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Seismic Analysis

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Seismic Analysis

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1 Introduction

This report contributes to the 5^{th} Framework Programme HTR-E WP 3. The aim of this work package is to give an insight in the dynamic behaviour of the GT-MHR rotor shaft assembly under various operating and emergency conditions. The report summarizes the results of the seismic analyses performed for the GT-MHR rotor shaft assembly.

Under normal operation conditions the GT-MHR rotor shaft is supported by Active Magnetic Bearings (AMBs). AMBs do not require lubrication and the stiffnesses of the bearings can be changed during operation by the control system to counter irregularities in the rotation of the rotor shaft.

Basically an AMB is coupled with a mechanical auxiliary Catcher Bearing (CB). A CB takes over the support of the rotor shaft in case of AMB failure.

The loads on the bearings and the response displacements of the rotor shaft under seismic conditions calculated with finite element dynamic analyses are presented in this report. The report focuses on the radial and axial bearing loads as a result of a postulated earthquake loading on the GT-MHR rotor shaft assembly.

2 Problem Definition

In the GT-MHR design for a high temperature gas-cooled reactor the generator, turbine, and compressors are mounted on a single vertically arranged rotor shaft. Figure 1 shows the layout of the rotor shaft. Under normal operating conditions the rotor shaft is supported by 6 radial and 1 axial Active Magnetic Bearings (AMBs). If the AMBs are not functioning the rotor shaft is supported by 5 radial and 1 axial Catcher Bearings (CBs). The Figures 2 and 3 show the position of bearings supporting the GT-MHR rotor shaft.

To determine the feasibility of the GT-MHR rotor shaft design and to design the Active Magnetic Bearings the bearing loads under various operational conditions must be known. The dynamic behaviour of the rotor shaft determines the bearing loads. The dynamic behaviour of the rotor shaft is a function of the natural frequencies of the rotor shaft. Mass distribution and stiffness of the rotor shaft, as well as the stiffnesses of the supports (bearings), determine the natural frequencies of the rotor shaft. In case of the AMBs the stiffness is not constant, but a function of the applied control system and the frequency (rotational velocity). In this report the dynamic behaviour of the rotor shaft has been investigated for the following support variants:

A - Active Magnetic Bearing support - rigid stiffness;
B - Active Magnetic Bearing support - open loop control system stiffness;
C - Active Magnetic Bearing support - closed loop control system stiffness;
D - Catcher Bearing support - rigid stiffness;
E - Catcher Bearing support - flexible stiffness (I);
F - Catcher Bearing support - flexible stiffness (II).

For the following load cases the bearing loads have been determined:

1. An unbalance in the exciter;
2. A central unbalance in the generator;
3. Opposite acting unbalances at the ends of the generator;
4. An unbalance in the disk of the axial AMB;
5. An unbalance in the middle of the hollow shaft;
6. An unbalance at the inlet stage of the turbine due to deblading;
7. An unbalance at the inlet stage of the LP-compressor due to deblading;
8. A seismic loading;

Radial bearing loads are a result of unbalance eccentricities in the various components of the rotor shaft or horizontal seismic accelerations. Axial bearing loads are caused by the gravitational acceleration and vertical seismic accelerations. The calculated bearing loads and response displacements for the load cases 1 to 7 are presented and discussed in [1]. In this report the calculated bearing loads and response displacements for load case 8 are presented. For the seismic load case the calculated bearing loads are compared with the maximum feasible bearing loads [2].

3 Approach

To determine the dynamic behaviour of the GT-MHR rotor shaft with respect to earthquake loading the following finite element analyses have to be performed:

1. Static dead weight analysis;
2. Mode frequency analysis;
3. Response spectrum analysis;
4. Load case combination.

These finite element calculations are performed with the general purpose finite element code ANSYS Release 6.0 [3]. By means of the static analysis the bearing loads for the GT-MHR rotor shaft due to the dead weight at gravity loading are calculated. The natural frequencies of the GT-MHR rotor shaft are determined with a mode frequency analysis. The bearing loads for the GT-MHR rotor shaft due to seismic loading are calculated with a response spectrum analysis. In a response spectrum analysis the results of a modal analysis are combined with a known spectrum to calculate the structural response of a structure. It is mainly used to determine the maximum structural response to random loading conditions such as earthquakes [3]. The spectrum consists of spectral base accelerations versus frequencies that capture the intensity and frequency content of time-history loads. The maximum response of the structure is assessed by mode combination according to the *Square Root of the Sum of the Squares* method from the NRC Regulatory Guide [4].

For the static and seismic analyses a linear elastic material model has been used. Therefore, the results due to the individual loads, which are calculated separately, can be combined by superposition. Because the results of the seismic analyses are expressed in amplitudes of displacements, strains, stresses, and forces the results of the seismic analyses are combined with the static load by superposition with a positive and a negative sign respectively.

3.1 Finite Element Model

Figures 2 and 3 show the finite element model of the GT-MHR rotor shaft. The finite element model consists of 441 elements and 450 nodal points. The ANSYS element types used in the finite element model are PIPE16 (pipe element) for the rotor shaft and COMBIN14 (spring-damper element) for the bearings [3]. The radius of the rotor shaft is specified as a pipe element property.

3.2 Material Properties

Linear elastic material behaviour has been assumed for the steel of the rotor shaft. For the Young's modulus, Poisson ratio, and material damping the following values have been applied:

E	=	210000	MPa
ν	=	0.3	-
damping	=	1.0	%

The assumed material damping is only used in the harmonic response analyses.

3.3 Boundary Conditions

The applied boundary conditions are different for each investigated support variant.

Active magnetic bearing support - rigid stiffness

Figure 4 shows the boundary conditions applied for this support variant. In this figure the cyan arrow symbols are suppressed displacements, the orange double arrow symbols are suppressed rotations, and the green symbols indicate coupled degrees of freedom. At the positions of the radial bearings the displacements perpendicular to the rotor shaft axis are suppressed (X- and Y-direction). At the position of the axial bearing all rotations are suppressed as well as the displacement in axial direction (Z-direction).

Active magnetic bearing support - open loop control system stiffness

Figure 5 shows the boundary conditions applied for this support variant. The bearings are modelled with spring-damper elements. At one end these elements are connected to the rotor shaft, at the other end all displacements and rotations are suppressed. At the position of the axial bearing the rotation around the rotor shaft axis is also suppressed (suppression of rigid body rotation). The stiffnesses used for the spring-damper elements are frequency dependent (Table 1). The values used are based on the data supplied by [5]. For all bearings a damping of 0.05 has been assumed.

table 1 The frequency dependent stiffnesses of the AMBs with an open loop control system

Freq. [Hz]	AMB1 [N/μm]	AMB2 [N/μm]	AMB3 [N/μm]	AMB4 [N/μm]	AMB5 [N/μm]	AMB6 [N/μm]	AMBax [N/μm]
10	299.57	313.48	306.01	302.07	301.41	301.29	6470.90
20	508.44	522.54	500.90	498.80	500.10	500.16	6997.60
30	674.90	727.48	620.99	621.53	632.66	634.16	7583.70
40	804.57	817.50	808.03	801.19	794.69	794.53	6665.20
50	859.87	874.55	848.63	846.84	846.66	844.05	6017.40
60	896.50	910.64	885.13	883.44	885.69	884.91	7076.00
70	916.14	920.77	911.08	911.54	915.61	915.62	7076.00
80	962.96	969.65	875.94	899.34	920.93	923.15	7076.00
90	884.29	880.13	900.83	898.08	897.90	897.69	7076.00
100	914.99	910.14	893.46	912.27	917.87	918.26	7076.00

table 2 The frequency dependent stiffnesses of the AMBs with an closed loop control system

Freq. [Hz]	AMB1 [N/μm]	AMB2 [N/μm]	AMB3 [N/μm]	AMB4 [N/μm]	AMB5 [N/μm]	AMB6 [N/μm]	AMBax [N/μm]
10	1856.1	4548.7	2134.1	1284.8	680.0	605.5	5796.5
20	2474.2	5666.3	2981.2	1791.7	944.1	840.1	4525.2
30	2347.4	4781.1	3327.2	1948.8	1004.6	891.4	3559.7
40	1718.4	3120.4	3616.6	1912.9	913.2	803.2	2741.0
50	1269.5	2335.8	2833.9	1425.6	674.6	592.9	3183.1
60	1675.9	3143.3	3532.0	1806.7	863.7	760.0	4989.6
70	2597.9	4801.4	5572.6	2851.0	1361.1	1197.1	4989.6
80	3746.7	6922.6	7386.9	3896.9	1890.2	1665.7	4989.6
90	4704.5	8896.0	9284.7	4896.1	2371.9	2089.8	4989.6
100	5903.2	11116.6	11316.2	6081.6	2958.0	2607.2	4989.6

Active magnetic bearing support - closed loop control system stiffness

Figure 5 shows the boundary conditions applied for this support variant. The bearings are modelled with spring-damper elements. At one end these elements are connected to the rotor shaft, at the other end all displacements and rotations are suppressed. At the position of the axial bearing the rotation around the rotor shaft axis is also suppressed (suppression of rigid body rotation). The stiffnesses used for the spring-damper elements are frequency dependent (Table 2). The values used are based on the data supplied by [5]. For all bearings a damping of 0.05 has been assumed.

Catcher bearing support - rigid stiffness

Figure 6 shows the boundary conditions applied for this support variant. At the positions of the radial bearings the displacements perpendicular to the rotor shaft axis are suppressed (X- and Y-direction). At the position of the axial bearing all rotations are suppressed as well as the displacement in axial direction Z-direction).

Catcher bearing support - flexible stiffness

The boundary conditions applied for this support variant are shown in Figure 7. The bearings are modelled with spring-damper elements. The stiffnesses used for the spring-damper elements are summarized hereafter. To study the influence of the bearing stiffness a small and large stiffness are used (Table 3). For all bearings a damping of 0.15 has been assumed.

table 3 The applied CB stiffnesses

	CB2 [N/μm]	CB3 [N/μm]	CB4 [N/μm]	CB5 [N/μm]	CB6 [N/μm]	CBax [N/μm]
I	150.0	150.0	150.0	150.0	150.0	2500.0
II	300.0	300.0	300.0	300.0	300.0	5000.0

3.4 Loading Conditions

The dead weight loading of the GT-MHR rotor shaft is a constant volume load. This loading is applied by specifying the gravitational acceleration g in negative Z-direction:

$$g = 9.81 \text{ m/s}^2$$

Figure 8 shows the seismic frequency response spectrum to be applied in horizontal and vertical direction for the GT-MHR rotor shaft. The horizontal spectrum is applied at the positions of the radial bearings and the vertical spectrum is applied at the position of the axial bearing. Because the bearing supports are not yet designed in sufficient detail, it is assumed that the bearing supports have a very large stiffness. This assumption results in a simplified dynamic response of the rotor shaft. The response spectrum at the position of the bearing supports can be amplified if the stiffnesses of the vessel and bearing supports are taken into account. This should be kept in mind when viewing the results of the performed dynamic analyses.

3.5 Evaluation Criteria

For the GT-MHR rotor shaft and active magnetic bearings the following requirements have been specified in [2]. The maximum load capacity of the radial AMBs is 100 kN and of the axial AMB is 1050 kN.

4 Mode Frequency Analyses

For the support variants mentioned in chapter 2 the natural frequencies and the mode shapes have been calculated with finite element modal analyses with the general purpose finite element program ANSYS [3]. The natural frequencies and mode shapes have been calculated for the frequency range 0 to 100 Hz. Table 4 summarizes for each support variant the natural frequencies.

table 4 The natural frequencies of the GT-MHR rotor shaft for the investigated support variants

Mode	A [Hz]	B [Hz]	C [Hz]	D [Hz]	E [Hz]	F [Hz]
1	15.78	11.11	14.77	10.49	8.10	8.97
2	24.59	18.55	22.14	16.59	10.22	12.01
3	26.20	24.59	24.59	22.29	11.94	14.33
4	31.18	30.35	27.01	28.24	21.01	25.81
5	38.73	31.18	31.18	28.41	23.05	28.25
6	55.74	33.84	36.33	44.20	28.25	28.41
7	61.88	36.42	47.36	57.77	28.37	30.66
8	67.73	45.61	52.79	69.66	28.41	35.20
9	67.87	60.82	56.52	70.18	35.67	42.24
10	73.73	66.09	60.79	71.63	45.87	49.70
11	78.93	67.73	66.05	78.41	55.96	61.52
12	103.94	75.71	67.73	84.90	66.17	66.36
13		78.93	71.20	94.99	69.66	69.66
14		81.90	78.57		70.06	72.94
15		101.62	78.93		78.41	78.41
16					89.96	92.43

For support variant A, AMB support with rigid stiffness, the mode shapes are shown in the Figures 9 and 10. The Figures 11 and 12 show the mode shapes for support variant B, AMB support with open loop control system stiffness. The mode shapes for the support variant AMB support with closed loop control system stiffness (C) are shown in the Figures 13 and 14. For the Catcher Bearing support variant with rigid stiffness (D) the Figures 15 and 16 show the mode shapes and the Figures 17 to 20 show the mode shapes for support variant E and F, CB support with flexible stiffness.

