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
-20
0
20
130
120
110
100
90
80
X axis (IN)
Y axis (IN)
<<
?
>>
Animate
Stop
Close

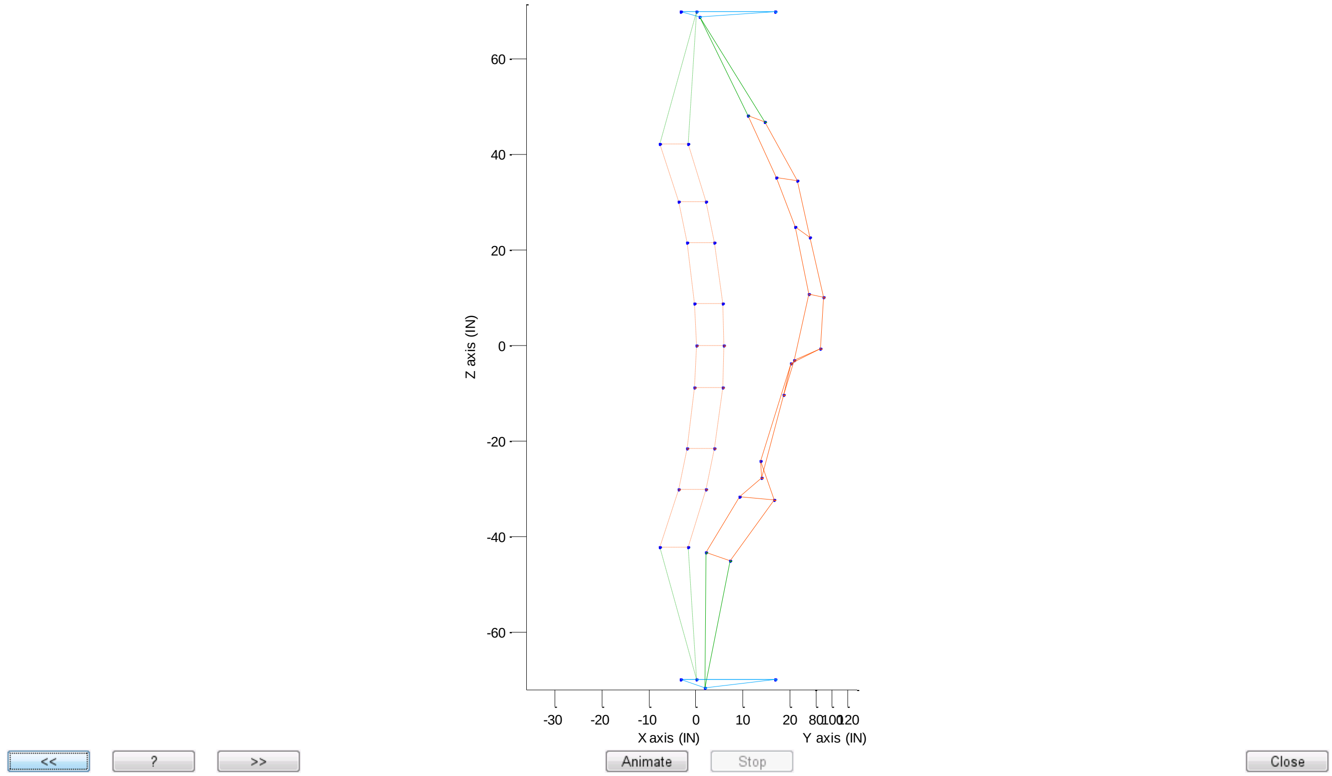

Mode 6
Frequency: 3.550 Hz
Damping: 1.085 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
80
60
40
20
0
-20
-40
-60
120
100
80
20
0
-20
Y axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 7
Frequency: 4.229 Hz
Damping: 1.709 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
80
60
40
20
0
-20
-40
-60
80
100
120
-20
-10
0
10
20
Y axis (IN)
<<
?
>>
Animate
Stop
Close

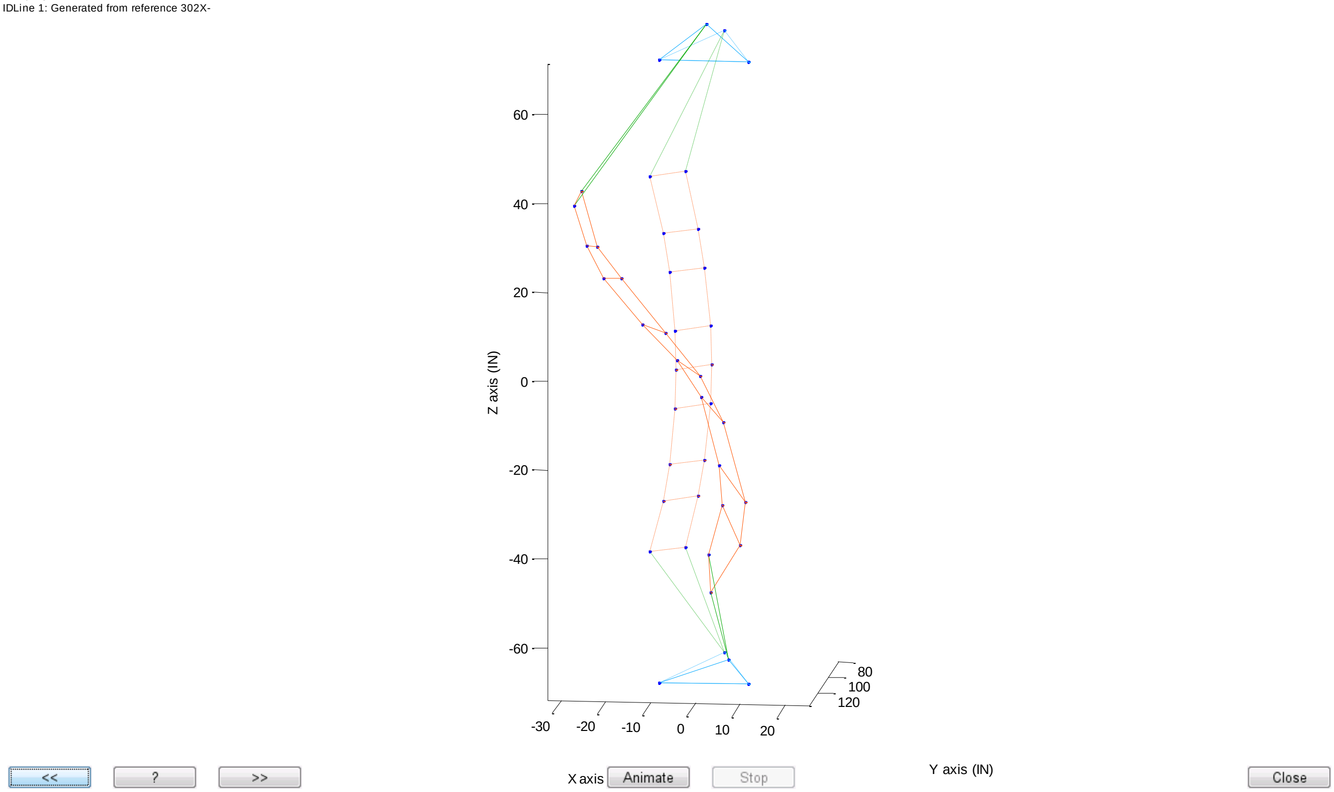

Mode 8
Frequency: 4.590 Hz
Damping: 0.535 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
80
60
40
20
0
-20
-40
-60
80
100
120
140
-20
0
20
Y axis (IN)
<<
?
>>
Animate
Stop
Close

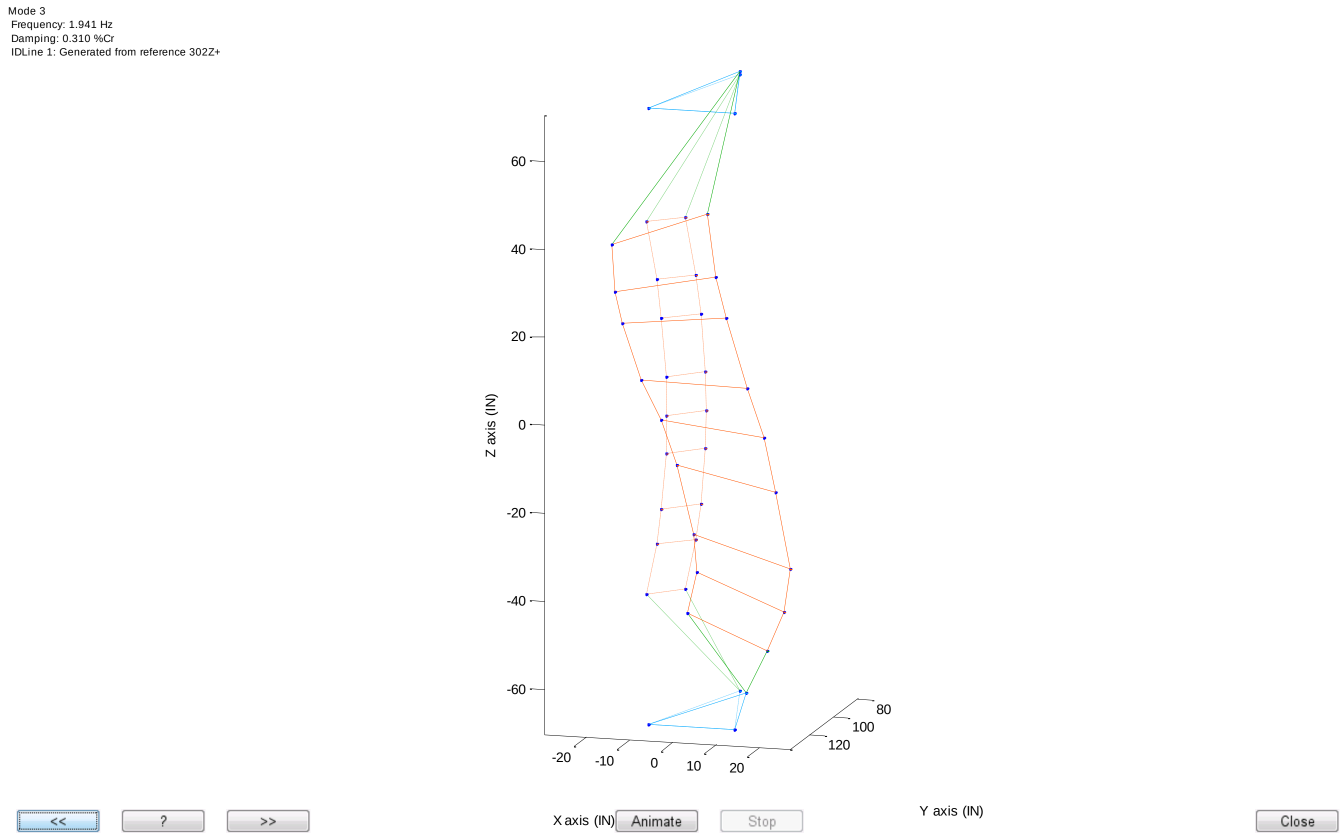
9.4 45 Degree High Tension Mode Shapes

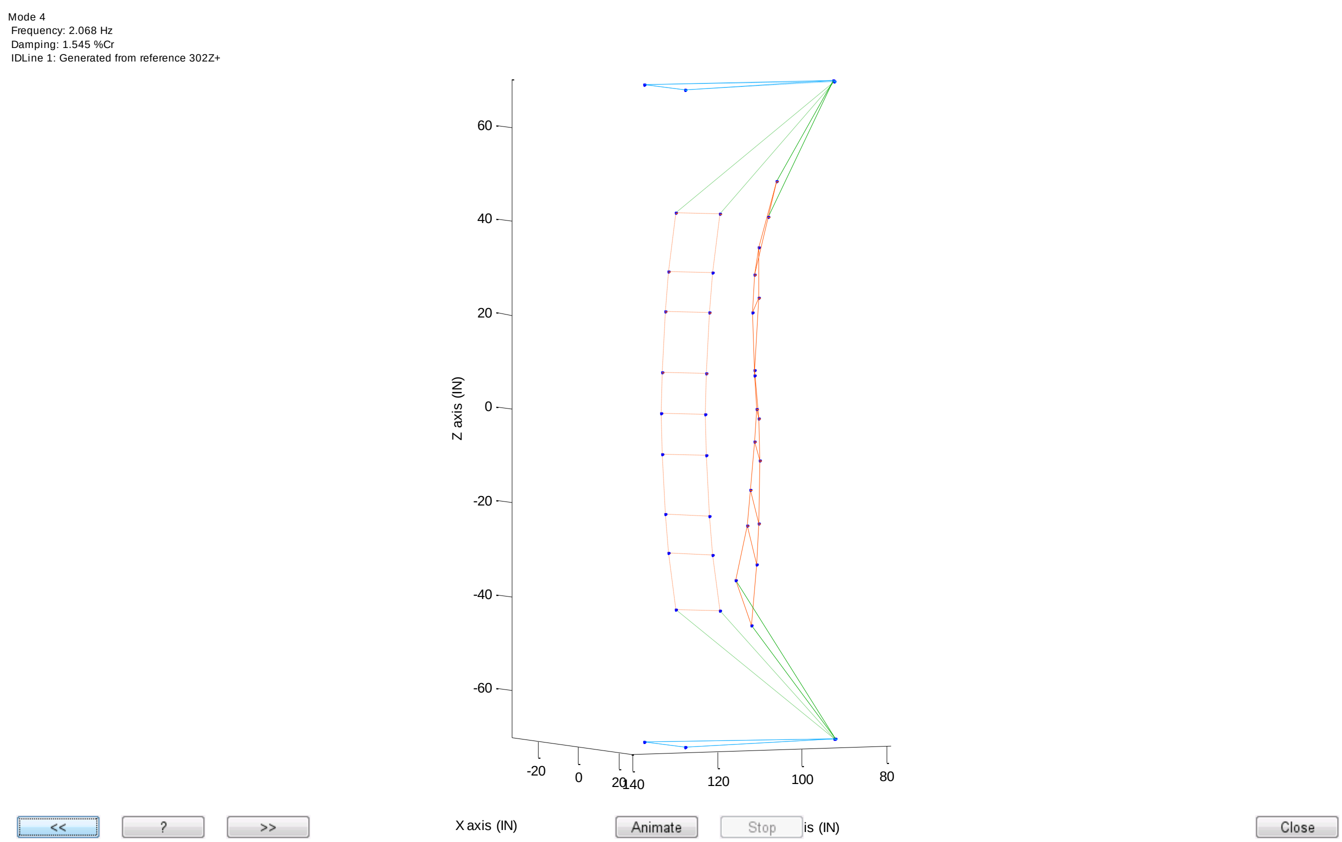
Mode 1
Frequency: 0.928 Hz
Damping: 1.351 %Cr
IDLine 1: Generated from reference 302Z+