5 Results of Load Combination

For each support variant the results of the dead weight analysis and the frequency response analyses for the horizontal and vertical seismic loading are given in this chapter. The various loads are combined for the following load combinations:

1) Dead weight + horizontal seismic loading + vertical seismic loading (DW + H + V);
2) Dead weight + horizontal seismic loading - vertical seismic loading (DW + H - V);

5.1 Active Magnetic Bearing Support - Rigid Stiffness

Table 5 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for the rigid active magnetic bearing support. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 6. Figure 21 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacement is 0.572 mm.

table 5 Active magnetic bearing support - (rigid)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		**Horizontal**		**Vertical**	
	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]
AMB1	0.00	0.00	17.08	0.00	0.00	0.00
AMB2	0.00	0.00	49.71	0.00	0.00	0.00
AMB3	0.00	0.00	77.05	0.00	0.00	0.00
AMB4	0.00	0.00	156.35	0.00	0.00	0.00
AMB5	0.00	0.00	97.47	0.00	0.00	0.00
AMB6	0.00	0.00	19.88	0.00	0.00	0.00
AMBax	0.00	1022.50	0.00	0.00	0.00	1.86

table 6 Active magnetic bearing support - (rigid)
Bearing loads due to load combination

	DW+H+V	**DW+H-V**
	[kN]	[kN]
AMB1	17.08	17.08
AMB2	49.71	49.71
AMB3	77.05	77.05
AMB4	156.35	156.35
AMB5	97.47	97.47
AMB6	19.88	19.88
AMBax	1020.64	1024.36

5.2 Active Magnetic Bearing Support - Open Loop

Table 7 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for this support variant. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 8. Figure 22 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacements for the load combinations (DW + H + V) and (DW + H - V) are 0.991 and 1.005 mm respectively.

table 7 Active magnetic bearing support - (open loop)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		Horizontal		Vertical	
	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]
AMB1	0.00	0.00	21.51	0.00	0.00	0.00
AMB2	0.00	0.00	128.48	0.00	0.00	0.00
AMB3	0.00	0.00	148.98	0.00	0.00	0.00
AMB4	0.00	0.00	19.64	0.00	0.00	0.00
AMB5	0.00	0.00	70.33	0.00	0.00	0.00
AMB6	0.00	0.00	14.47	0.00	0.00	0.00
AMBax	0.00	1022.50	0.00	0.00	0.00	161.55

table 8 Active magnetic bearing support - (open loop)
Bearing loads due to load combination

	DW+H+V	DW+H-V
	[kN]	[kN]
AMB1	21.51	21.51
AMB2	128.48	128.48
AMB3	148.98	148.98
AMB4	19.64	19.64
AMB5	70.33	70.33
AMB6	14.47	14.47
AMBax	860.95	1184.05

5.3 Active Magnetic Bearing Support - Closed Loop

Table 9 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for this support variant. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 10. Figure 23 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacements for the load combinations (DW + H + V) and (DW + H - V) are 0.670 and 0.729 mm respectively.

table 9 Active magnetic bearing support - (closed loop)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		Horizontal		Vertical	
	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]
AMB1	0.00	0.00	20.82	0.00	0.00	0.00
AMB2	0.00	0.00	103.62	0.00	0.00	0.00
AMB3	0.00	0.00	137.41	0.00	0.00	0.00
AMB4	0.00	0.00	75.57	0.00	0.00	0.00
AMB5	0.00	0.00	57.16	0.00	0.00	0.00
AMB6	0.00	0.00	14.18	0.00	0.00	0.00
AMBax	0.00	1022.50	0.00	0.00	0.00	258.67

table 10 Active magnetic bearing support - (closed loop)
Bearing loads due to load combination

	DW+H+V	**DW+H-V**
	[kN]	[kN]
AMB1	20.82	20.82
AMB2	103.62	103.62
AMB3	137.41	137.41
AMB4	75.57	75.57
AMB5	57.16	57.16
AMB6	14.18	14.18
AMBax	763.83	1281.17

5.4 Catcher Bearing Support - Rigid Stiffness

Table 11 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for the rigid catcher bearing support. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 12. Figure 24 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacement is 2.694 mm.

table 11 Catcher bearing support - (rigid)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		**Horizontal**		**Vertical**	
	F_{rad}	F_{ax}	F_{rad}	F_{ax}	F_{rad}	F_{ax}
	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
CB2	0.00	0.00	23.27	0.00	0.00	0.00
CB3	0.00	0.00	64.12	0.00	0.00	0.00
CB4	0.00	0.00	93.48	0.00	0.00	0.00
CB5	0.00	0.00	161.13	0.00	0.00	0.00
CB6	0.00	0.00	139.90	0.00	0.00	0.00
CBax	0.00	1022.50	0.00	0.00	0.00	3.07

table 12 Catcher bearing support - (rigid)
Bearing loads due to load combination

	DW+H+V	**DW+H-V**
	[kN]	[kN]
CB2	23.27	23.27
CB3	64.12	64.12
CB4	93.48	93.48
CB5	161.13	161.13
CB6	139.90	139.90
CBax	1019.43	1025.27

5.5 Catcher Bearing Support - Flexible I

Table 13 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for this support variant. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 14. Figure 25 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacements for the load combinations (DW + H + V) and (DW + H - V) are 3.272 and 3.311 mm respectively.

table 13 Catcher bearing support - (flexible I)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		Horizontal		Vertical	
	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]
CB2	0.00	0.00	125.50	0.00	0.00	0.00
CB3	0.00	0.00	131.64	0.00	0.00	0.00
CB4	0.00	0.00	88.90	0.00	0.00	0.00
CB5	0.00	0.00	75.77	0.00	0.00	0.00
CB6	0.00	0.00	8.64	0.00	0.00	0.00
CBax	0.00	1022.50	0.00	0.00	0.00	259.70

table 14 Catcher bearing support - (flexible I)
Bearing loads due to load combination

	DW+H+V	DW+H-V
	[kN]	[kN]
CB2	125.50	125.50
CB3	131.64	131.64
CB4	88.90	88.90
CB5	75.77	75.77
CB6	8.64	8.64
CBax	762.80	1282.20

5.6 Catcher Bearing Support - Flexible II

Table 15 summarizes the bearing loads due to the dead weight loading, the horizontal earthquake loading, and the vertical earthquake loading for this support variant. The bearing loads for the load combinations (DW + H + V) and (DW + H - V) are summarized in Table 16. Figure 26 shows the response of the GT-MHR rotor shaft as a result of the load combinations dead weight and seismic. The maximum response displacements for the load combinations (DW + H + V) and (DW + H - V) are 3.799 and 3.811 mm respectively.

table 15 Catcher bearing support - (flexible II)
Bearing loads due to dead weight and horizontal and vertical seismic loading

	Dead weight		Horizontal		Vertical	
	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]	F_{rad} [kN]	F_{ax} [kN]
CB2	0.00	0.00	130.62	0.00	0.00	0.00
CB3	0.00	0.00	115.62	0.00	0.00	0.00
CB4	0.00	0.00	92.13	0.00	0.00	0.00
CB5	0.00	0.00	84.08	0.00	0.00	0.00
CB6	0.00	0.00	15.56	0.00	0.00	0.00
CBax	0.00	1022.50	0.00	0.00	0.00	257.54

table 16 Catcher bearing support - (flexible II)
Bearing loads due to load combination

	DW+H+V	**DW+H-V**
	[kN]	[kN]
CB2	130.62	130.62
CB3	115.62	115.62
CB4	92.13	92.13
CB5	84.08	84.08
CB6	15.56	15.56
CBax	764.96	1280.04

6 Summary and Conclusions

In the GT-MHR design for a high temperature gas-cooled reactor the generator, turbine, and compressors are mounted on a single vertically arranged rotor shaft. To determine the feasibility of this rotor shaft design and to design the AMBs the bearing loads under various operational conditions have been determined. The bearing loads have been calculated with finite element dynamic analyses. In these analyses it is taken account of the mass distribution and the stiffness of the rotor shaft as well as the stiffnesses of the supports (bearings), which determine the dynamic behaviour of the rotor shaft. The dynamic behaviour of the rotor shaft has been investigated for the following support variants:

A - Active Magnetic Bearing support - rigid stiffness;
B - Active Magnetic Bearing support - open loop control system stiffness;
C - Active Magnetic Bearing support - closed loop control system stiffness;
D - Catcher Bearing support - rigid stiffness;
E - Catcher Bearing support - flexible stiffness (I);
F - Catcher Bearing support - flexible stiffness (II).

In this report attention is focused on the bearing loads caused by a seismic loading on the rotor shaft. Table 17 summarizes the maximum bearing loads and response displacements that occur for the various support variants under combined dead weight and seismic loading.

table 17 Maximum bearing loads and response displacements for each support variant due to a combined dead weight and seismic loading

	DW + H + V			**DW + H - V**		
	F_{rad} [kN]	F_{ax} [kN]	u_{resp} [mm]	F_{rad} [kN]	F_{ax} [kN]	u_{resp} [mm]
AMB support - rigid	156.35	1020.64	0.572	156.35	1024.36	0.572
AMB support - open loop	148.98	860.95	0.991	148.98	1184.05	1.005
AMB support - closed loop	137.41	763.83	0.670	137.41	1281.17	0.729
CB support - rigid	139.90	1019.43	2.694	139.90	1025.27	2.694
CB support - flexible I	131.64	762.80	3.272	131.64	1282.20	3.311
CB support - flexible II	130.62	764.96	3.799	130.62	1280.04	3.811

In Table 17 it can be seen that during an earthquake the load bearing capacity for the radial (100 kN) and axial (1050 kN) AMBs is exceeded. Under seismic loading the GT-MHR rotor shaft support will be transferred from the AMBs to the CBs. The required load capacity for the CBs is, based on the seismic loading only, approximately 140 kN for the radial CB and 1300 kN for the axial CB.

It should be noted that it has been assumed that the bearing supports have a very large stiffness. The response spectrum at the positions of the bearing supports can be amplified if the stiffnesses of the vessel and bearing supports are taken into account. The influence of the stiffnesses of the vessel and bearing supports on the response of the rotor shaft has to be investigated, when these stiffnesses become available.

References

[1] J.H. Fokkens. *HTR-E WP 3 - Load Analysis*. NRG report 20793/03.56445/C, 10 March 2004.

[2] F. Cellier. *WP3 Magnetic bearings and catcher bearings - Functional requirements*. Framatome ANP, Document N^{o}: HTR-E-02/06-D-3-1-1, November 2002.

[3] *ANSYS User's Manual Release 6.0*. ANSYS Inc., October 2001.

[4] *Regulatory Guide 1.92*. U.S. Regulatory Commission, February 1976.

[5] H. Stegemann. *Stiffness Radial and Axial AMB*. Personal communication, E-mail messages 27-6-2003 and 28-10-2003.

Figures

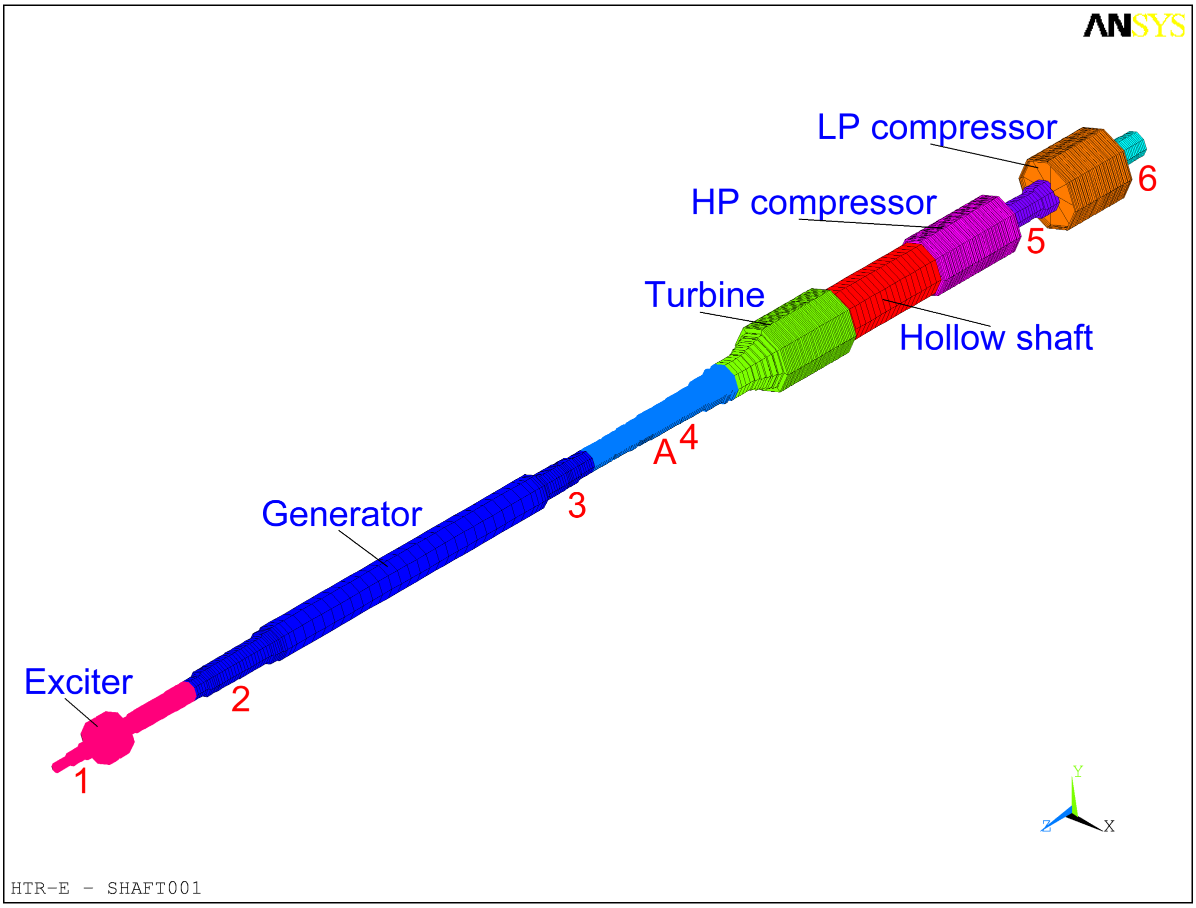


figure 1 Layout of the GT-MHR rotor shaft

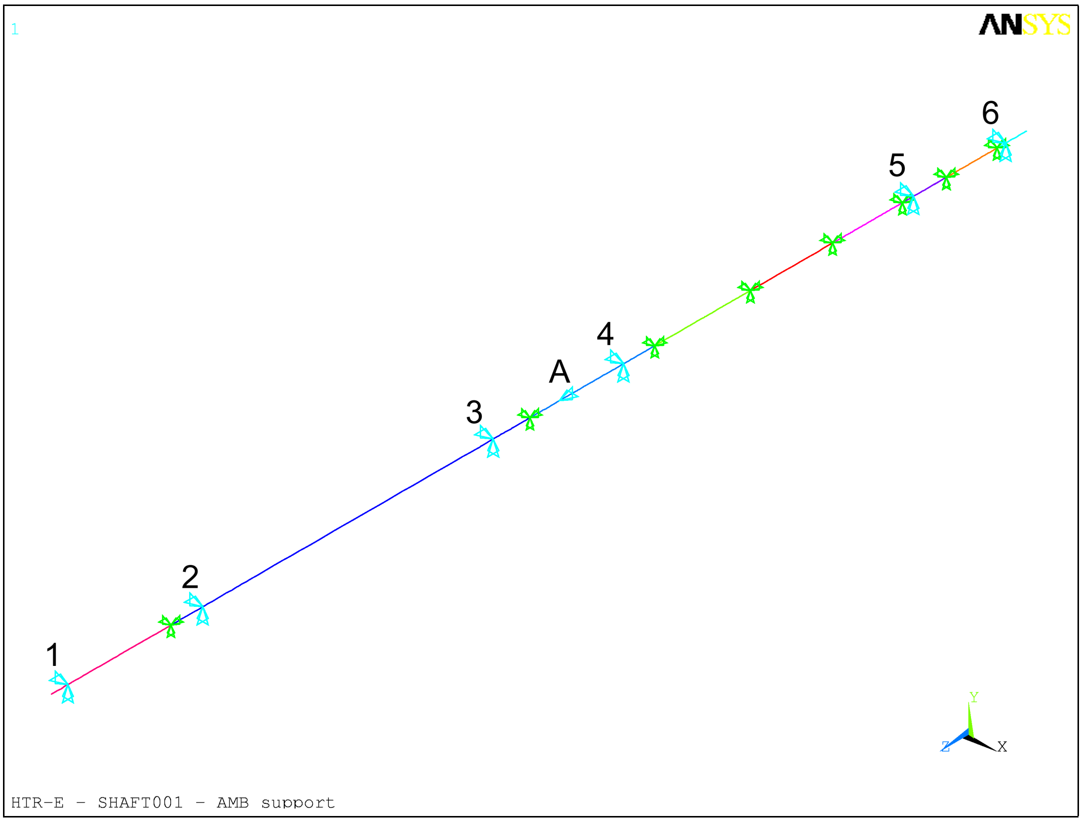


figure 2 The positions of the Active Magnetic Bearings supporting the GT-MHR rotor shaft