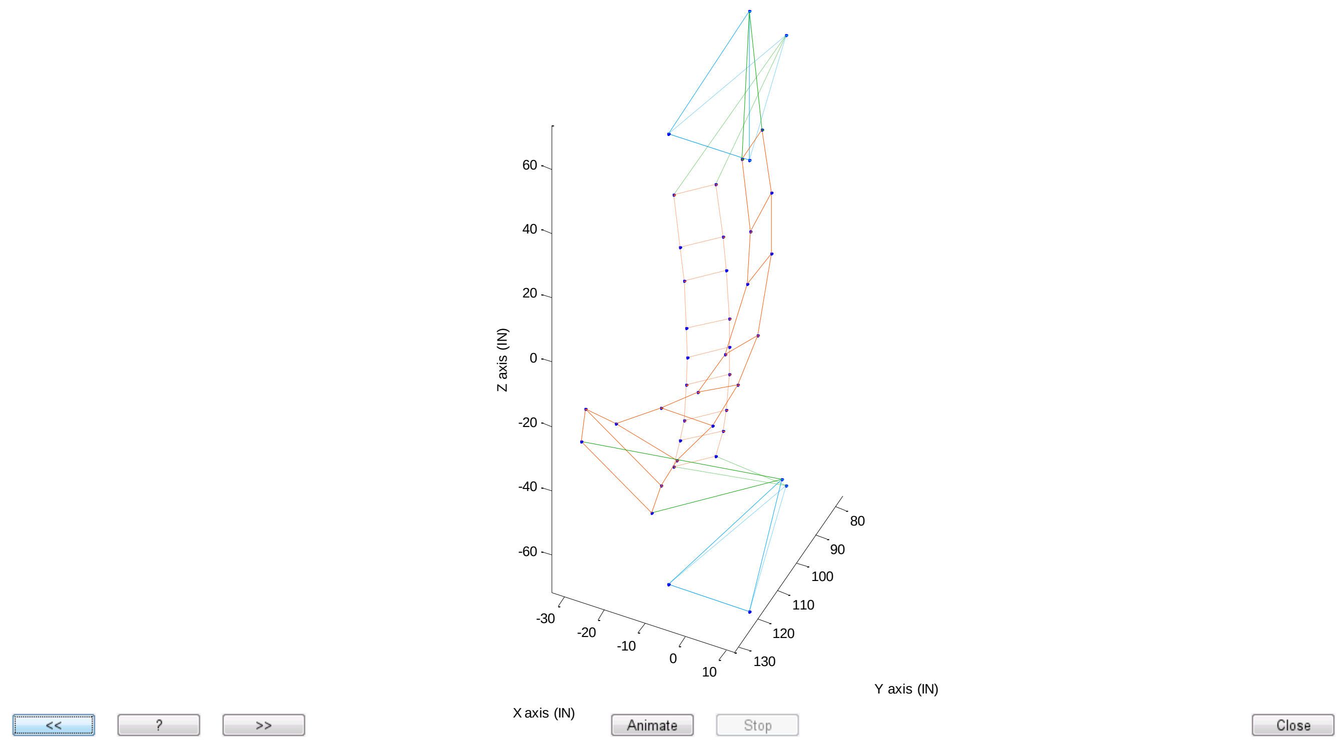
Mode 2
Frequency: 1.853 Hz
Damping: 0.940 %Cr
IDLine 1: Generated from reference 302X-



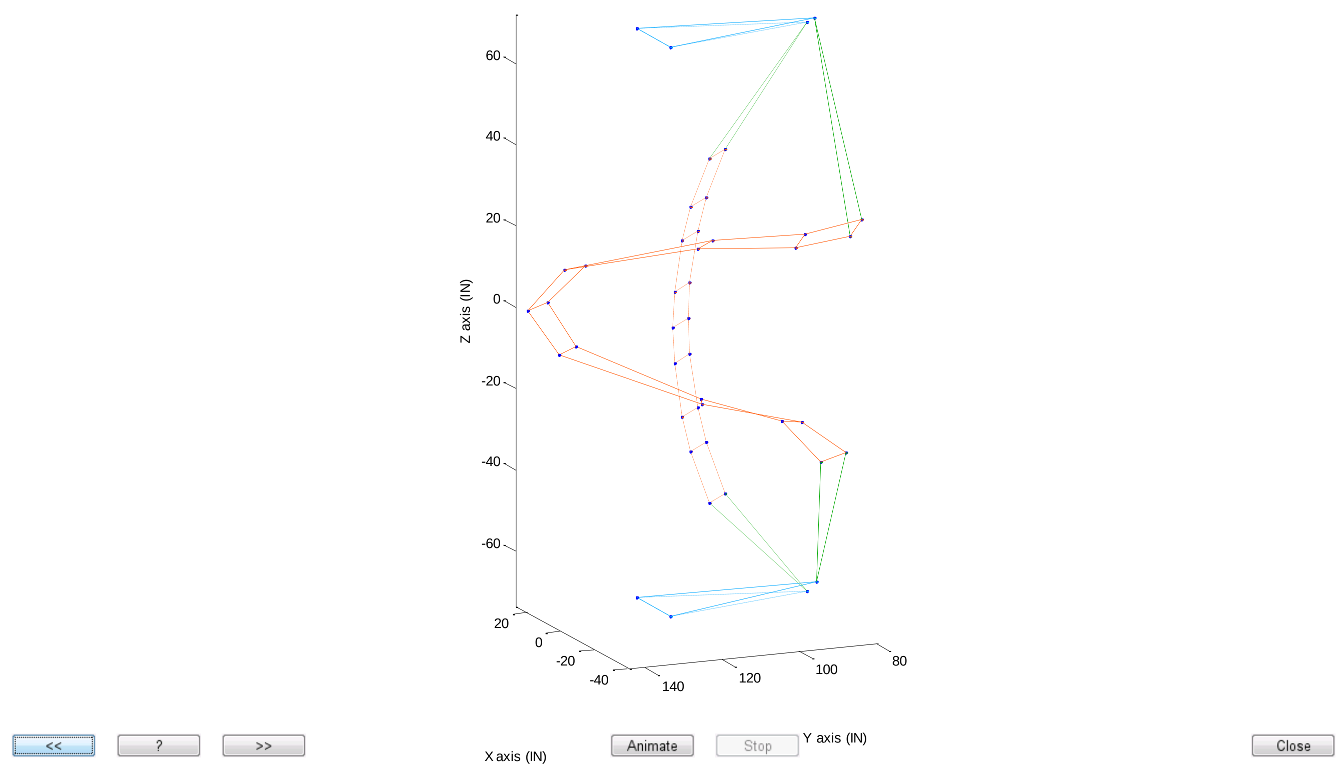

Mode 3
Frequency: 1.941 Hz
Damping: 0.310 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
X axis (IN)
Y axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 4
Frequency: 2.068 Hz
Damping: 1.545 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
X axis (IN)
<<
?
>>
Animate
Stop
Close

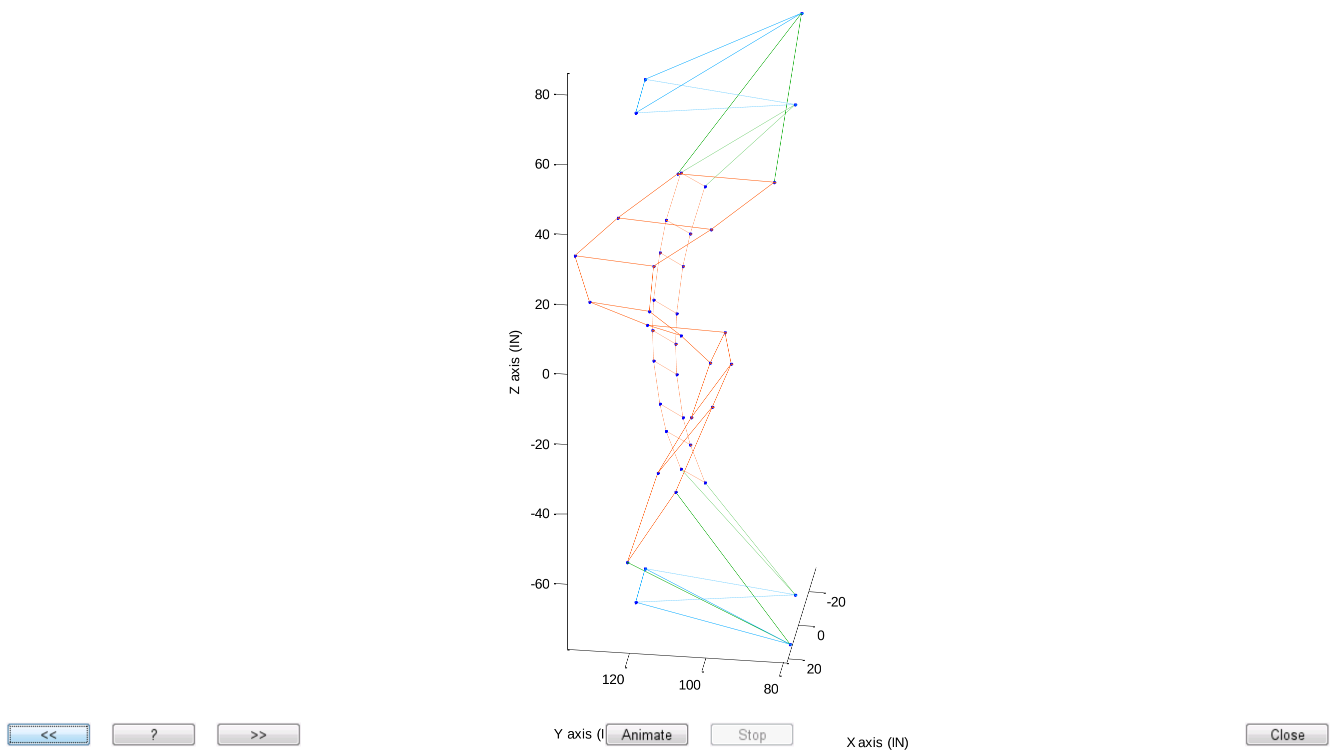
Mode 5
Frequency: 2.746 Hz
Damping: 0.695 %Cr
IDLine 1: Generated from reference 302X-



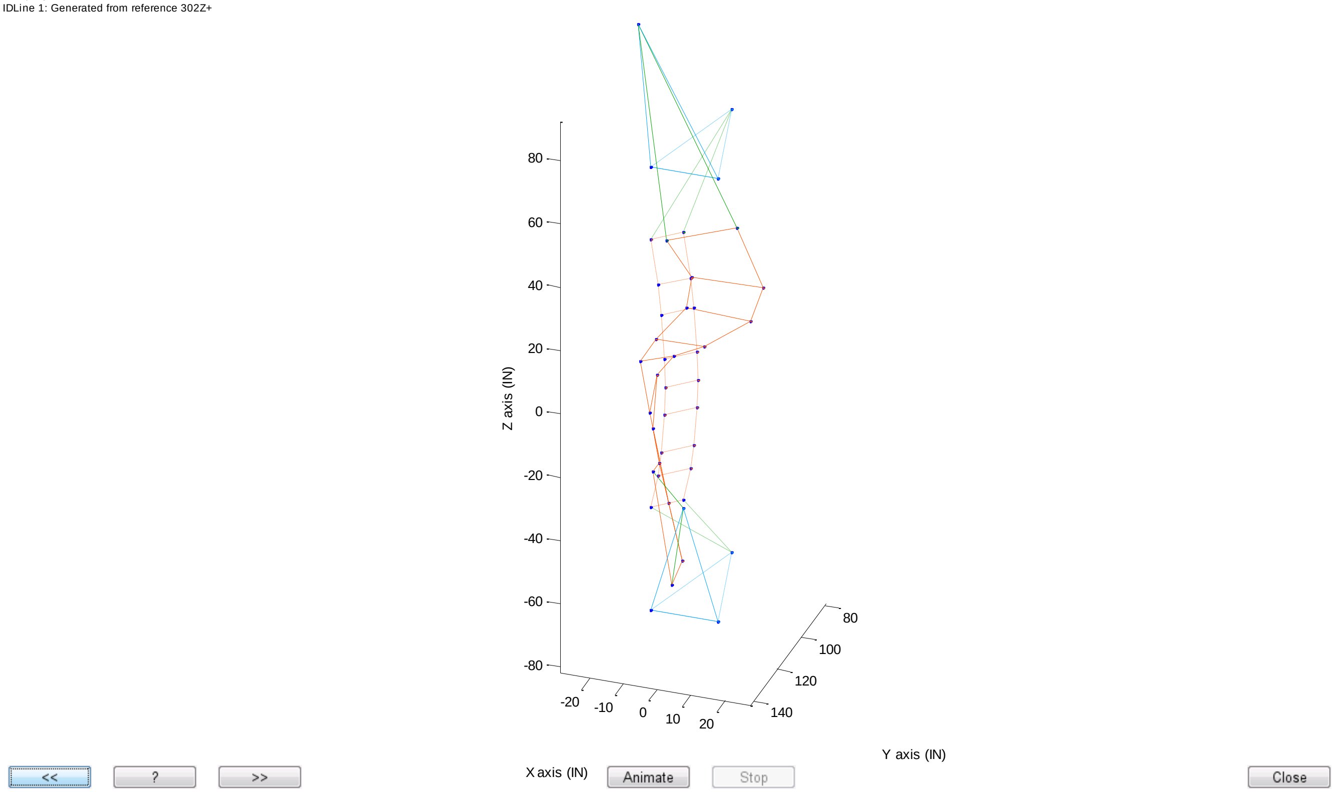
Mode 6
Frequency: 2.862 Hz
Damping: 0.240 %Cr
IDLine 1: Generated from reference 302X-