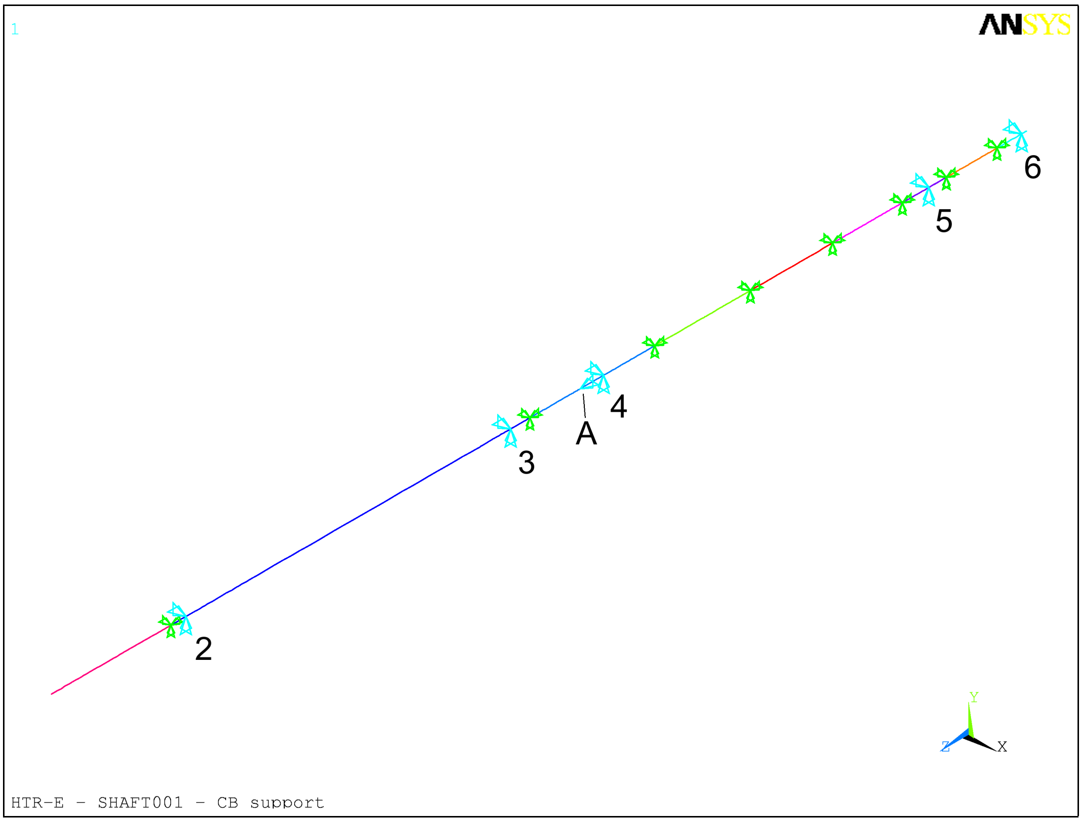


figure 3 The positions of the Catcher Bearings supporting the GT-MHR rotor shaft

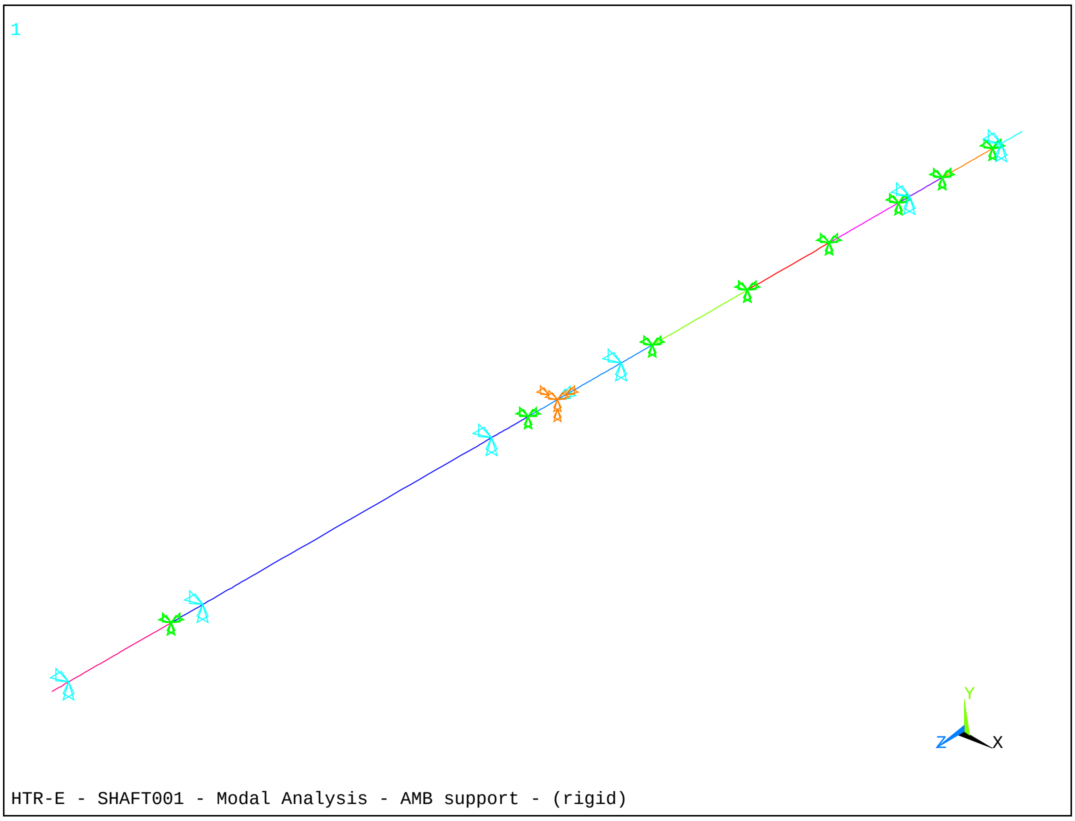


figure 4 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (rigid stiffness)

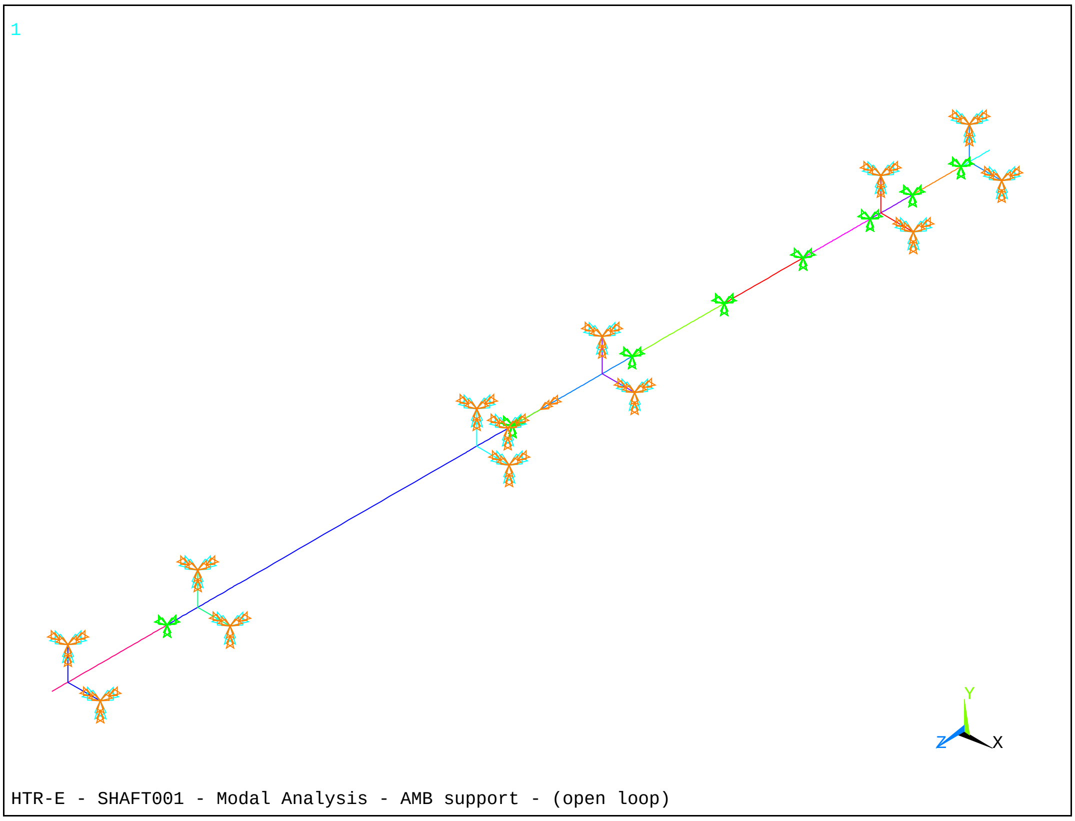


figure 5 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (flexible stiffness)

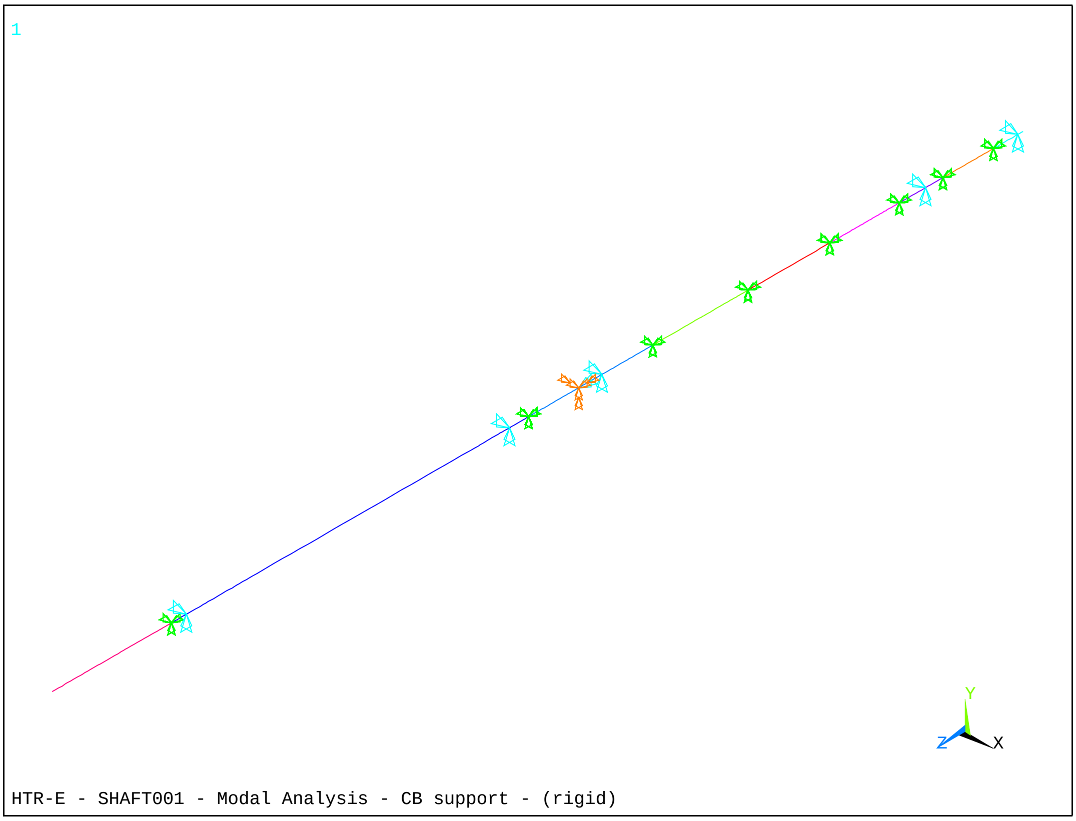


figure 6 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (rigid stiffness)

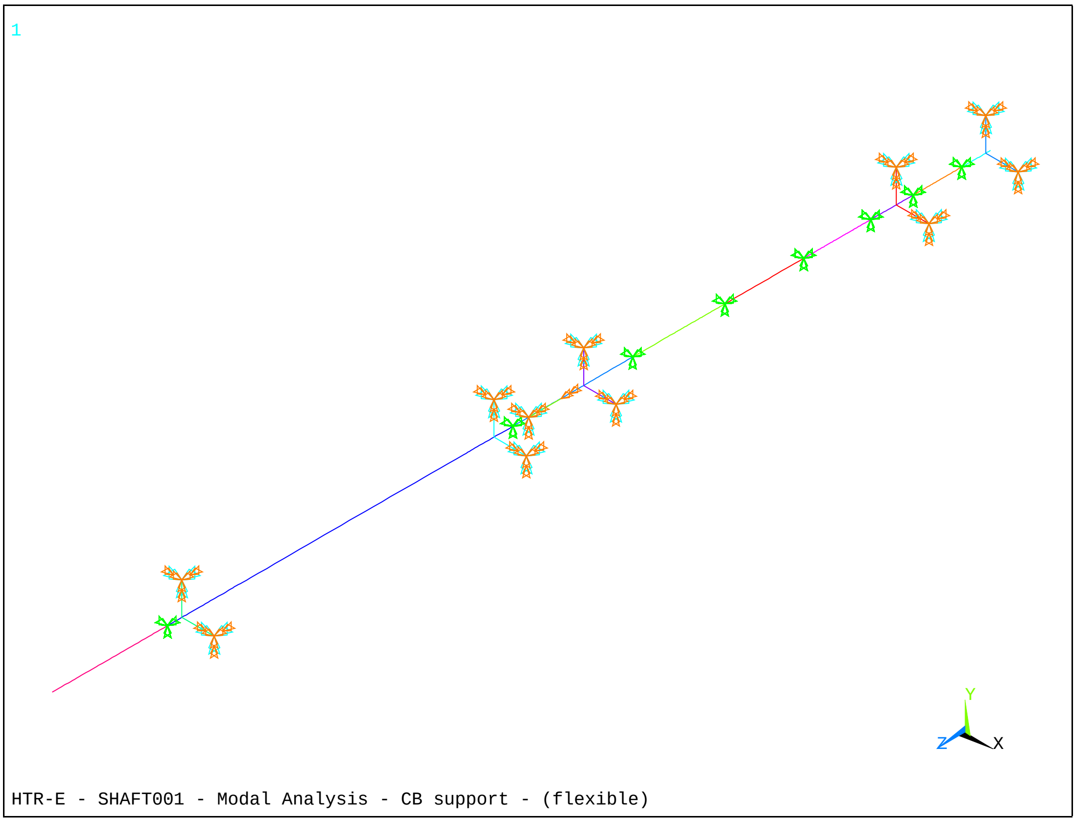


figure 7 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (flexible stiffness)

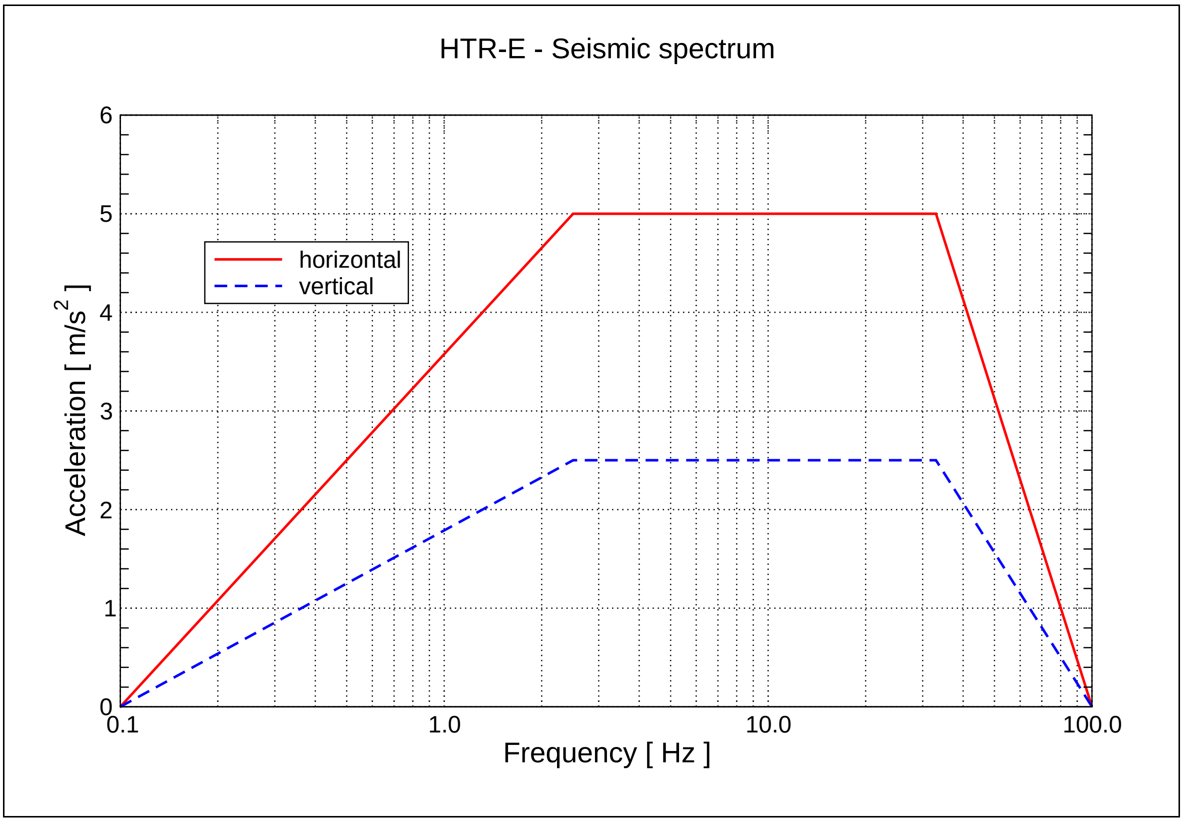


figure 8 Applied seismic acceleration spectrum for the GT-MHR rotor shaft

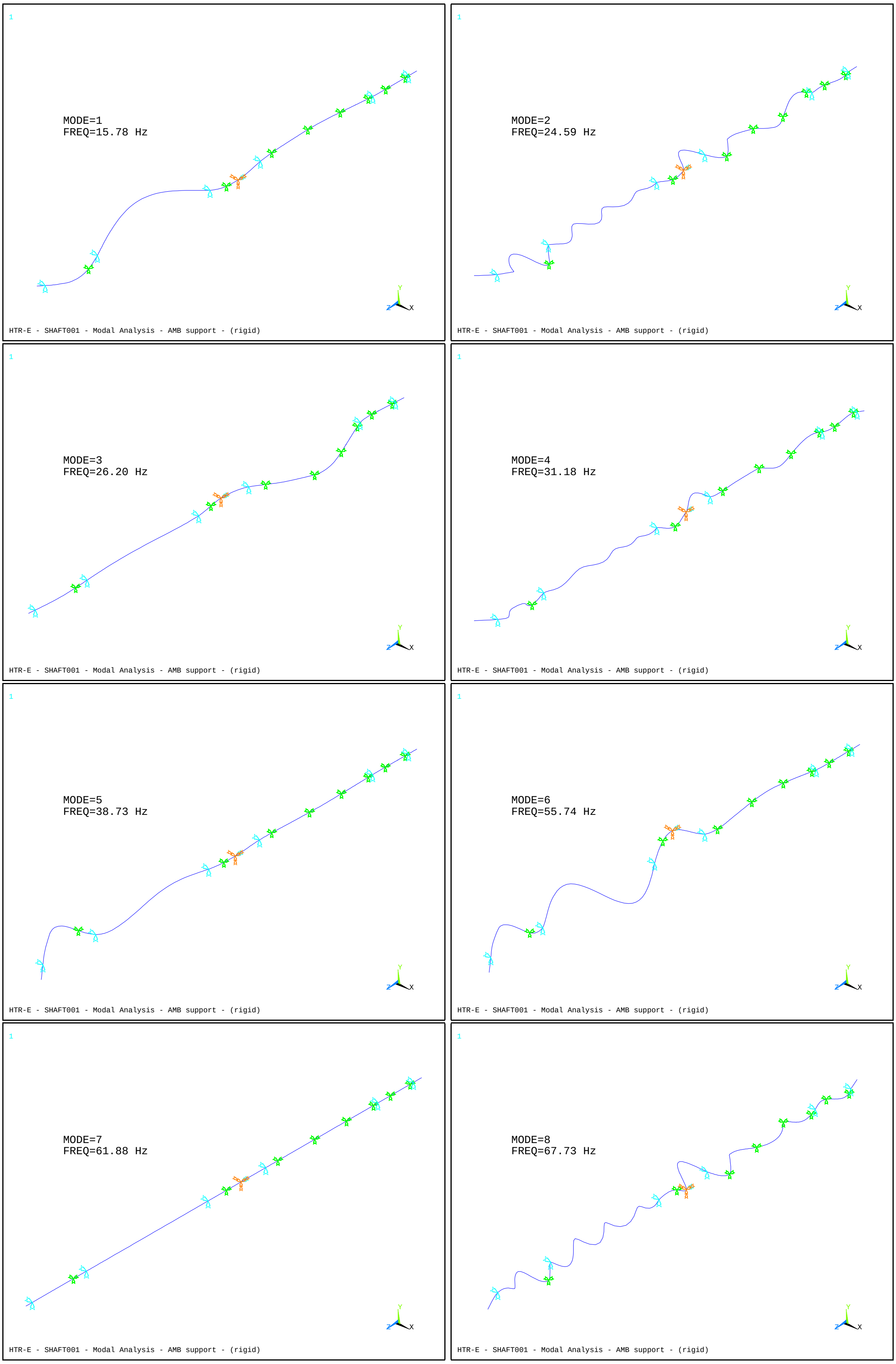


figure 9 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 1 to 8

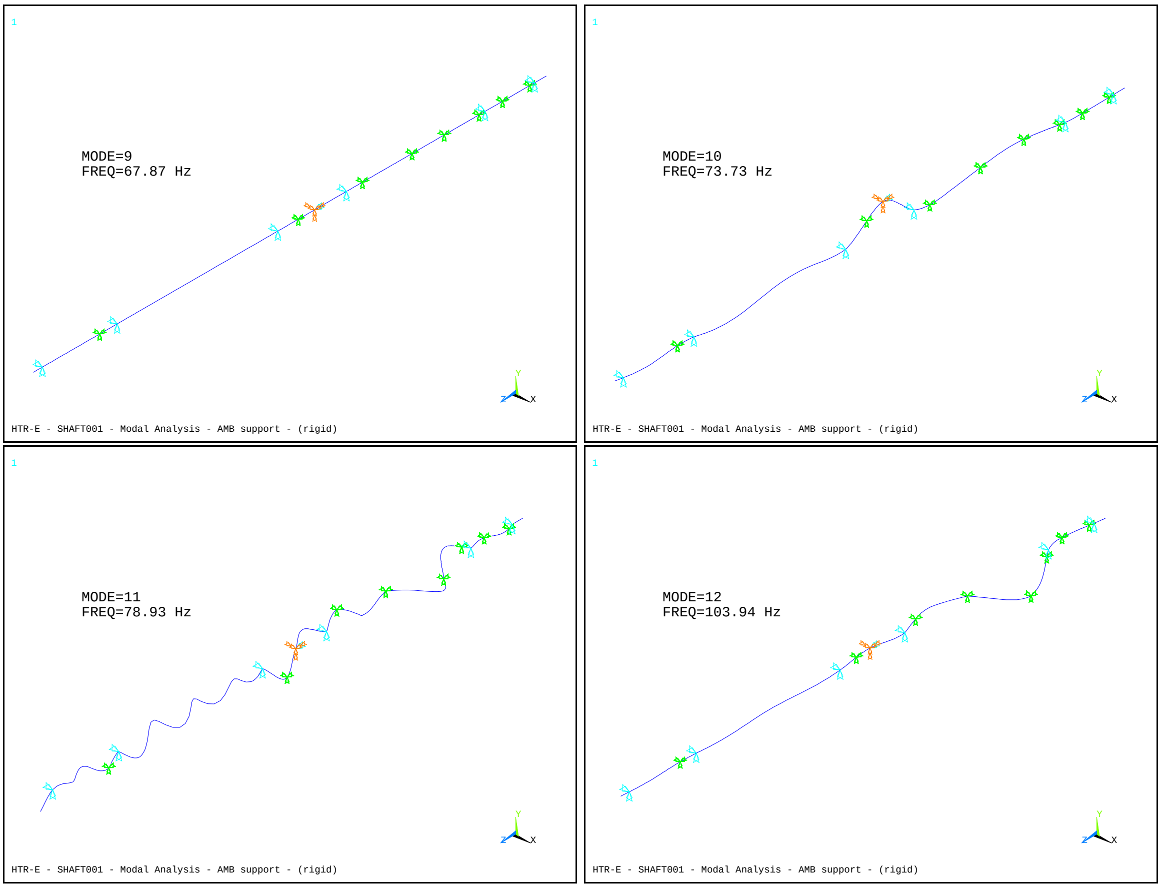


figure 10 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 9 to 12

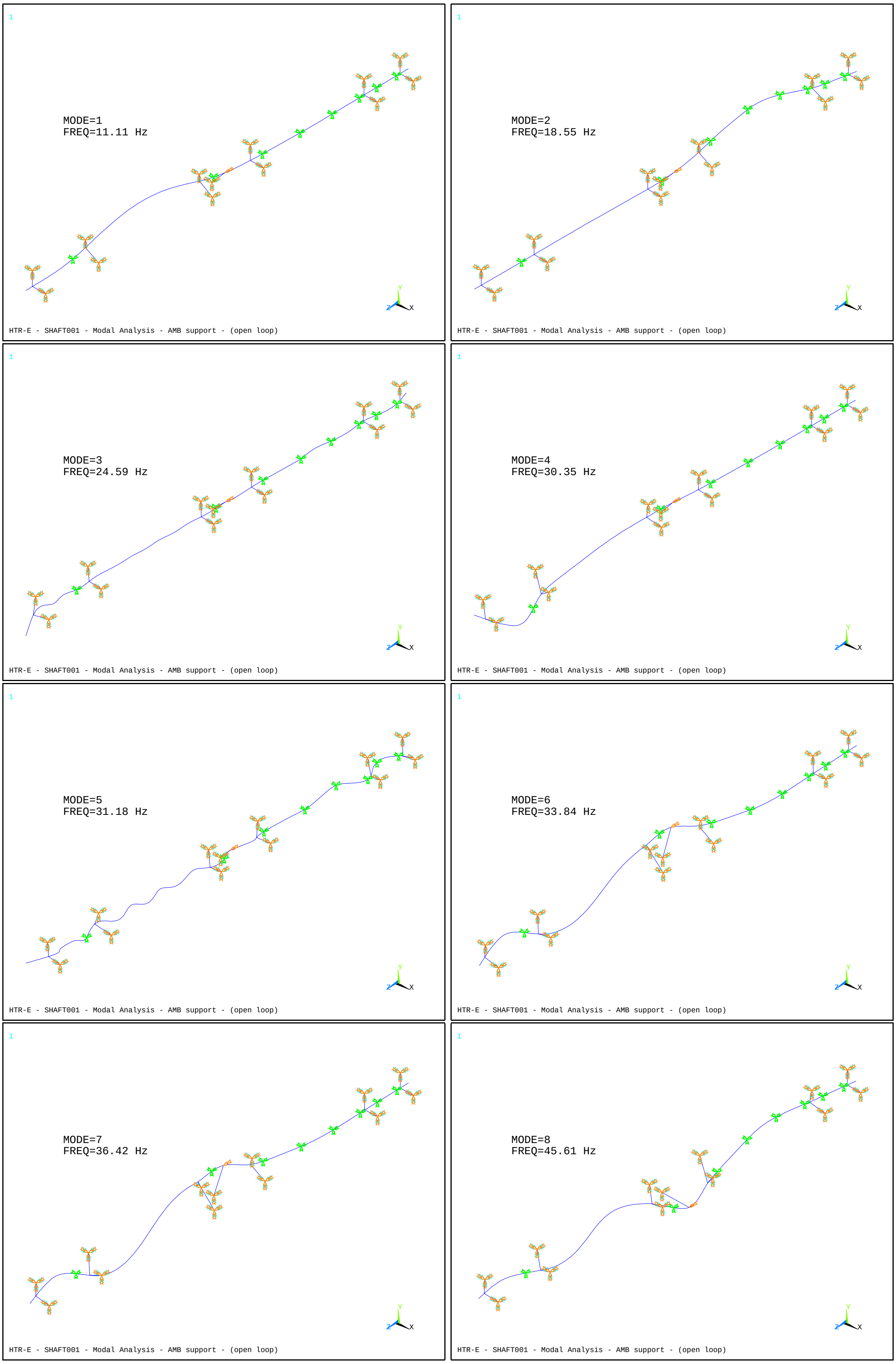


figure 11 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 1 to 8