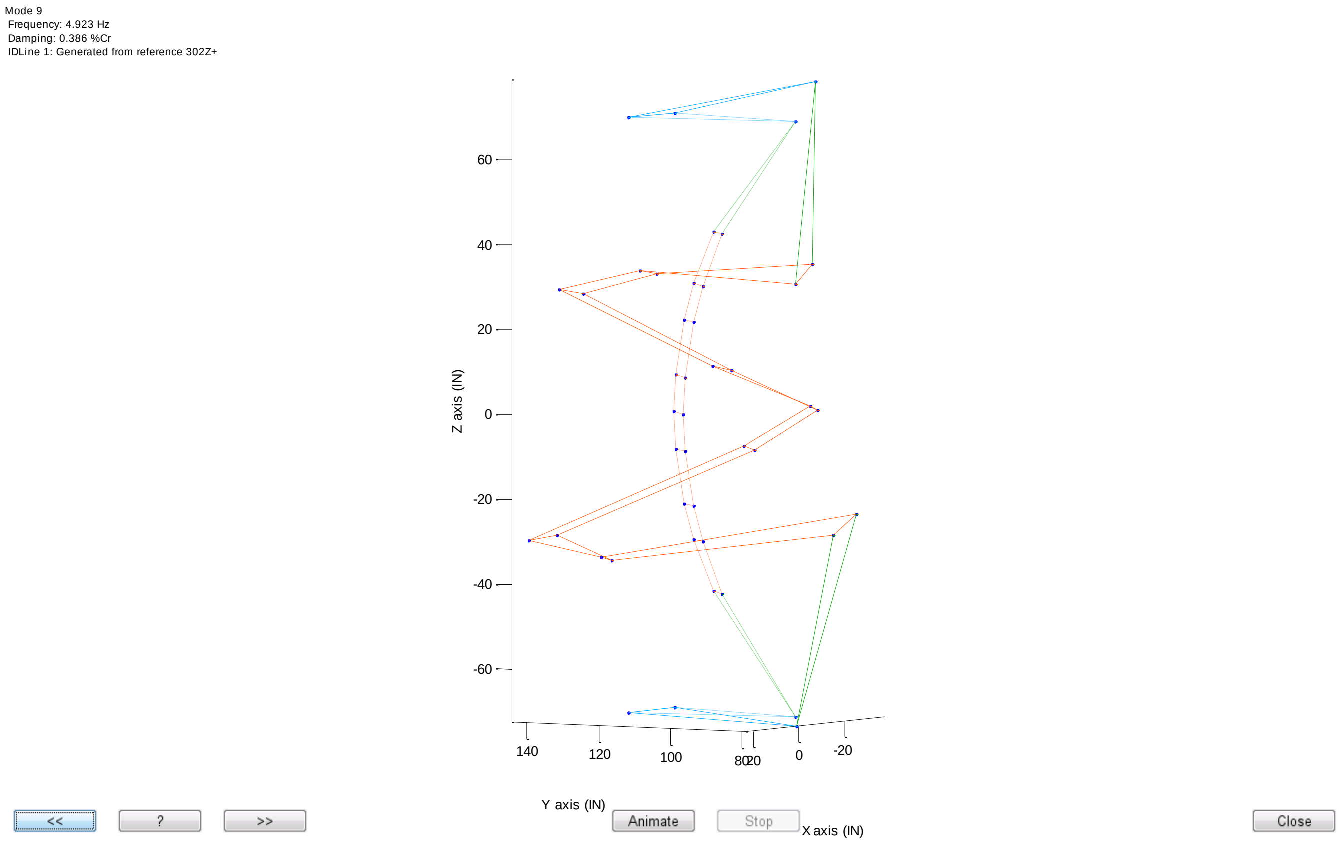


Mode 7
Frequency: 3.550 Hz
Damping: 2.107 %Cr
IDLine 1: Generated from reference 302Z+



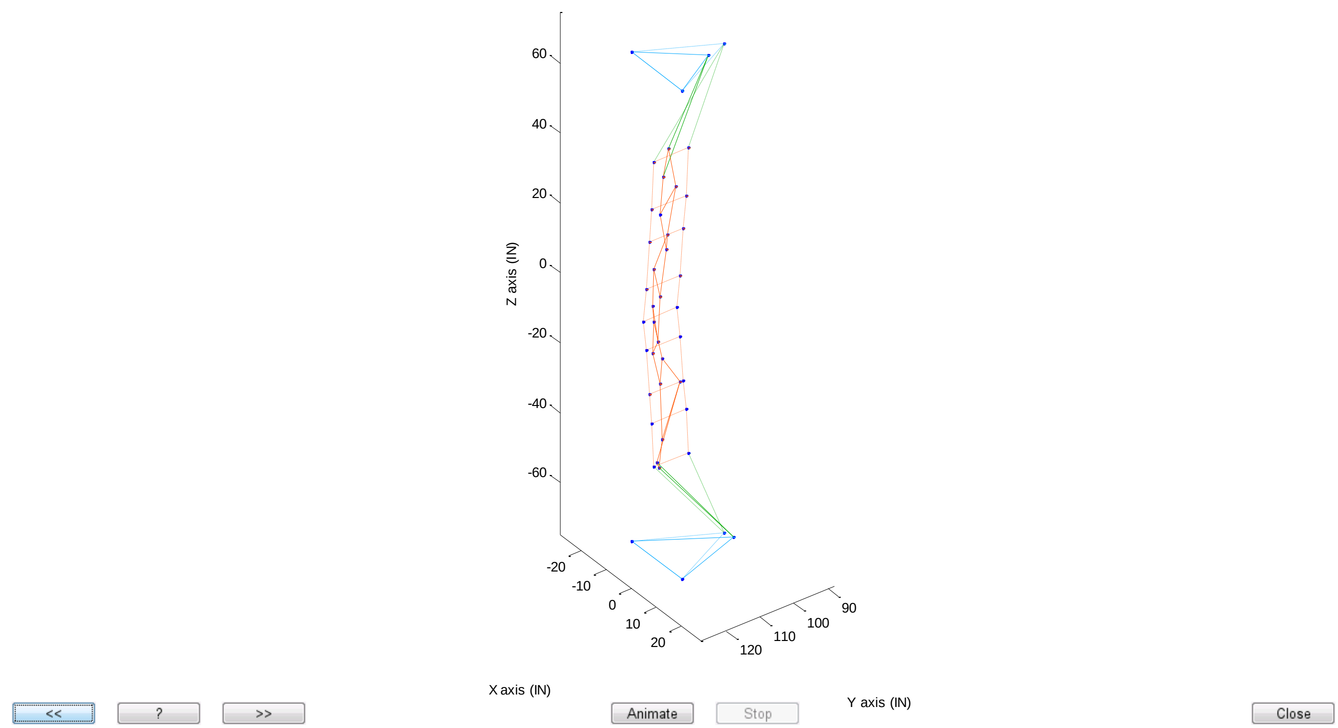
Mode 8
Frequency: 3.809 Hz
Damping: 1.248 %Cr
IDLine 1: Generated from reference 302Z+



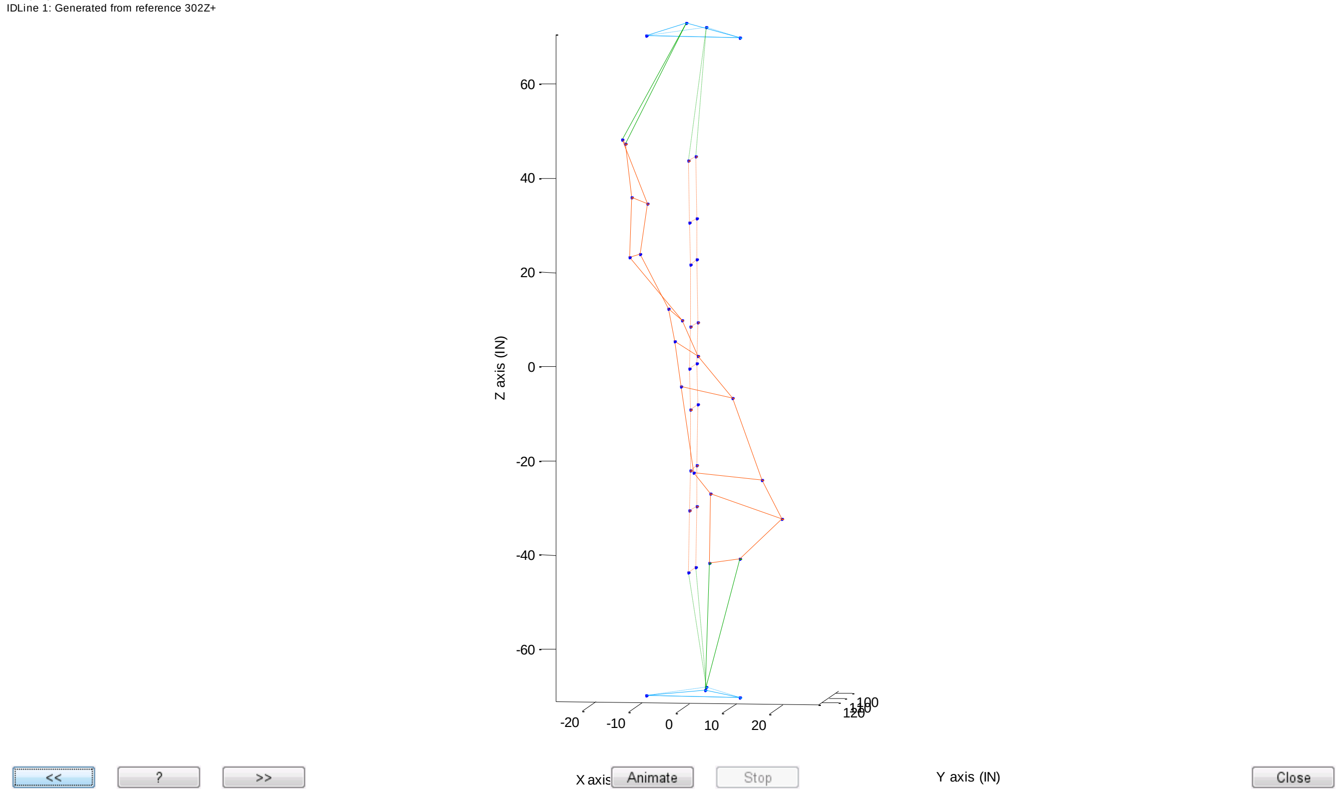

Mode 9
Frequency: 4.923 Hz
Damping: 0.386 %Cr
IDLine 1: Generated from reference 302Z+
60
40
20
0
-20
-40
-60
Z axis (IN)
140
120
100
80
20
0
-20
Y axis (IN)
X axis (IN)
<<
?
>>
Animate
Stop
Close