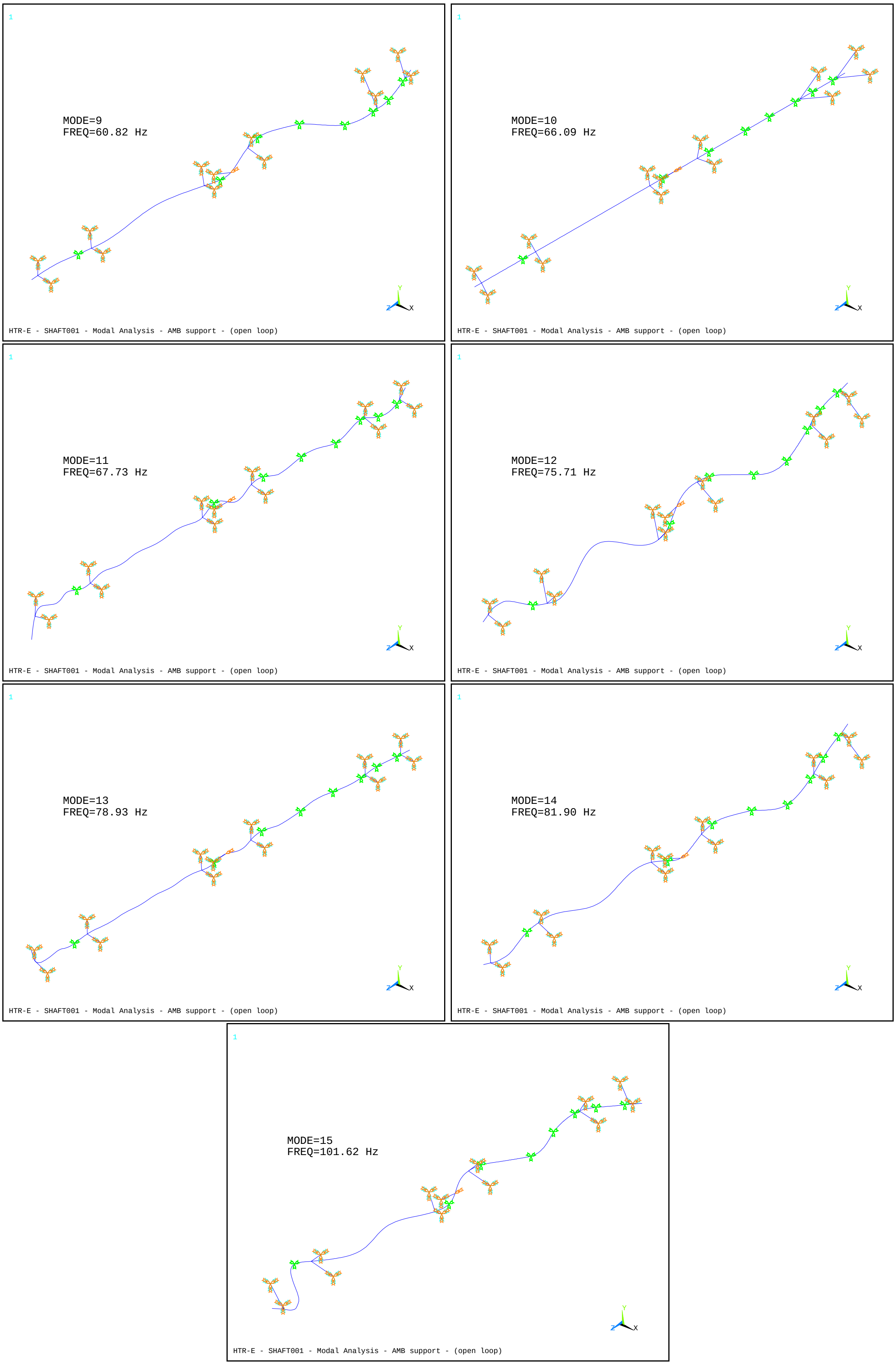


figure 12 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 9 to 15

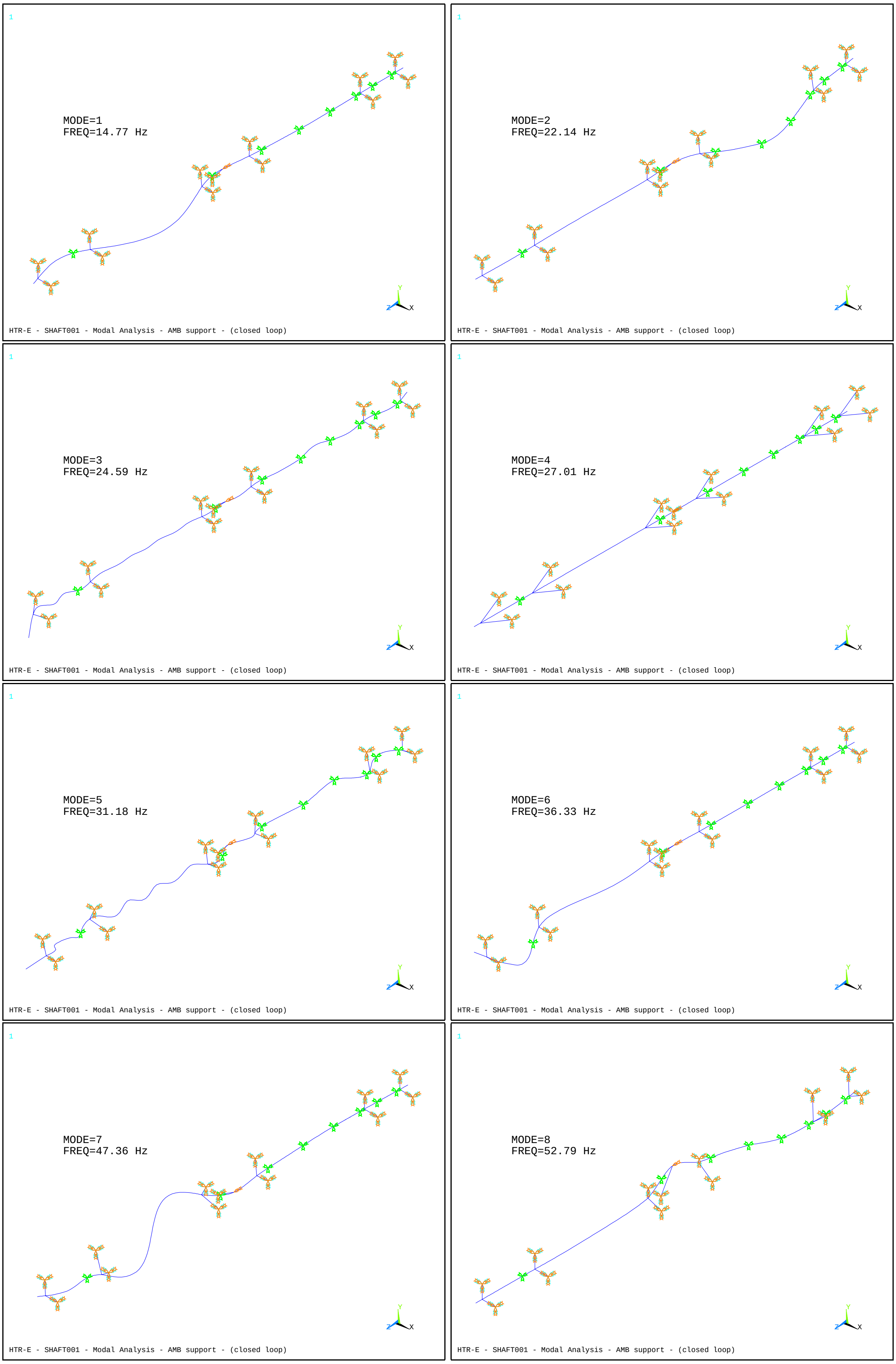


figure 13 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 1 to 8

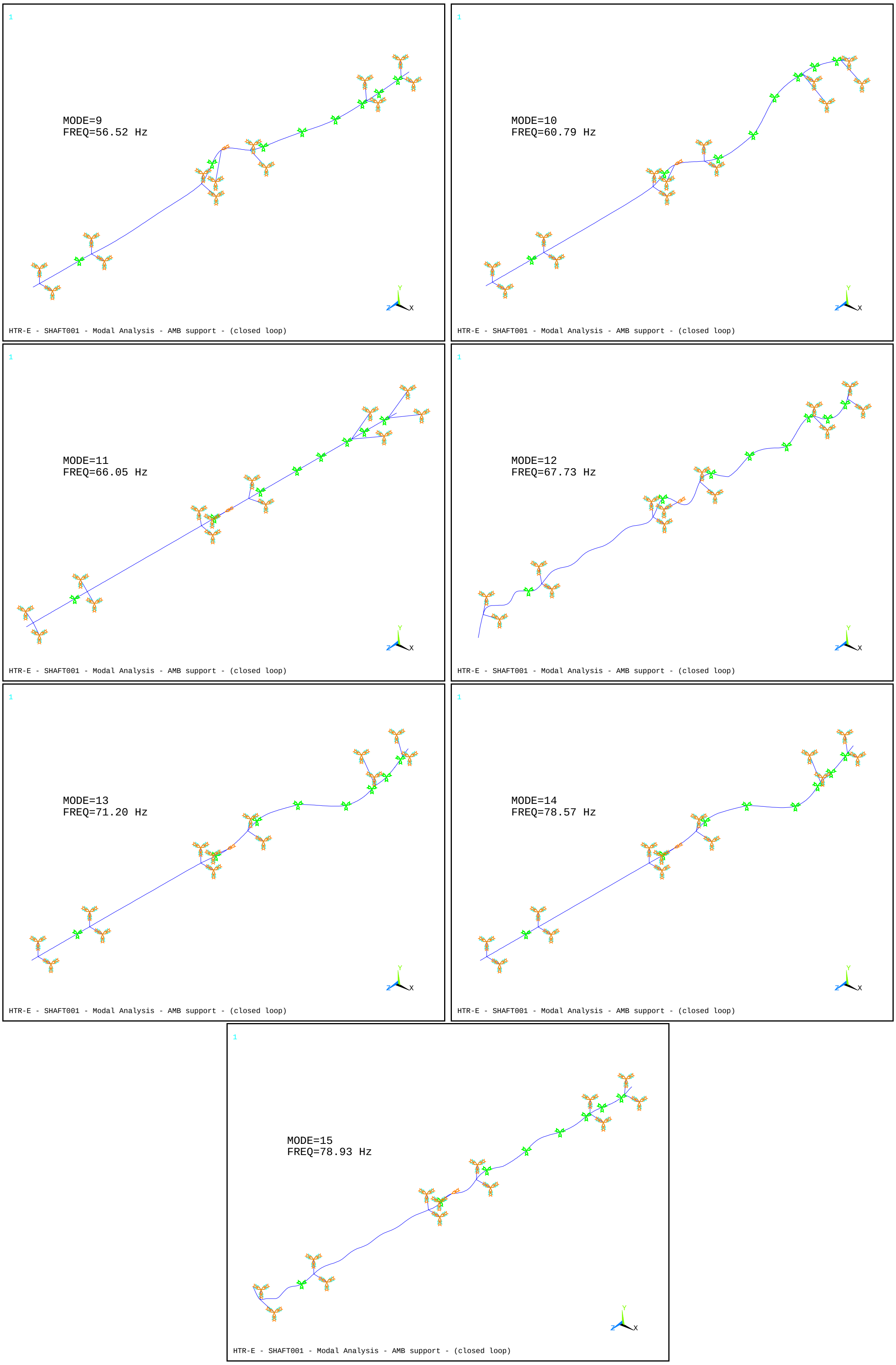


figure 14 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 9 to 15

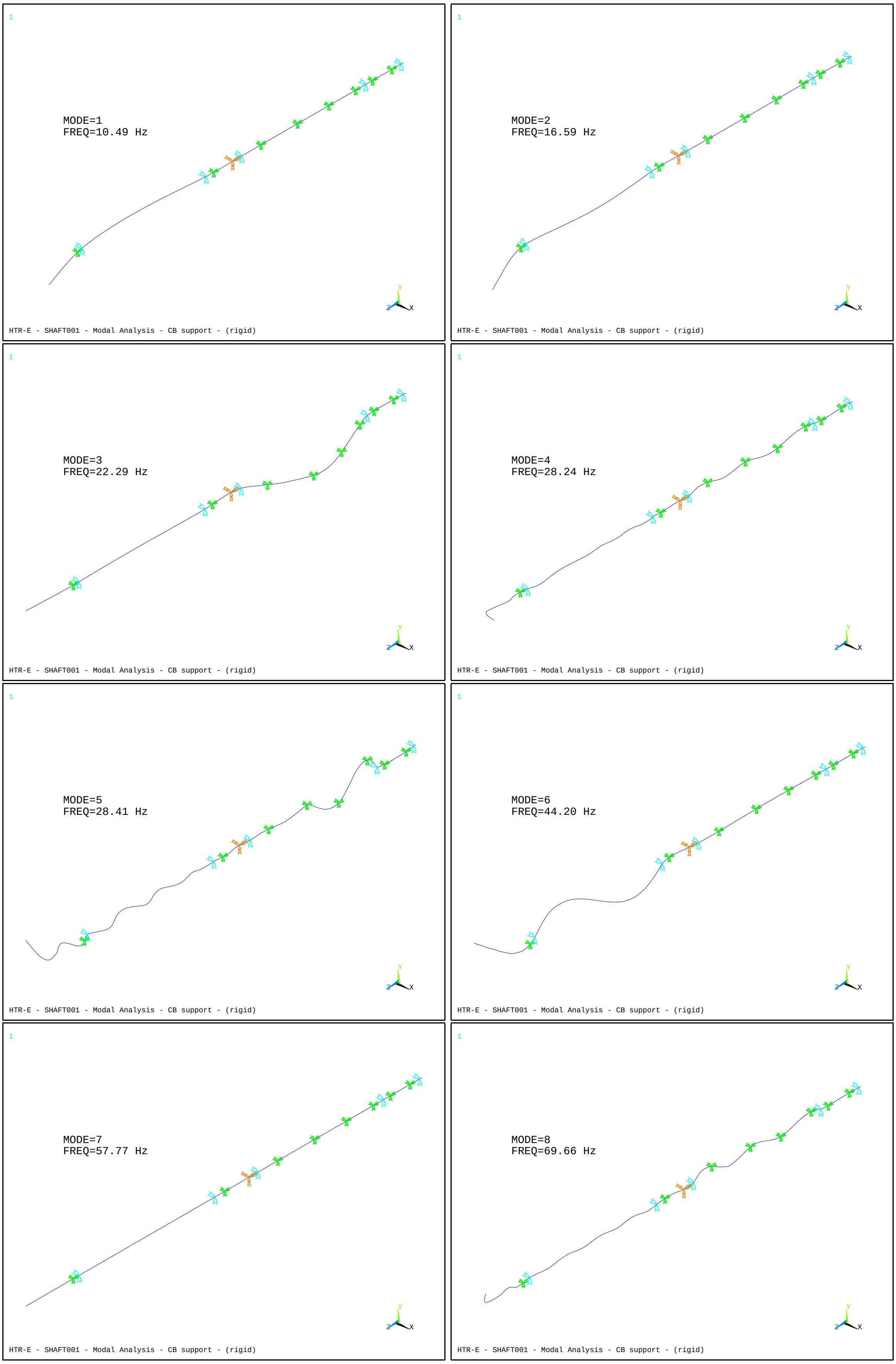