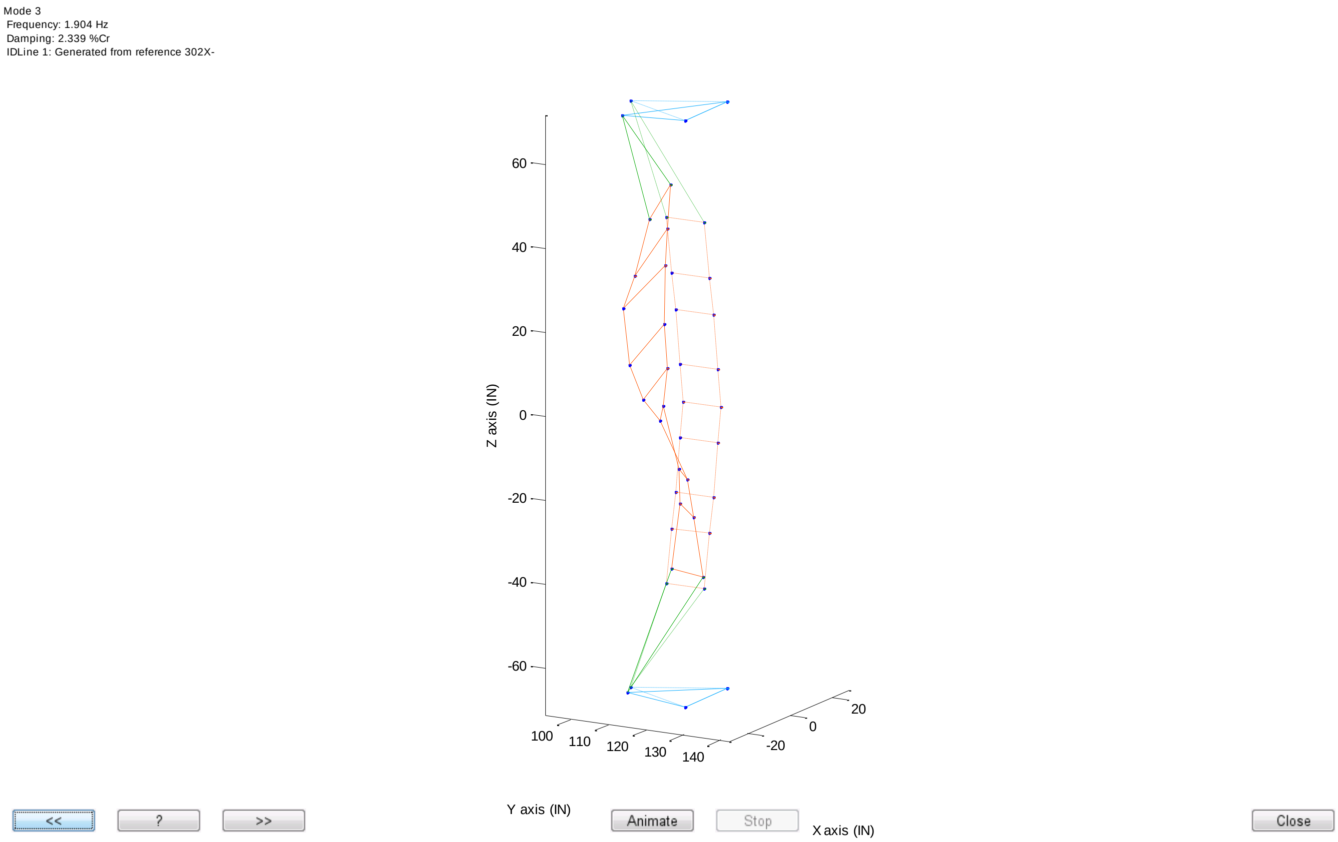
9.5 90 Degree Low Tension Mode Shapes

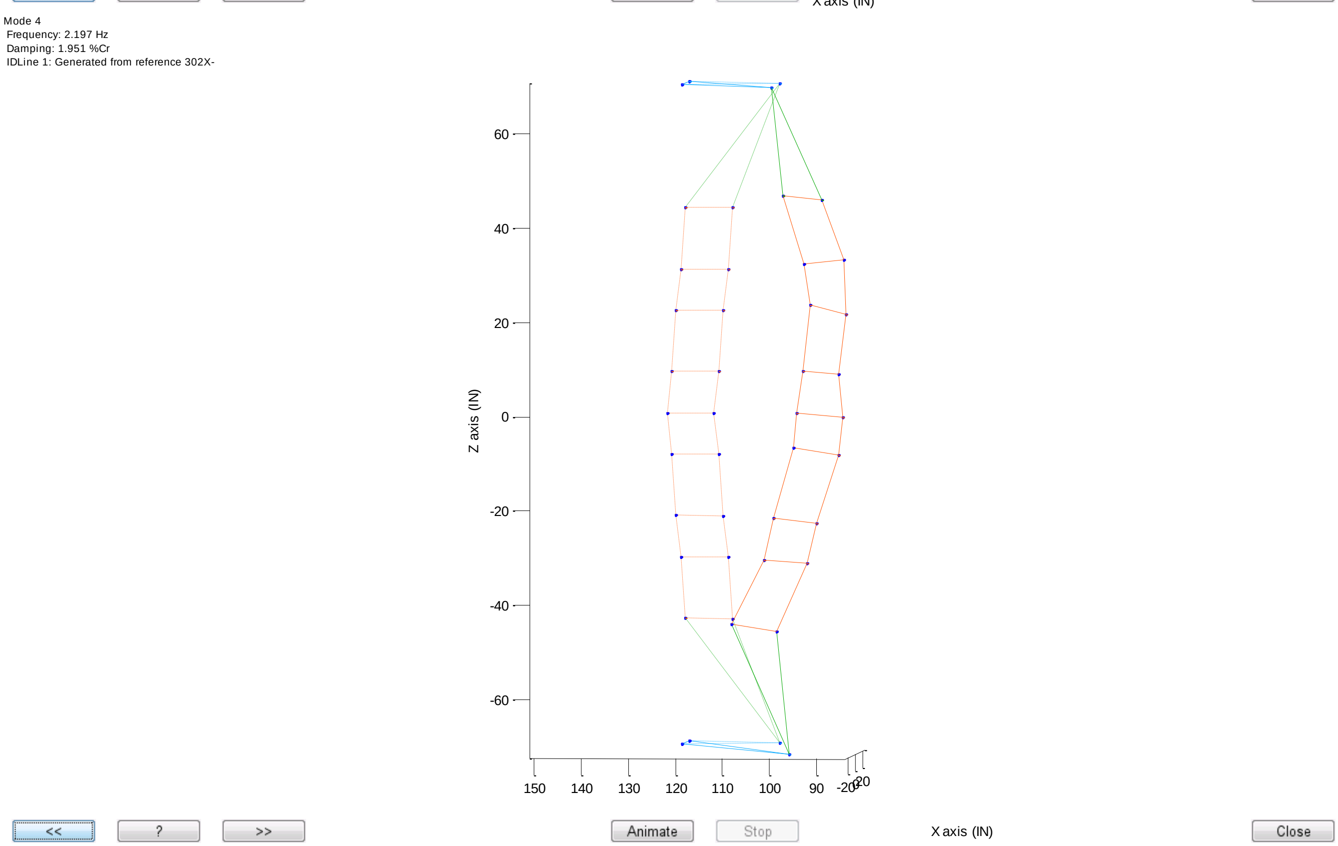
Mode 1
Frequency: 0.963 Hz
Damping: 0.016 %Cr
IDLine 1: Generated from reference 302Z+

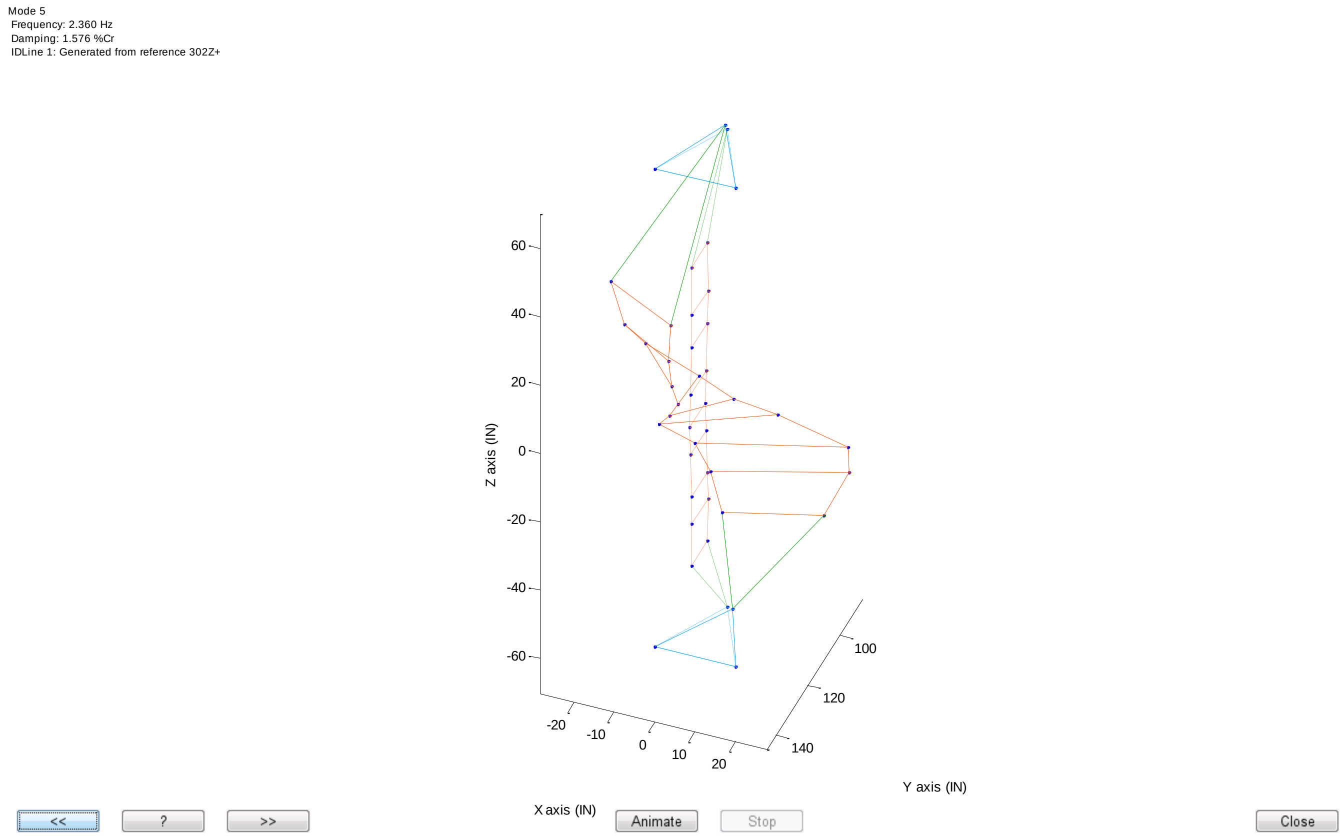


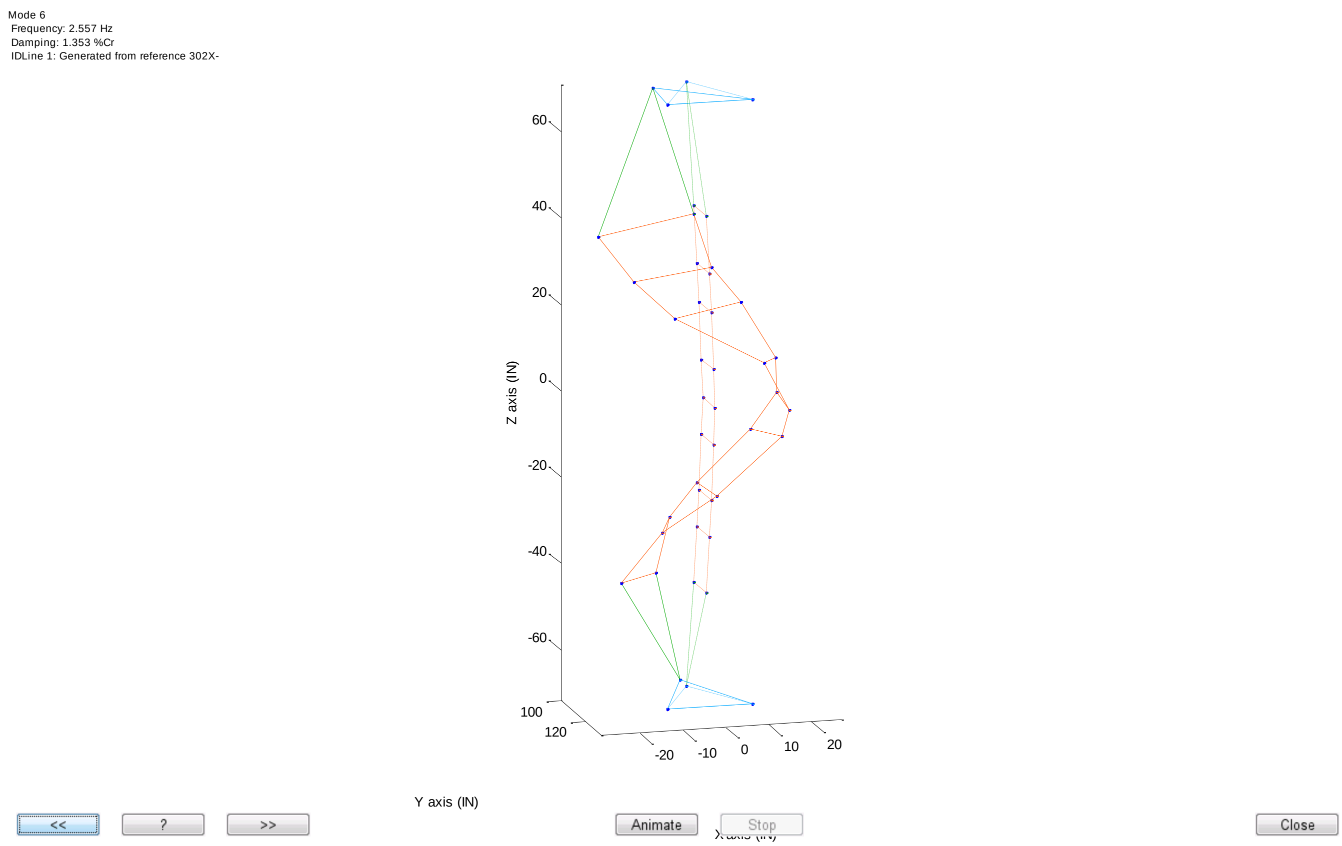
Mode 2
Frequency: 1.645 Hz
Damping: 1.595 %Cr
IDLine 1: Generated from reference 302Z+



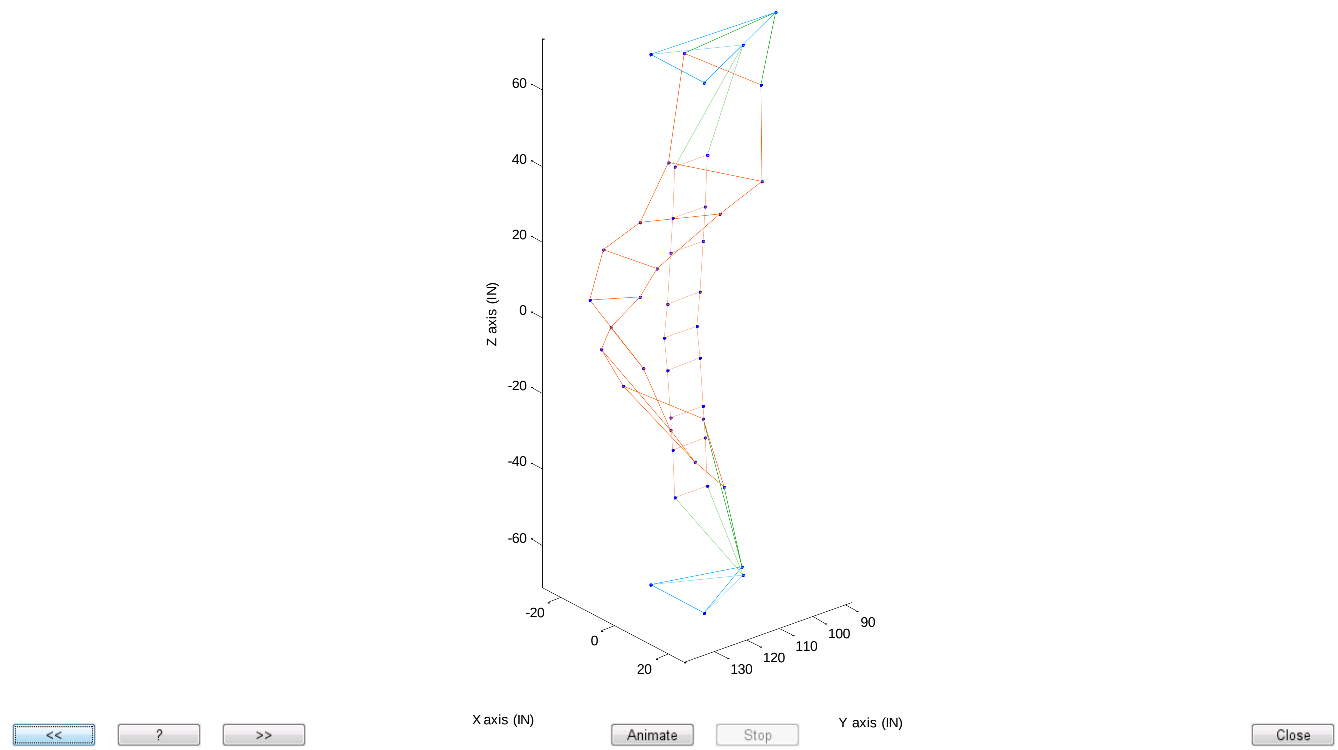

Mode 3
Frequency: 1.904 Hz
Damping: 2.339 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
100
110
120
130
140
-20
0
20
Y axis (IN)
X axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 4
Frequency: 2.197 Hz
Damping: 1.951 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
150
140
130
120
110
100
90
-20
20
X axis (IN)
<<
?
>>
Animate
Stop
Close

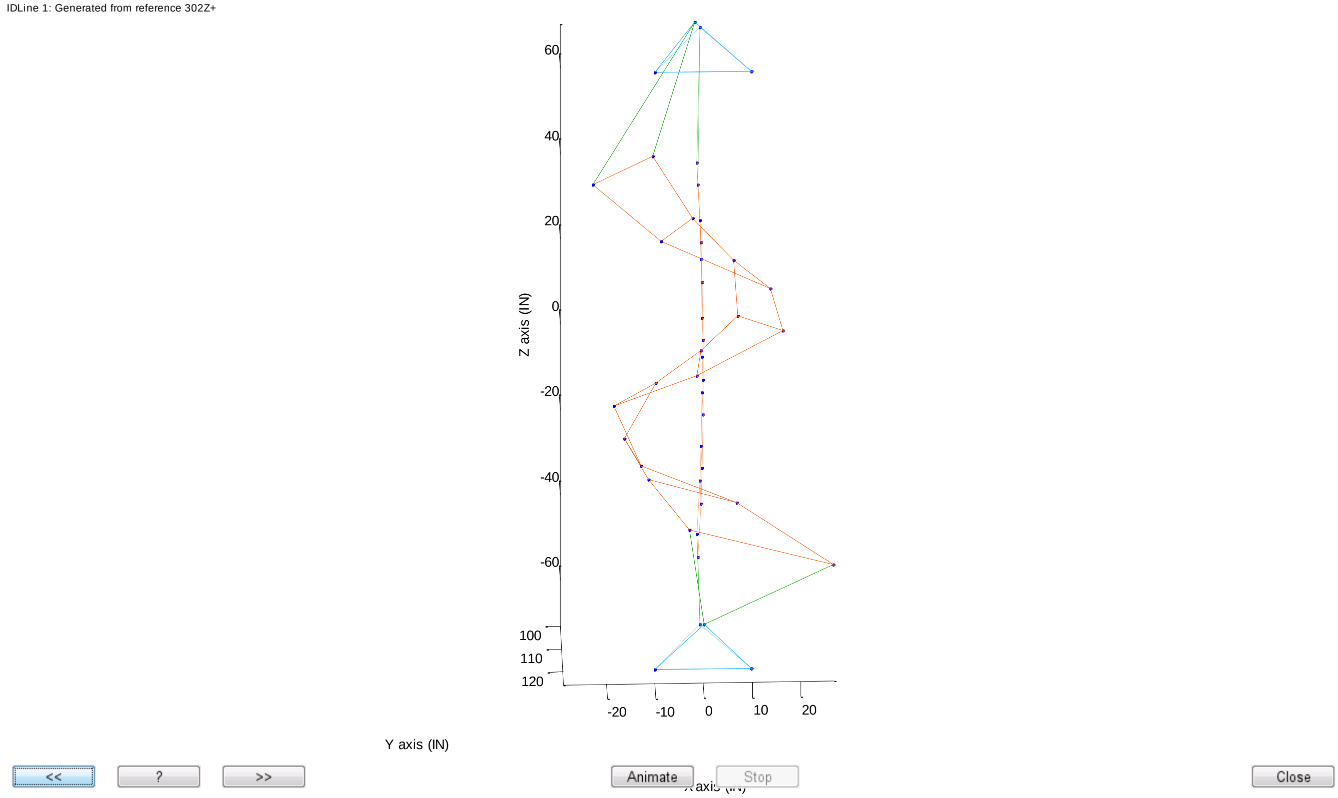

Mode 5
Frequency: 2.360 Hz
Damping: 1.576 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
-20
-10
0
10
20
X axis (IN)
100
120
140
Y axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 6
Frequency: 2.557 Hz
Damping: 1.353 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
100
120
Y axis (IN)
-20
-10
0
10
20
<<
?
>>
Animate
Stop
Close

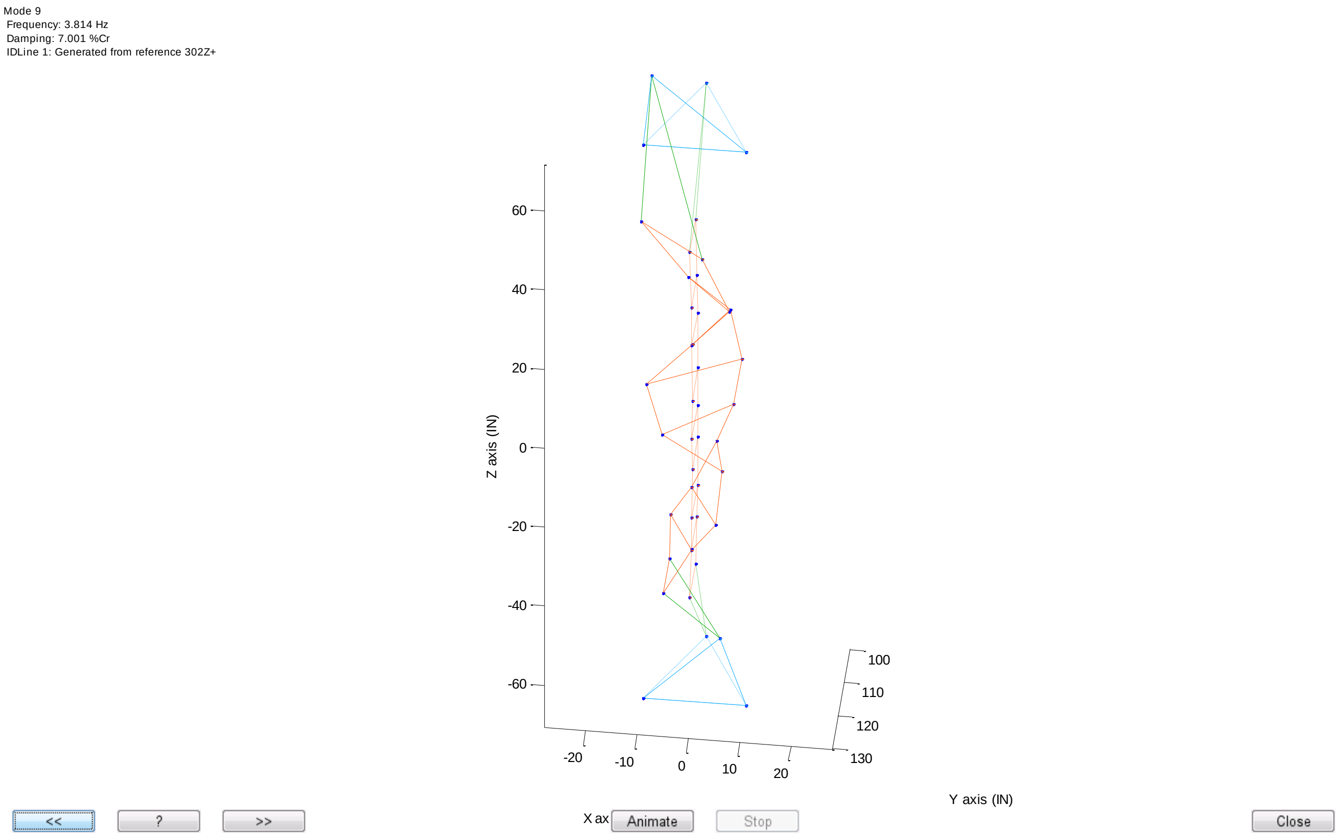
Mode 7
Frequency: 2.898 Hz
Damping: 6.095 %Cr
IDLine 1: Generated from reference 302Z+

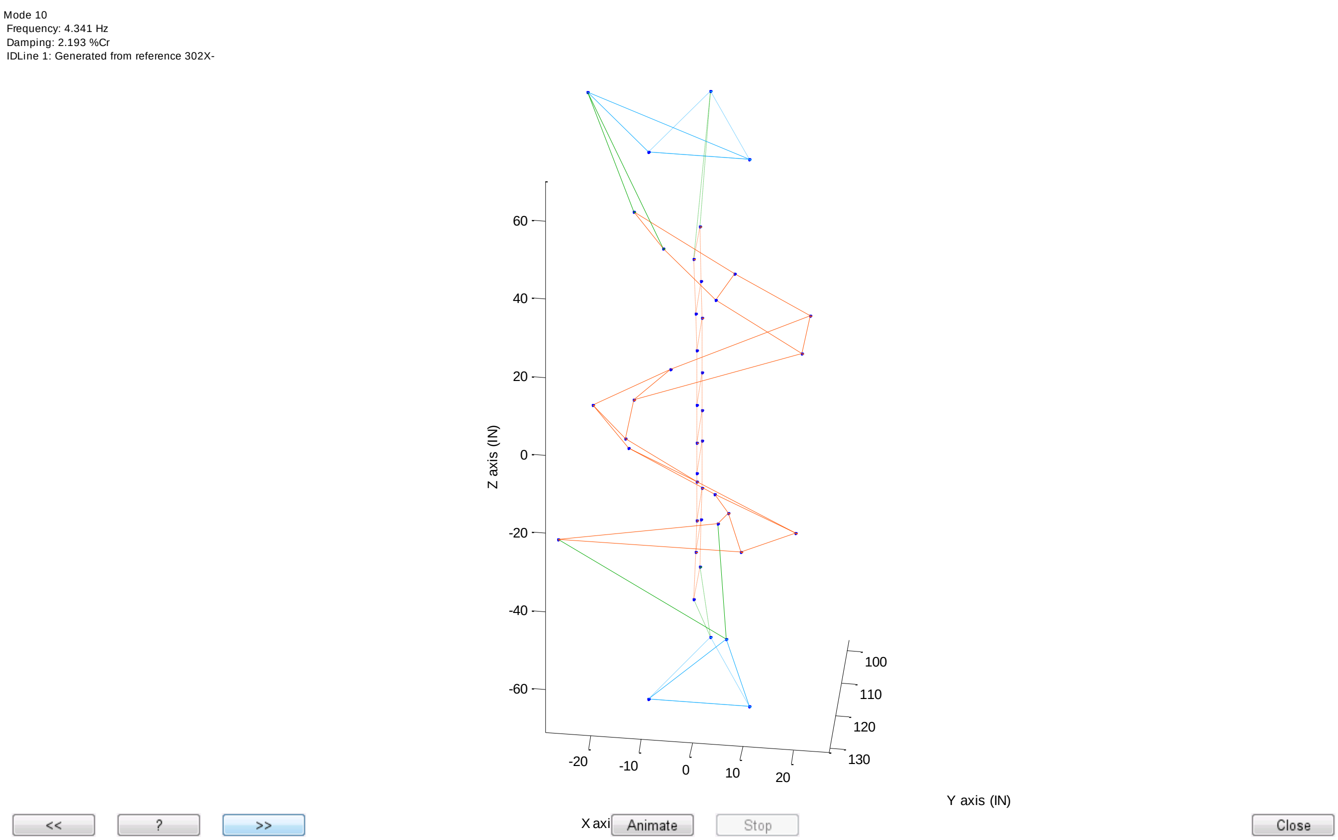


Mode 8
Frequency: 3.375 Hz
Damping: 1.709 %Cr
IDLine 1: Generated from reference 302Z+