figure 15 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 1 to 8

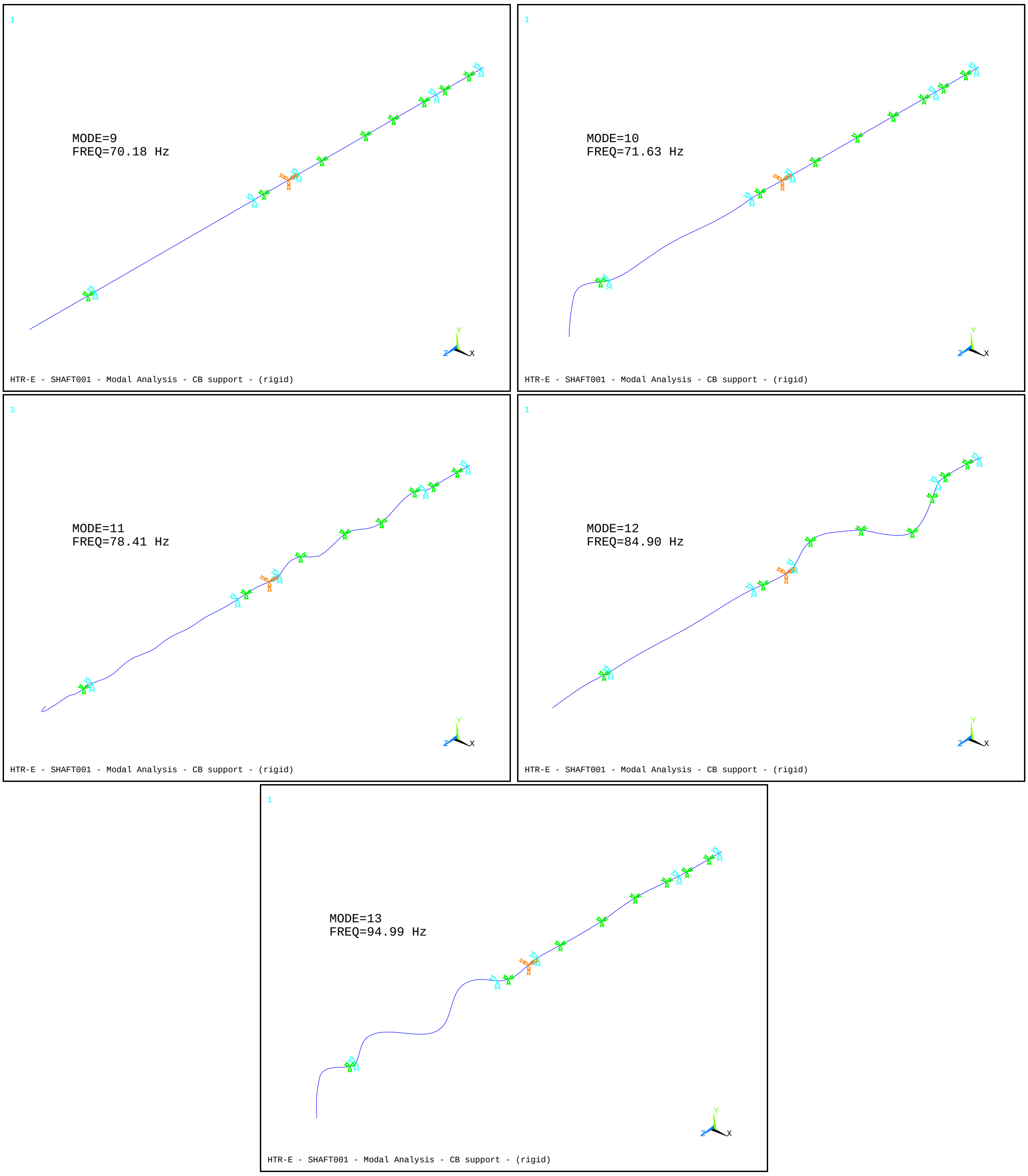


figure 16 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 9 to 13

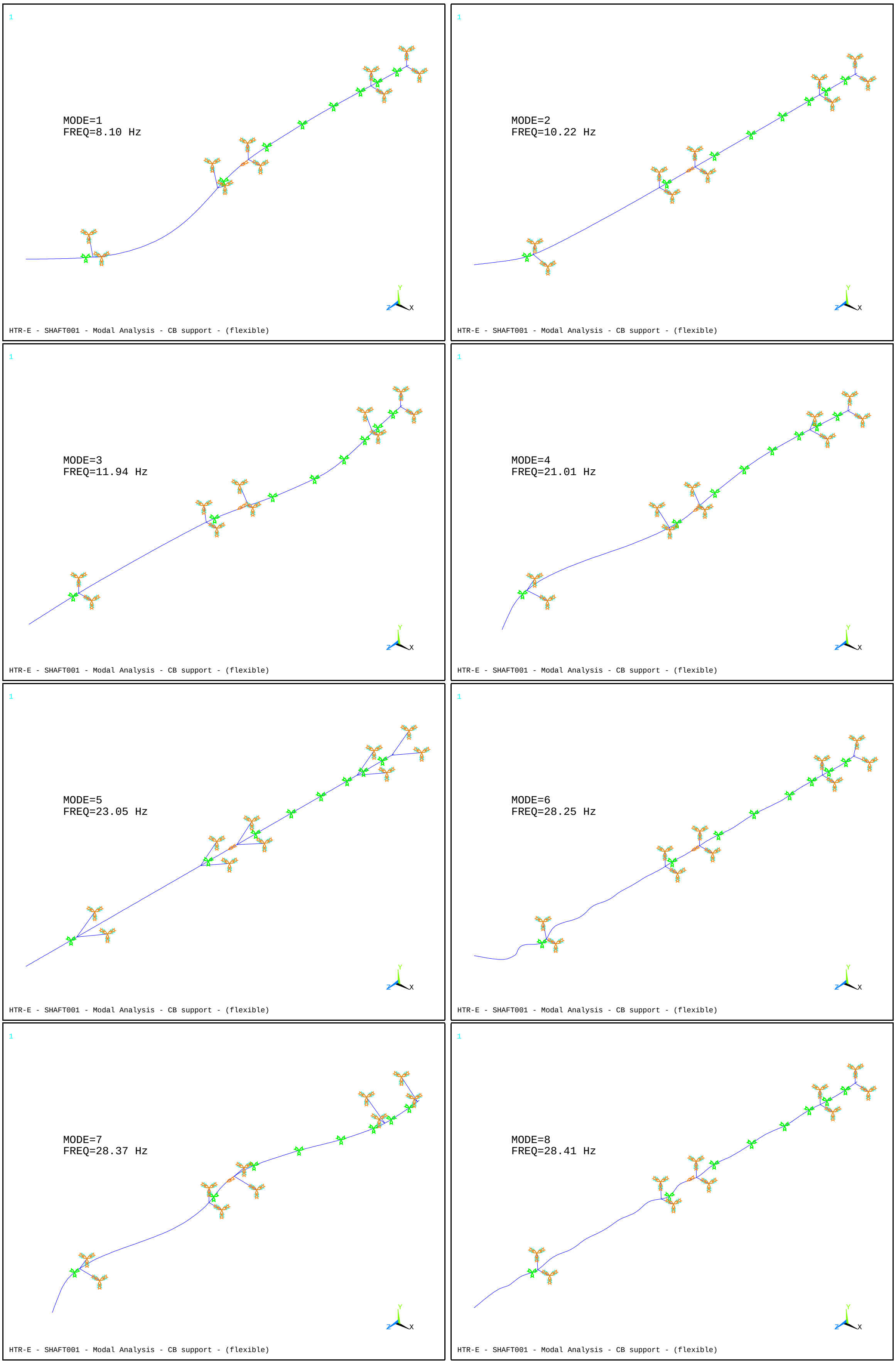


figure 17 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 1 to 8

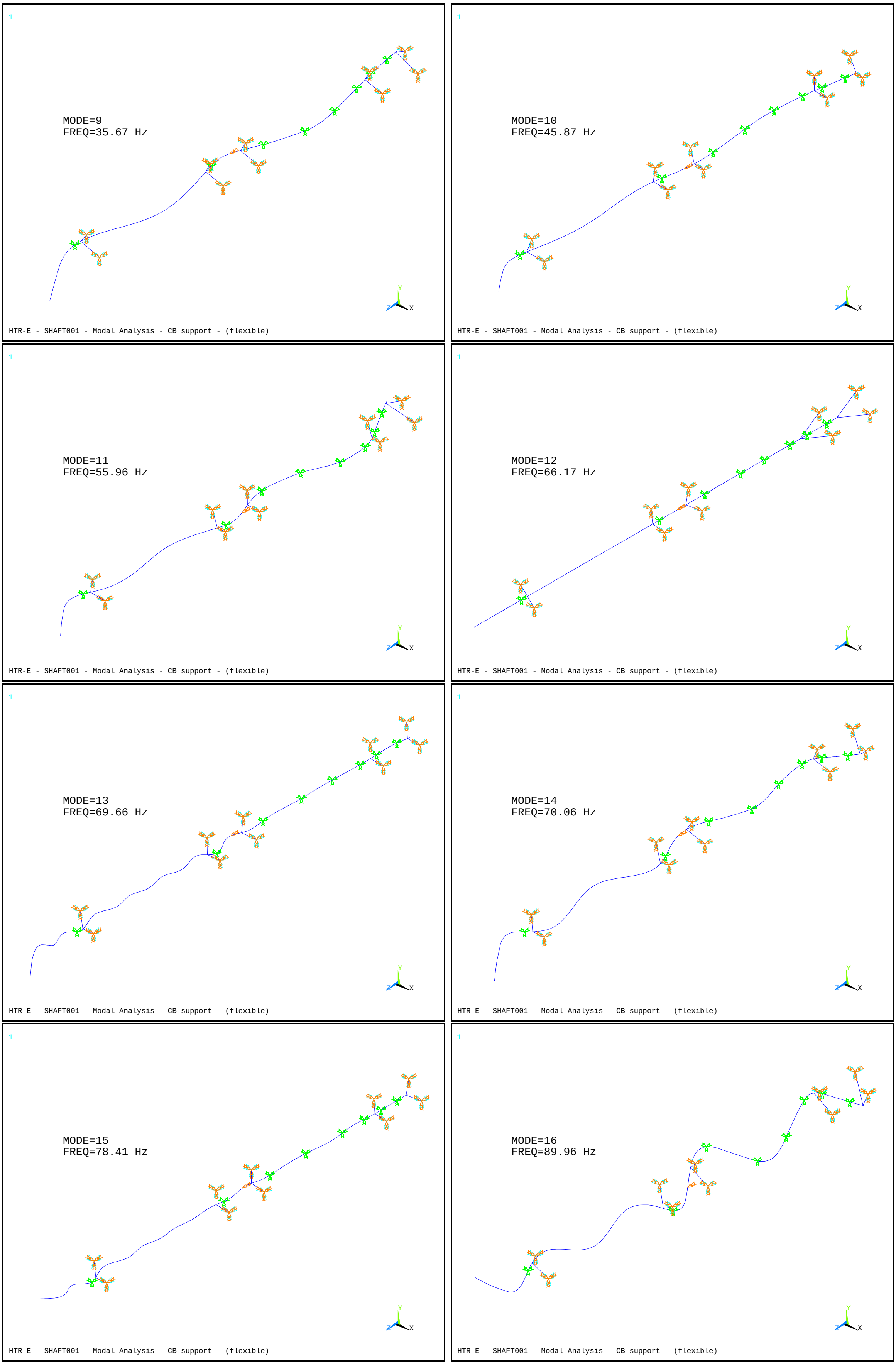


figure 18 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 9 to 16