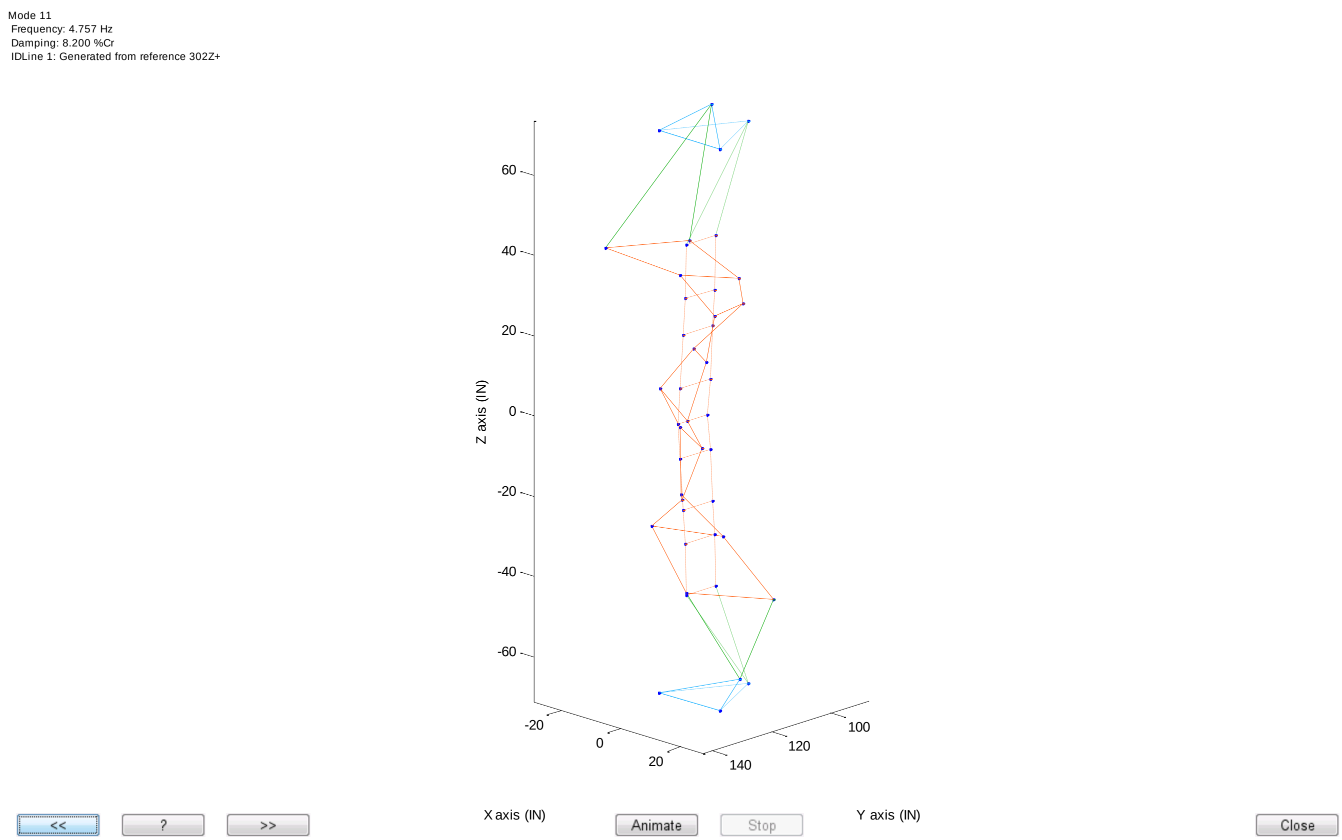


UUR / UNCLASSIFIED UNLIMITED RELEASE



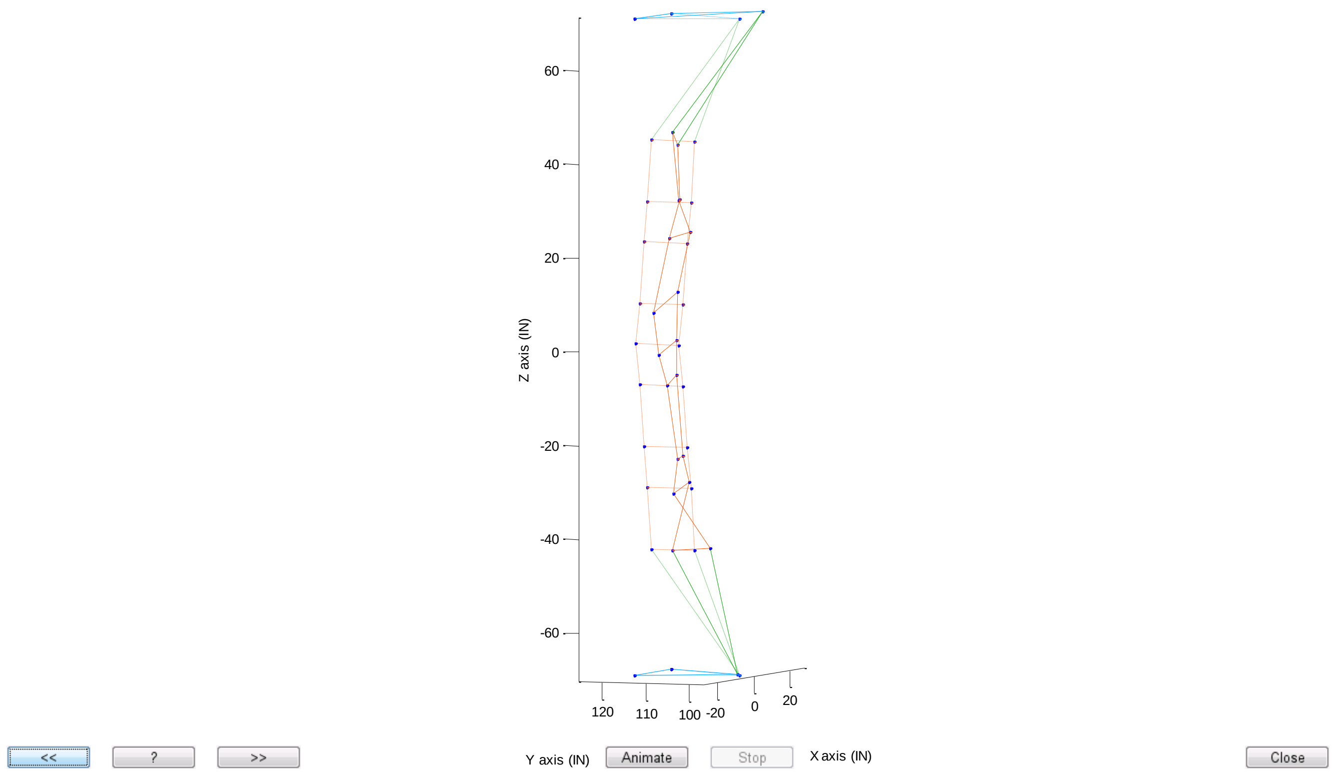


UUR / UNCLASSIFIED UNLIMITED RELEASE

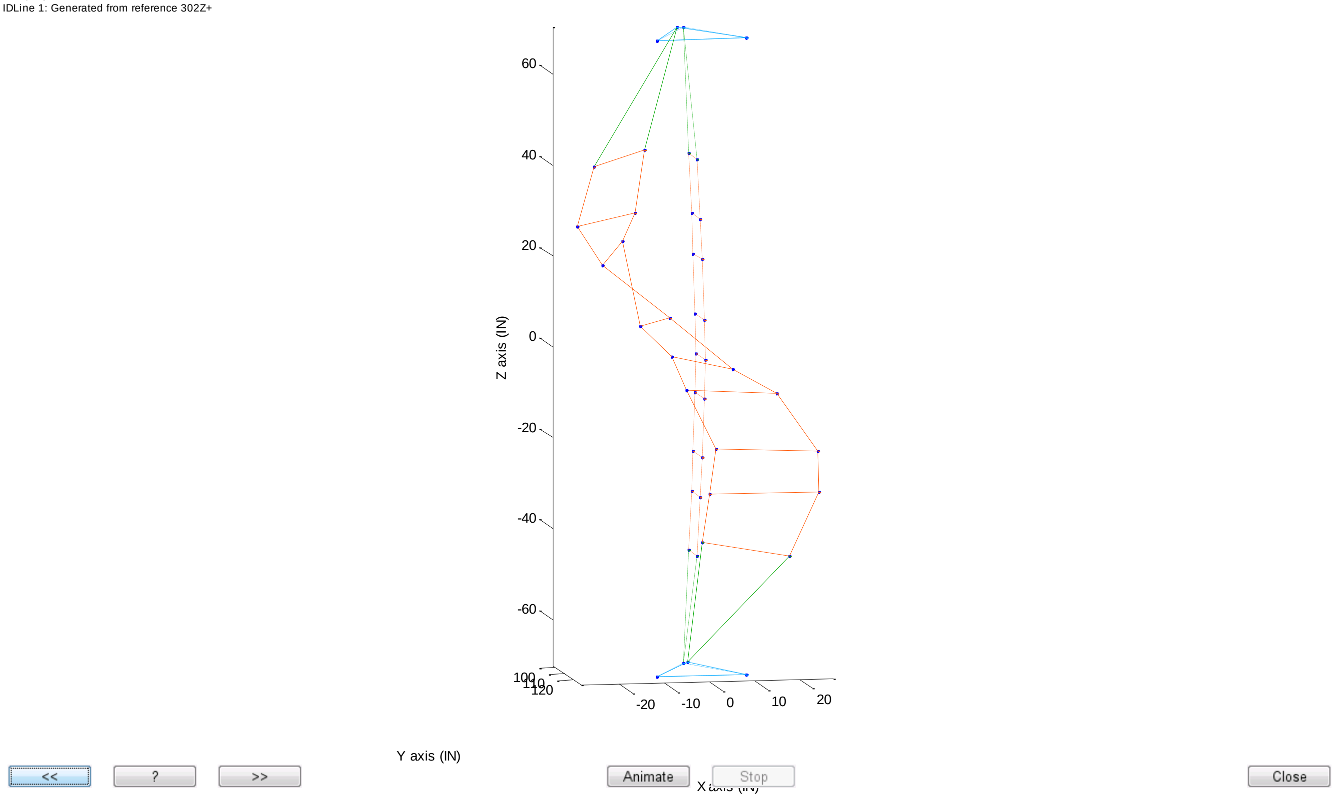

Mode 11
Frequency: 4.757 Hz
Damping: 8.200 %Cr
IDLine 1: Generated from reference 302Z+
60
40
20
0
-20
-40
-60
Z axis (IN)
-20
0
20
140
120
100
X axis (IN)
Y axis (IN)
<<
?
>>
Animate
Stop
Close

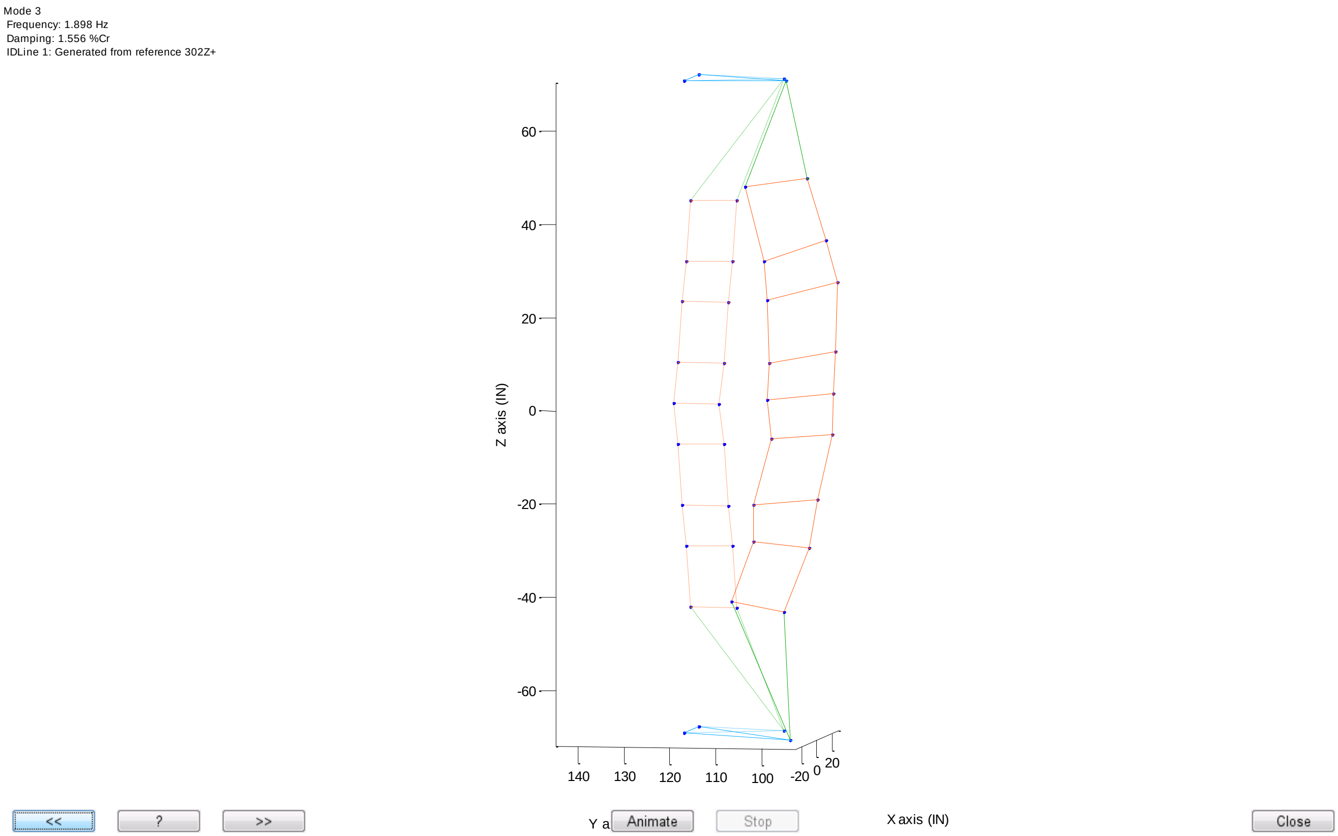
9.6 90 Degree High Tension Mode Shapes

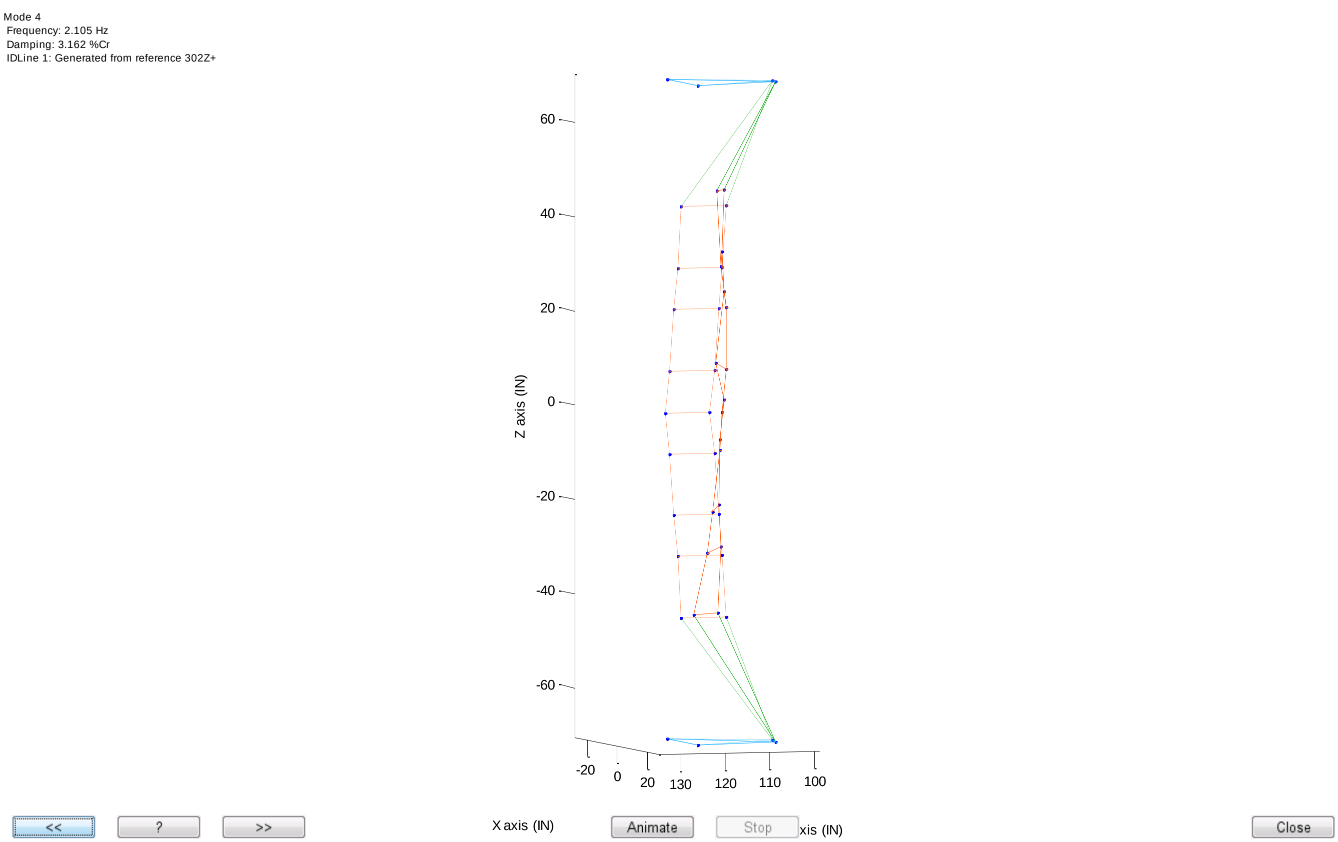
Mode 1
Frequency: 0.944 Hz
Damping: 0.849 %Cr
IDLine 1: Generated from reference 302X-

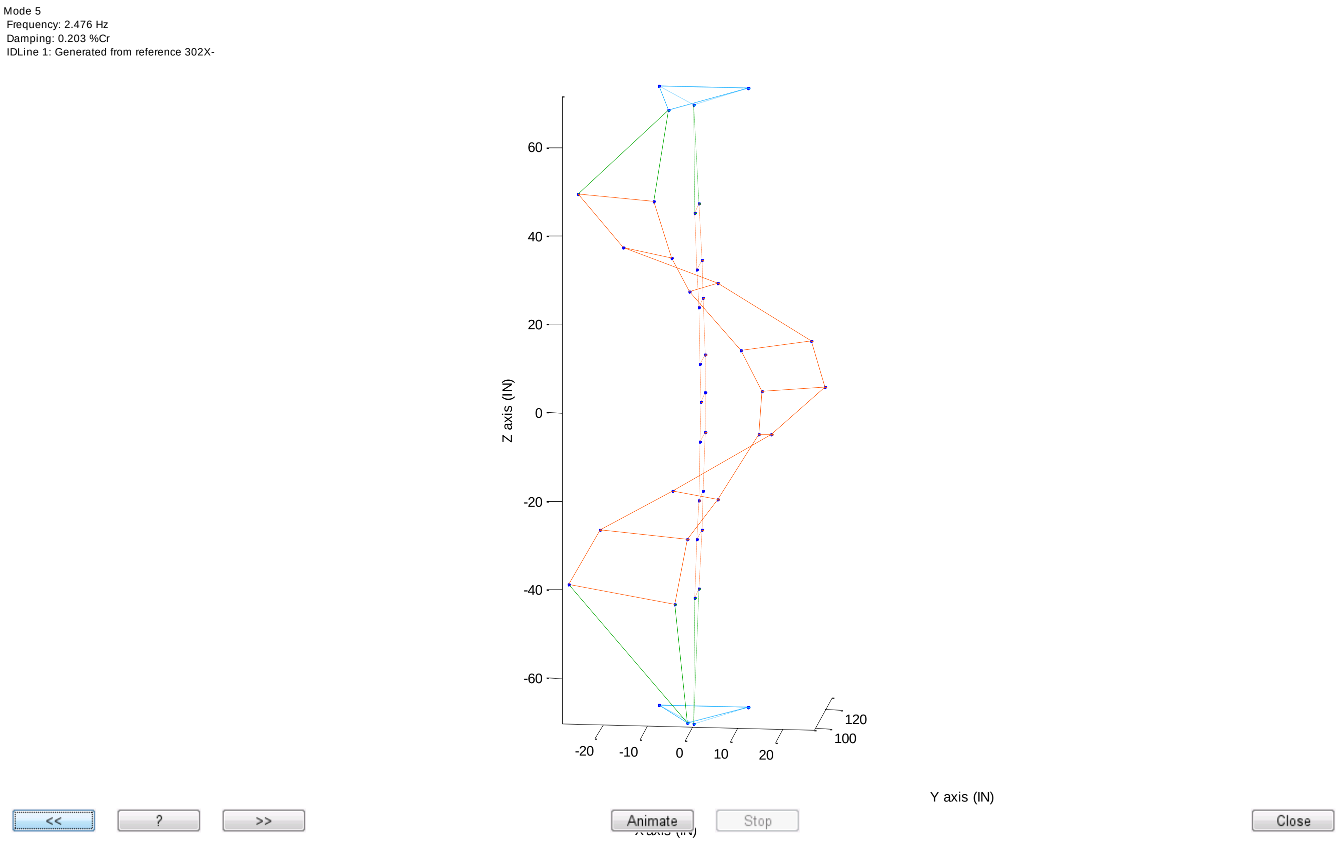


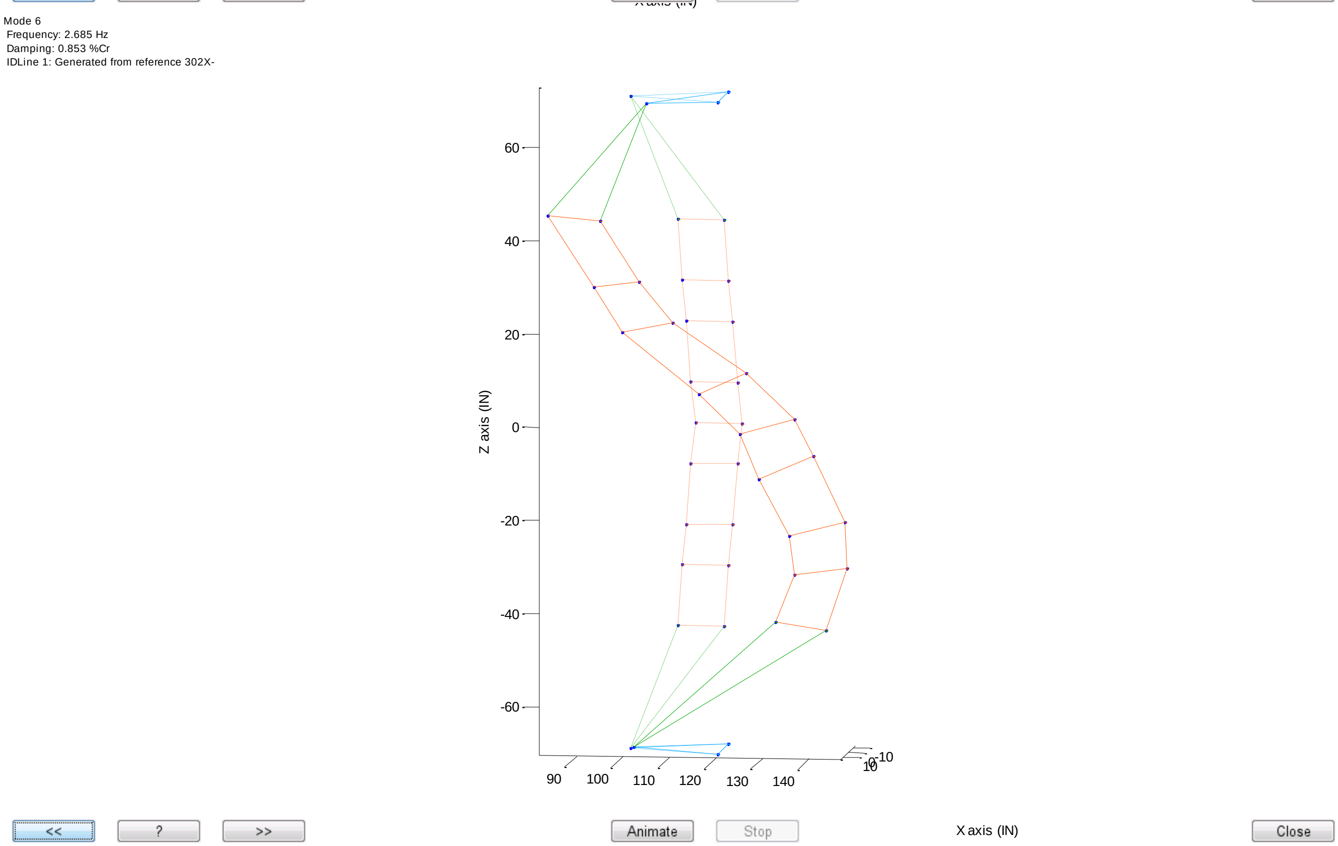
Mode 2
Frequency: 1.684 Hz
Damping: 0.299 %Cr
IDLine 1: Generated from reference 302Z+



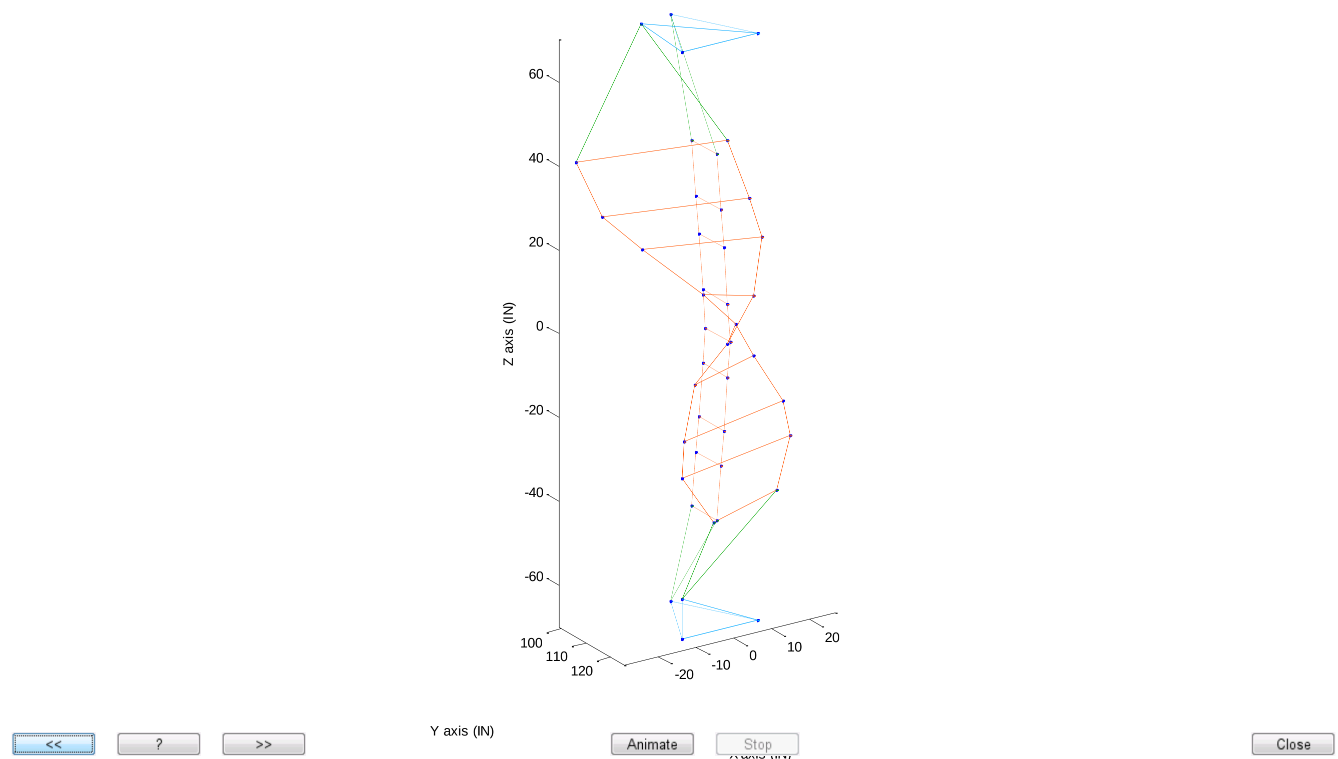

Mode 3
Frequency: 1.898 Hz
Damping: 1.556 %Cr
IDLine 1: Generated from reference 302Z+
60
40
20
0
-20
-40
-60
Z axis (IN)
140
130
120
110
100
-20
0
20
Y a
X axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 4
Frequency: 2.105 Hz
Damping: 3.162 %Cr
IDLine 1: Generated from reference 302Z+
60
40
20
0
-20
-40
-60
Z axis (IN)
-20
0
20
130
120
110
100
X axis (IN)
xis (IN)
<<
?
>>
Animate
Stop
Close