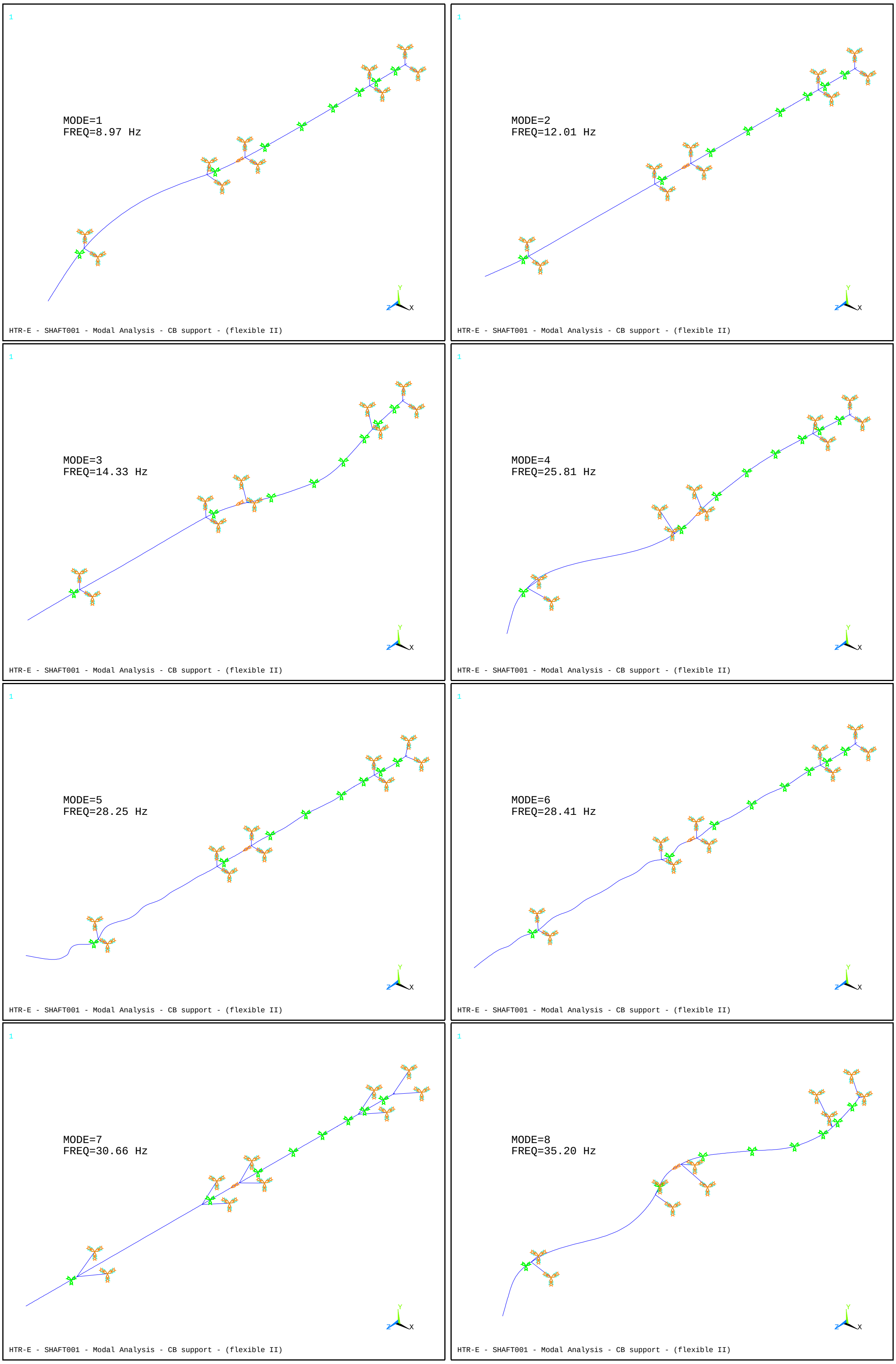


figure 19 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 1 to 8

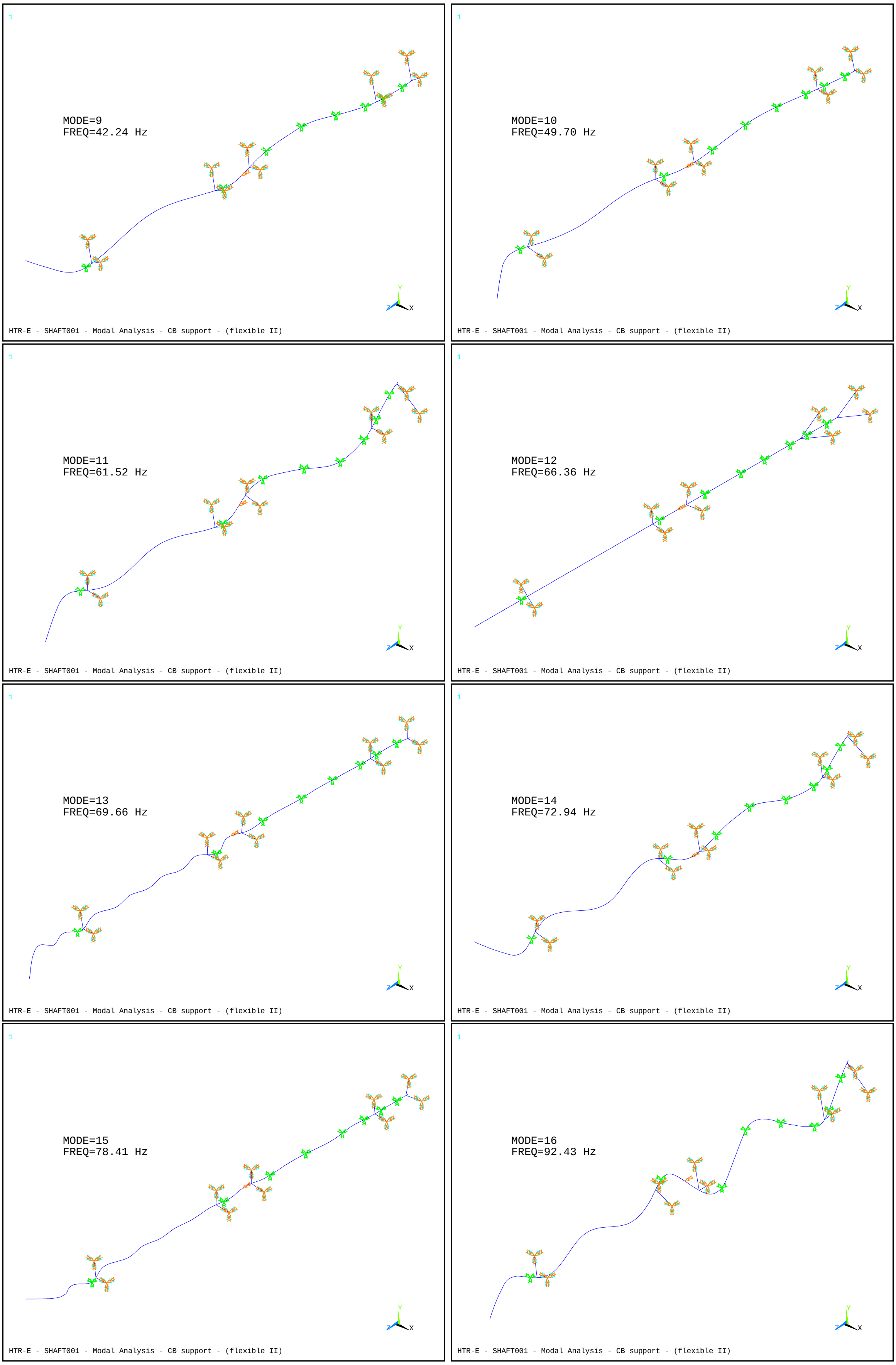
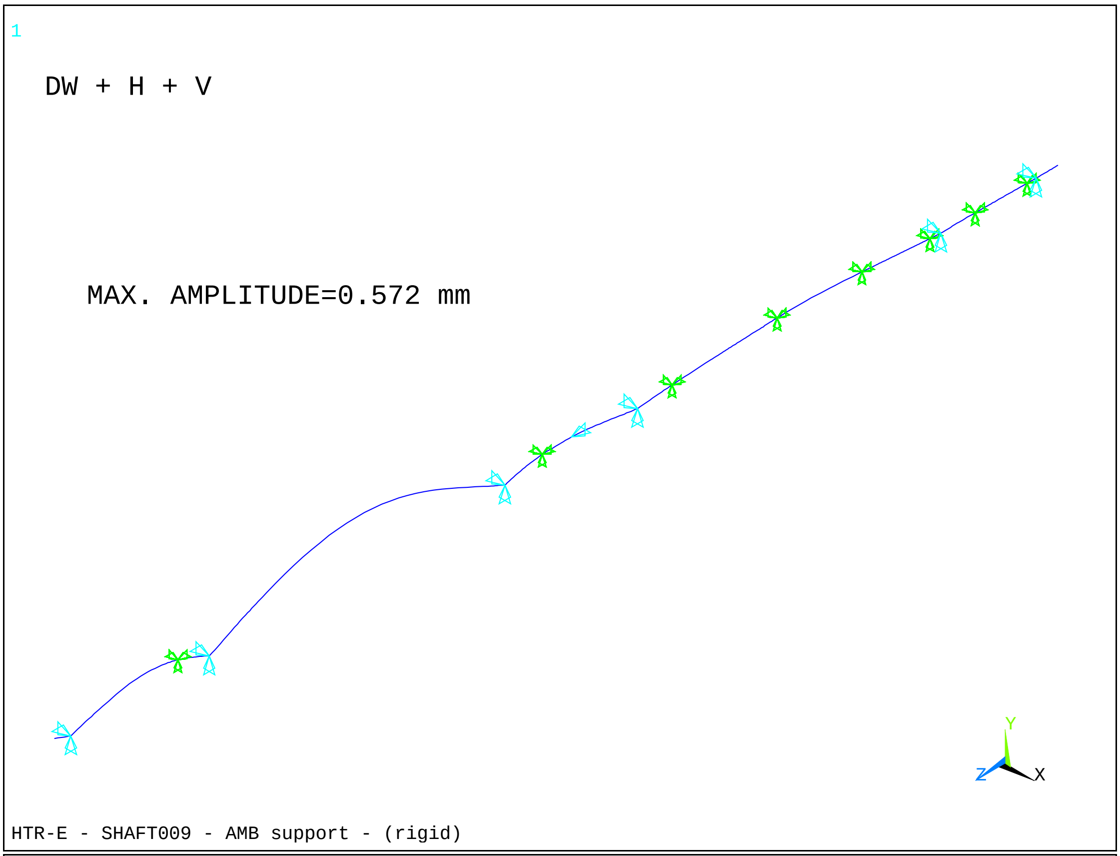


figure 20 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 9 to 16



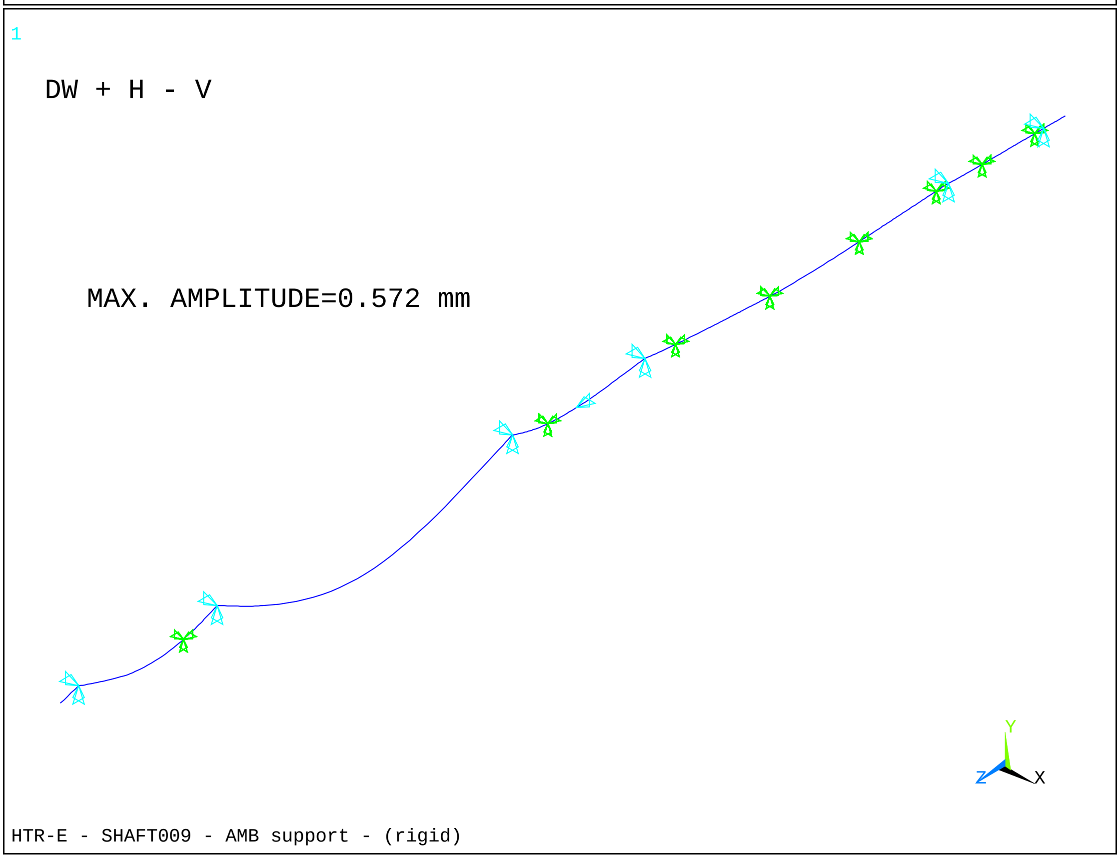
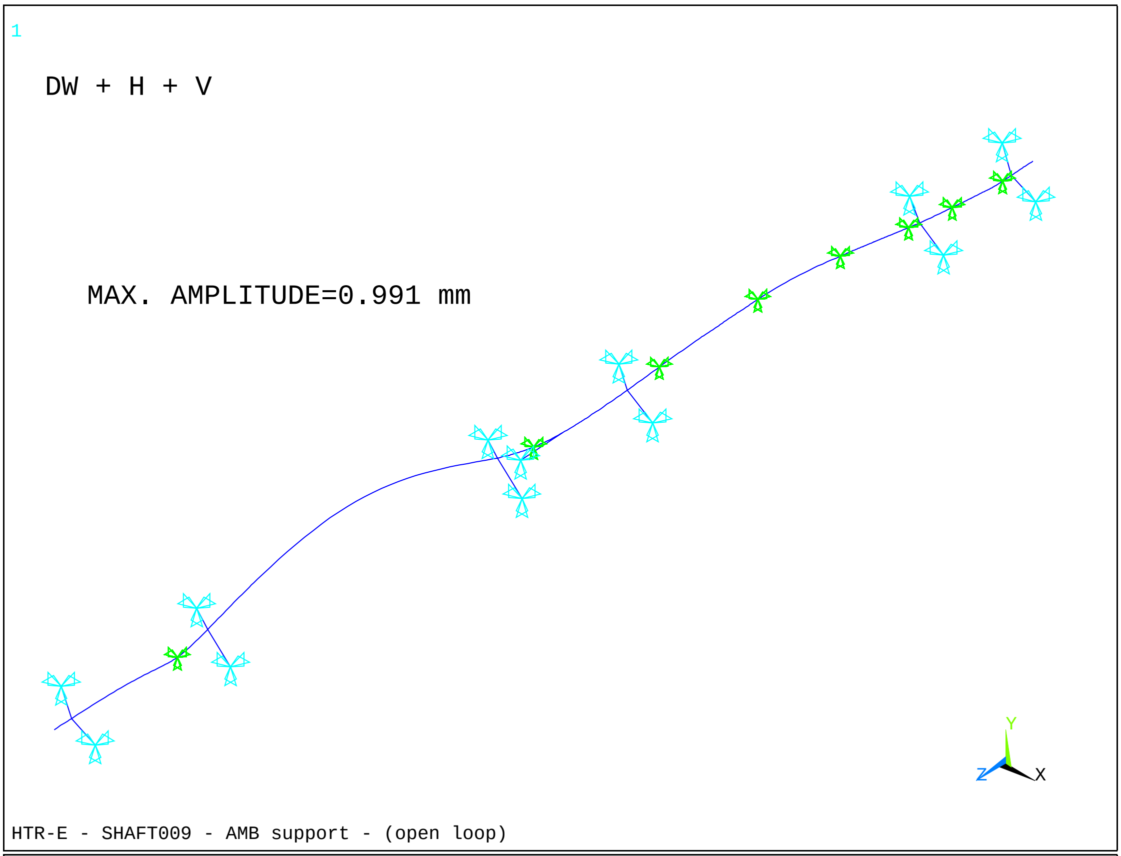


figure 21 AMB support (rigid)
Response due to load combination dead weight and seismic