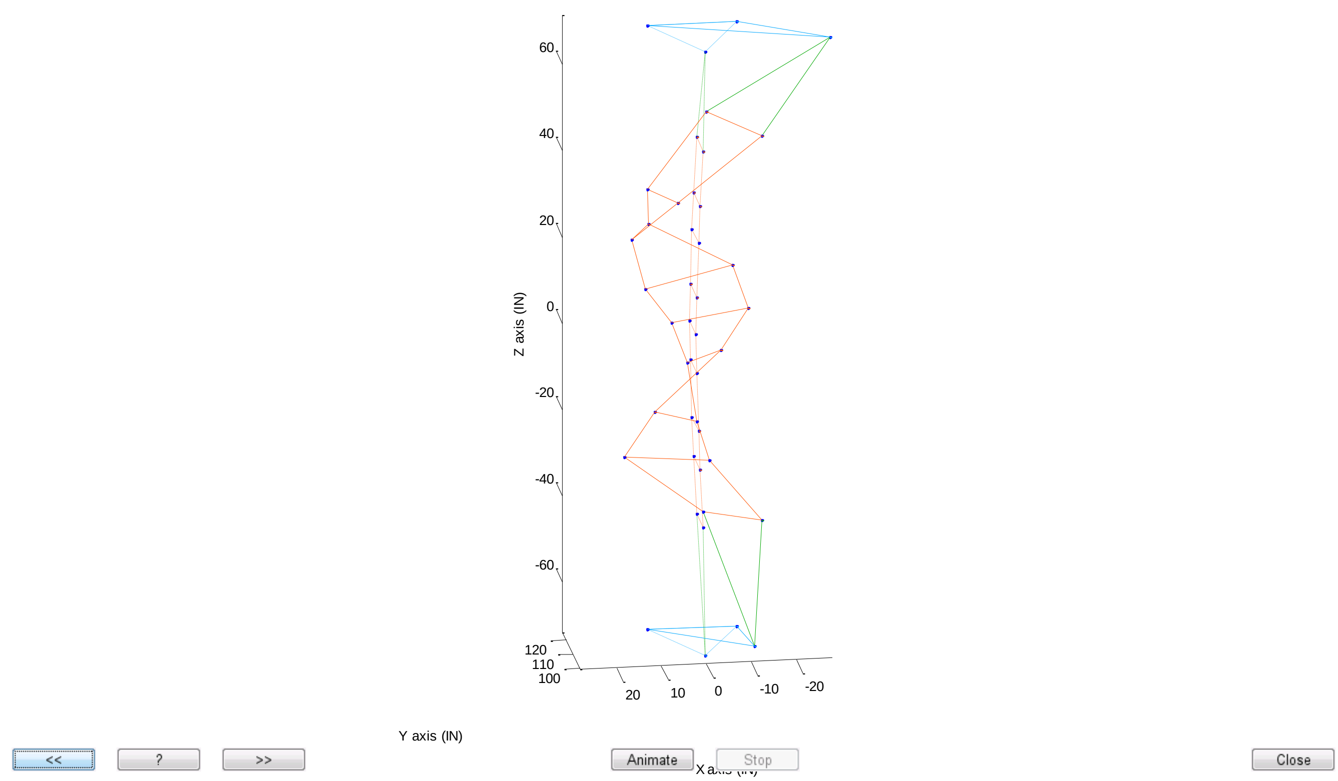

Mode 5
Frequency: 2.476 Hz
Damping: 0.203 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
-20
-10
0
10
20
120
100
Y axis (IN)
<<
?
>>
Animate
Stop
Close

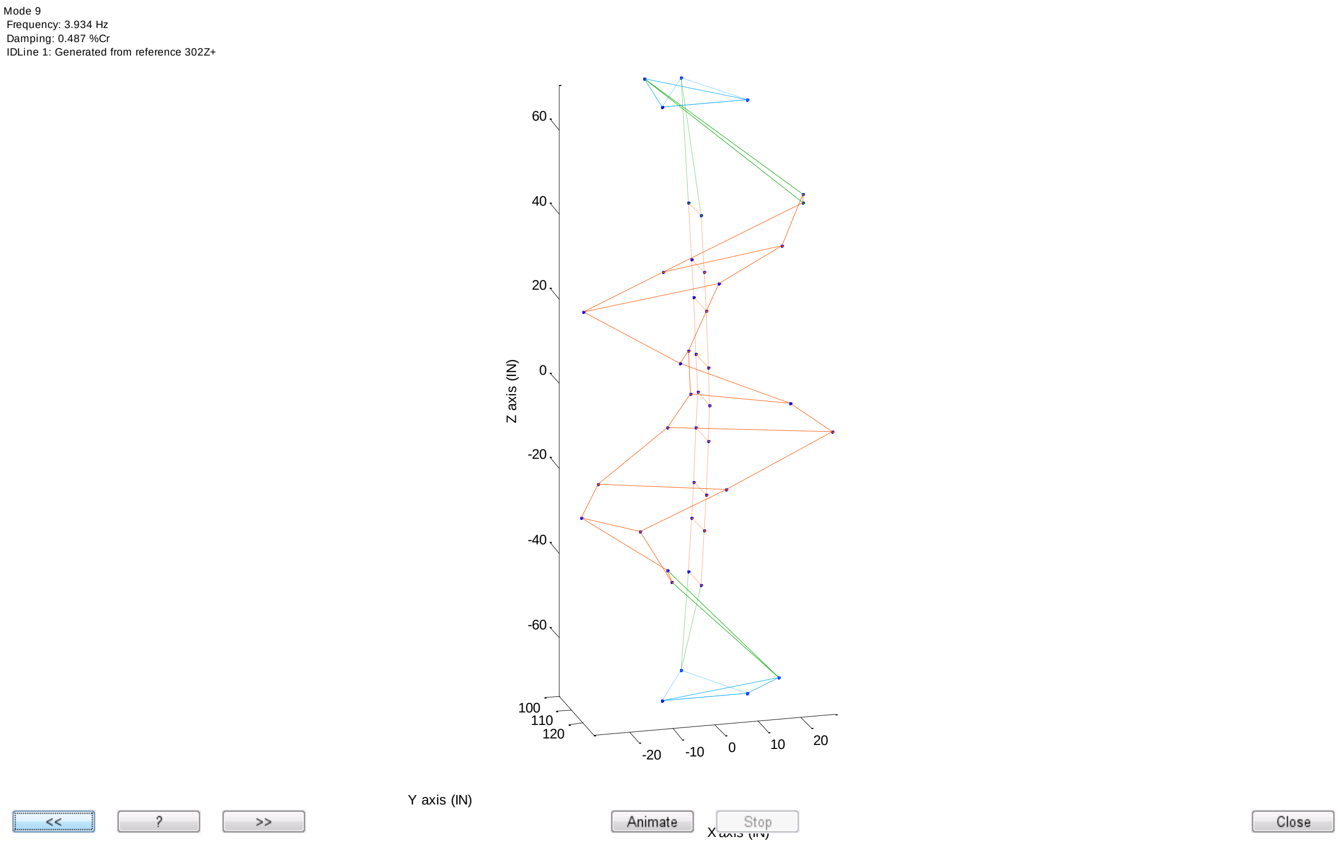

Mode 6
Frequency: 2.685 Hz
Damping: 0.853 %Cr
IDLine 1: Generated from reference 302X-
Z axis (IN)
60
40
20
0
-20
-40
-60
90
100
110
120
130
140
X axis (IN)
<<
?
>>
Animate
Stop
Close

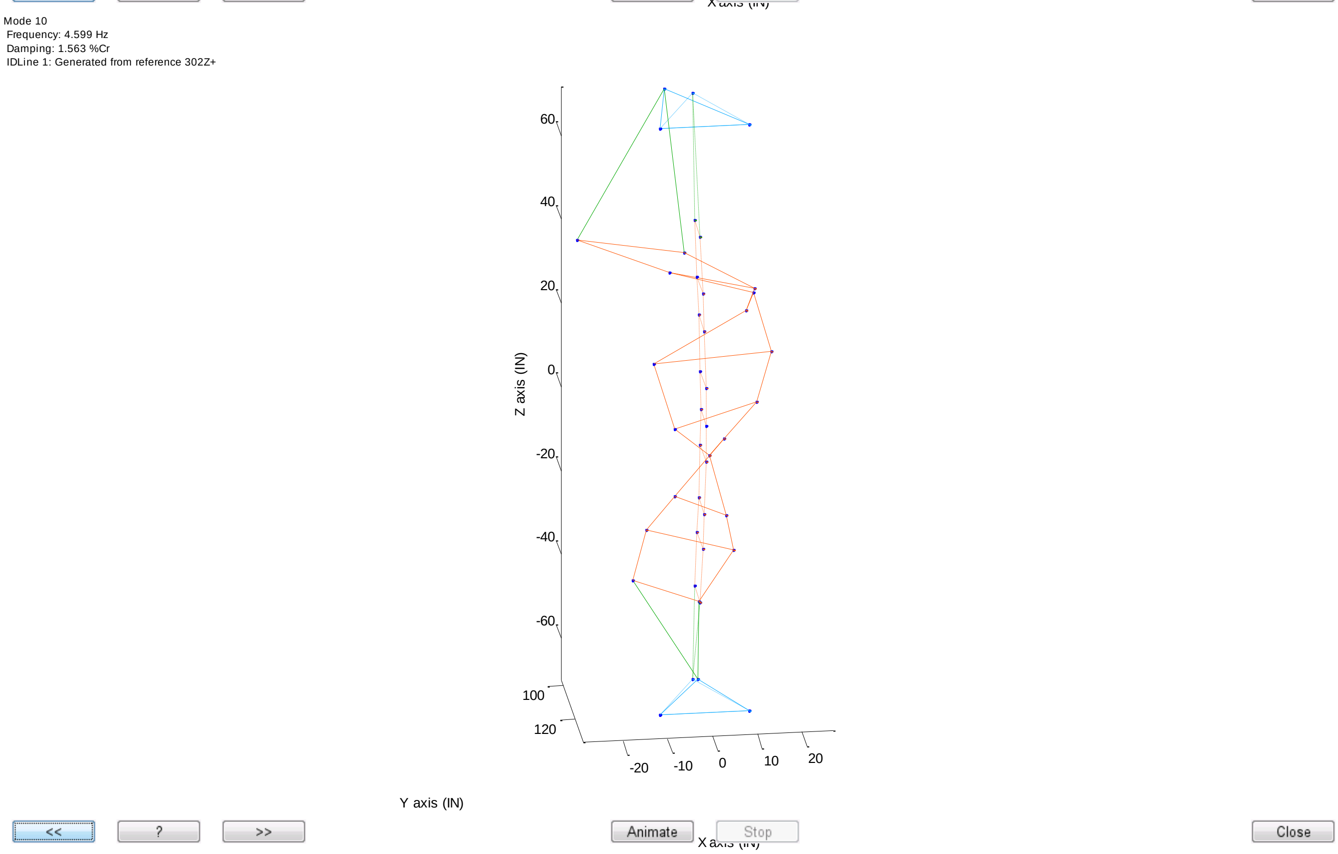
Mode 7
Frequency: 3.216 Hz
Damping: 2.634 %Cr
IDLine 1: Generated from reference 302X-



Mode 8
Frequency: 3.839 Hz
Damping: 1.484 %Cr
IDLine 1: Generated from reference 302Z+




Mode 9
Frequency: 3.934 Hz
Damping: 0.487 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
100
110
120
-20
-10
0
10
20
Y axis (IN)
X axis (IN)
<<
?
>>
Animate
Stop
Close


Mode 10
Frequency: 4.599 Hz
Damping: 1.563 %Cr
IDLine 1: Generated from reference 302Z+
Z axis (IN)
60
40
20
0
-20
-40
-60
100
120
-20
-10
0
10
20
Y axis (IN)
X axis (IN)
<<
?
>>
Animate
Stop
Close