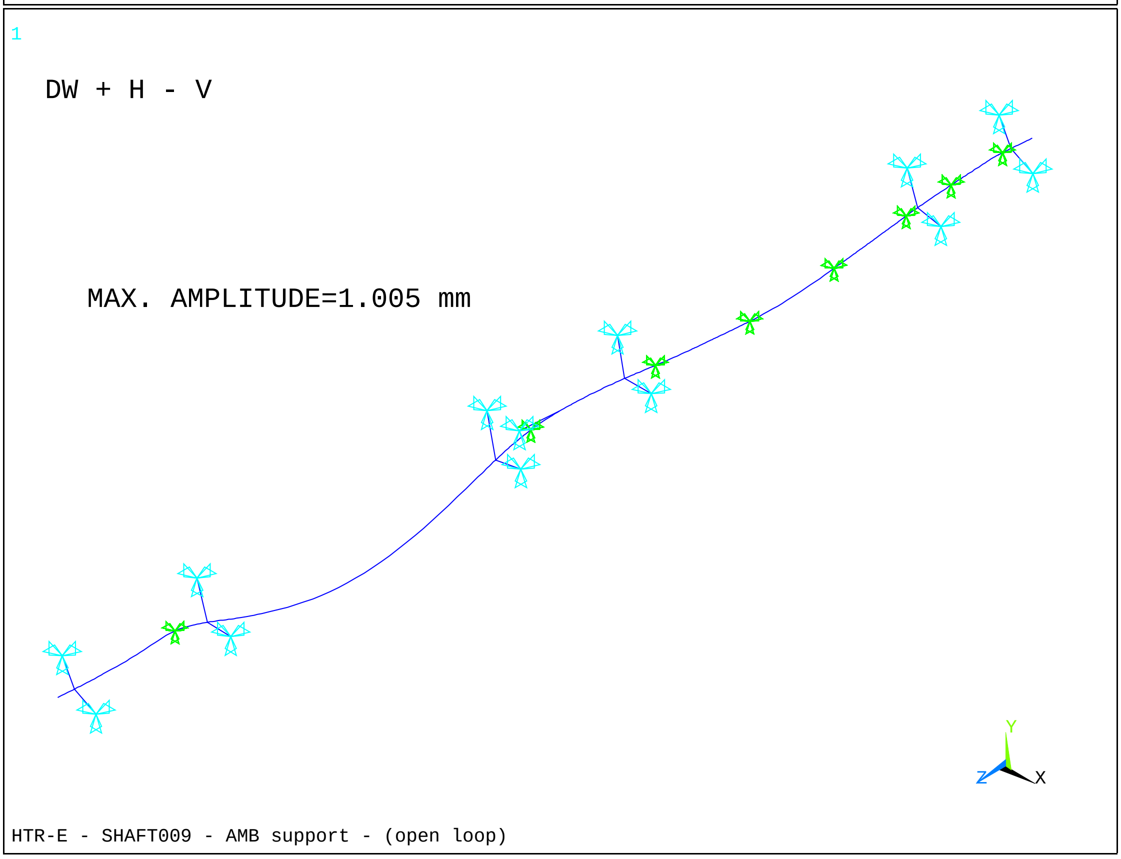
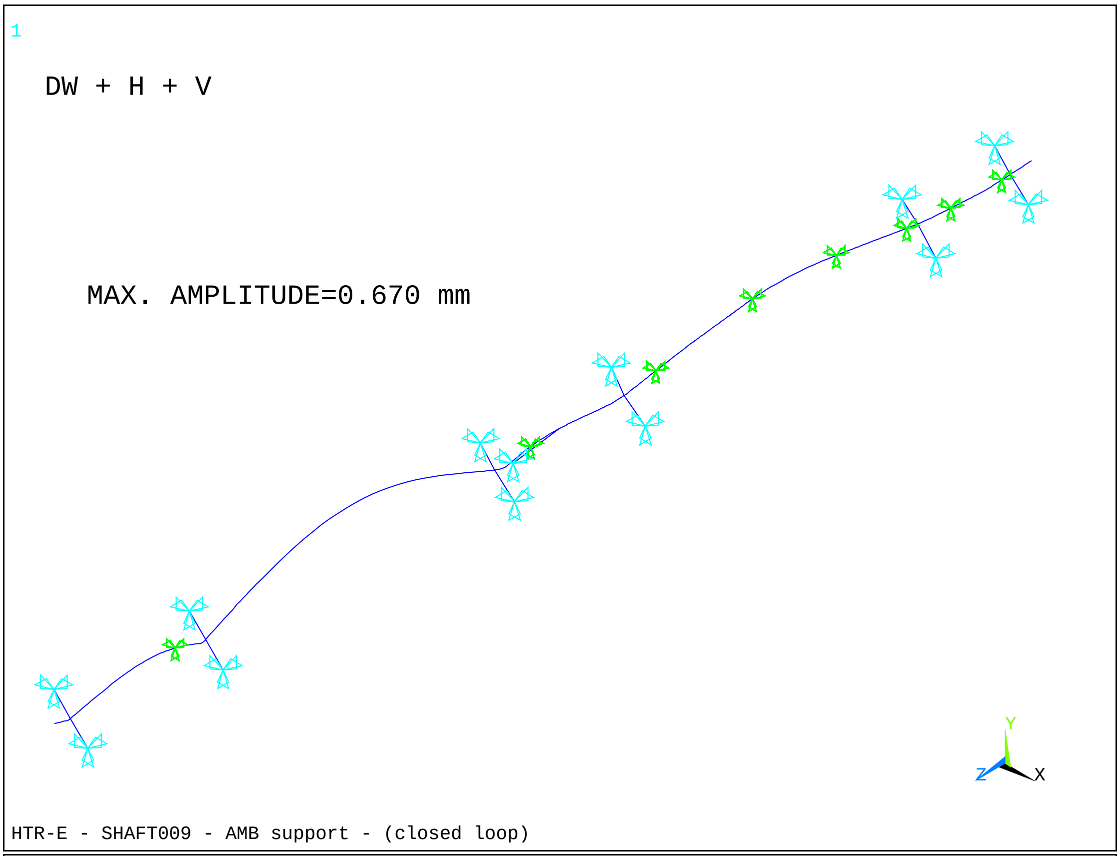


figure 22 AMB support (open loop)
Response due to load combination dead weight and seismic



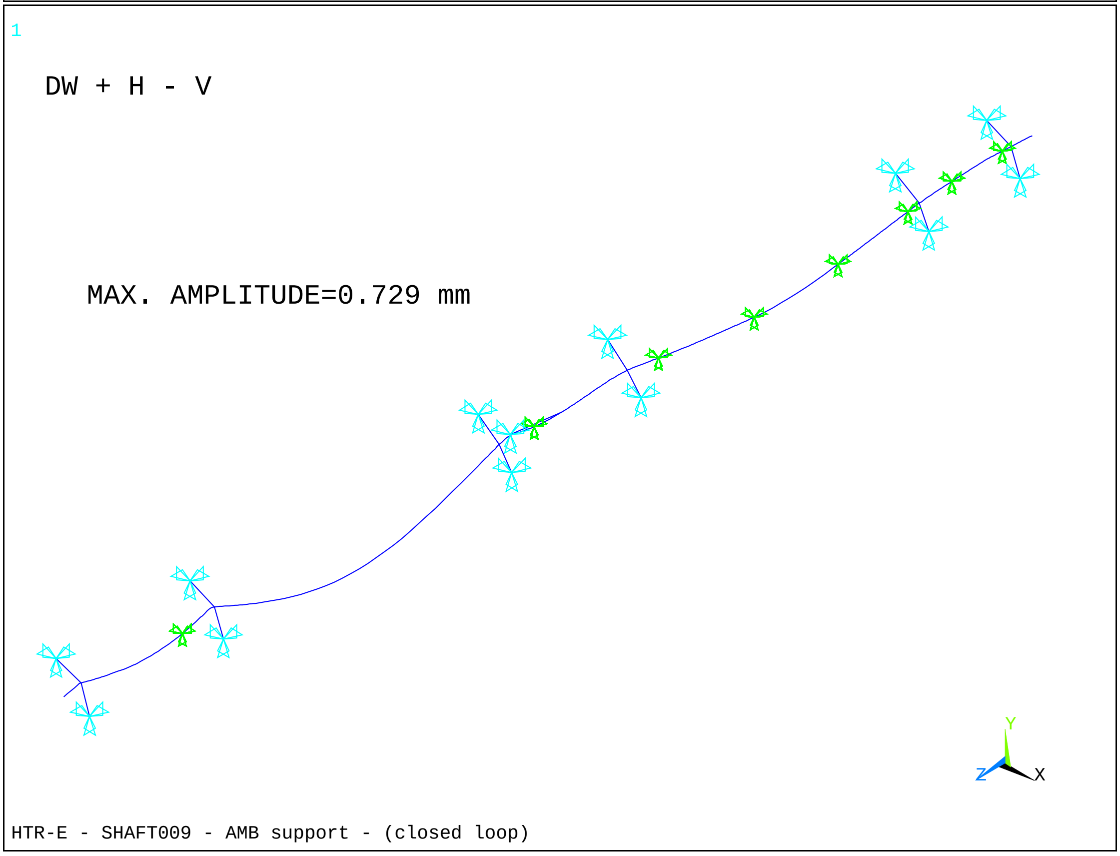
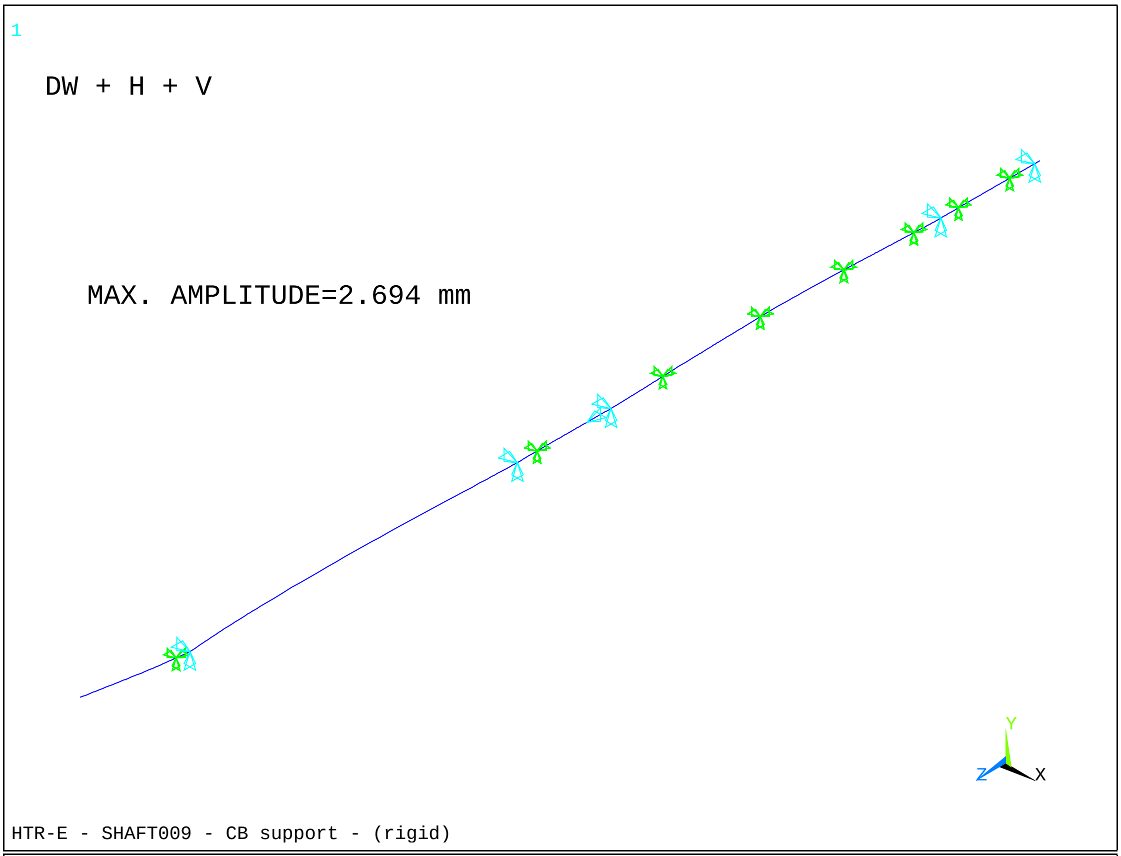


figure 23 AMB support (closed loop)
Response due to load combination dead weight and seismic



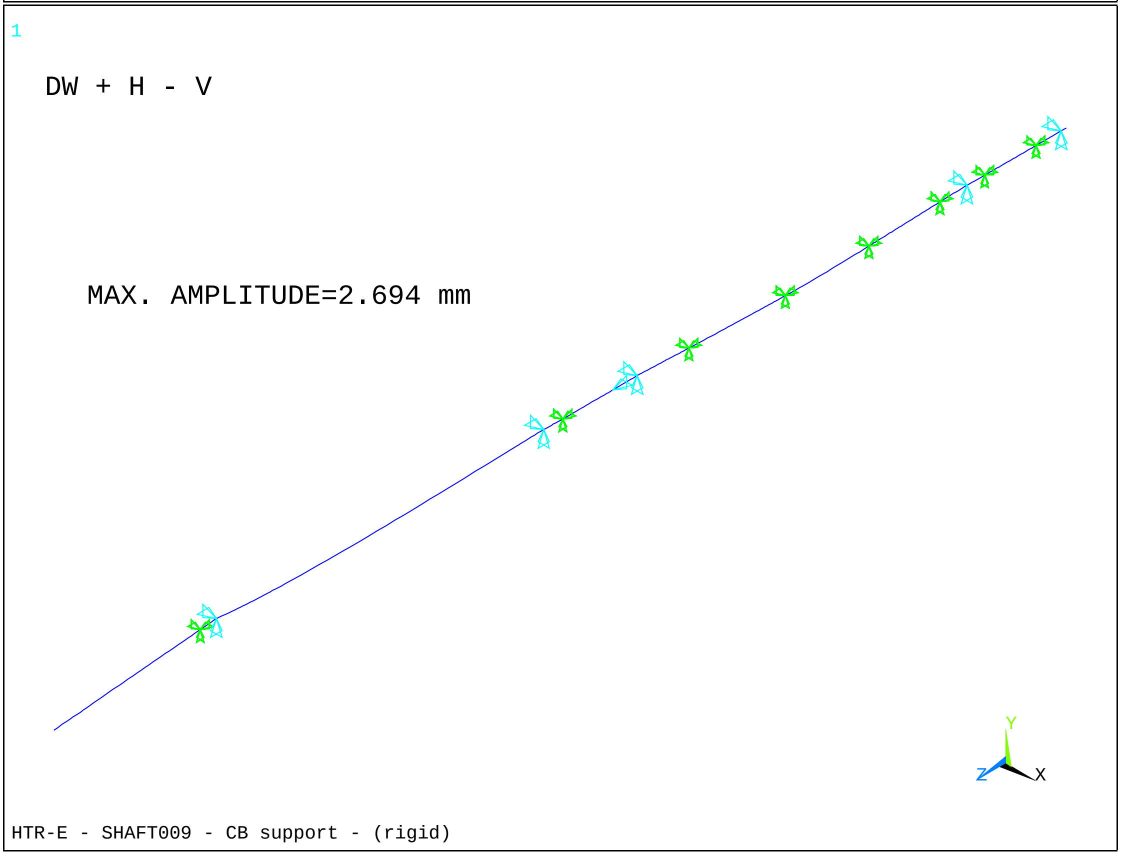
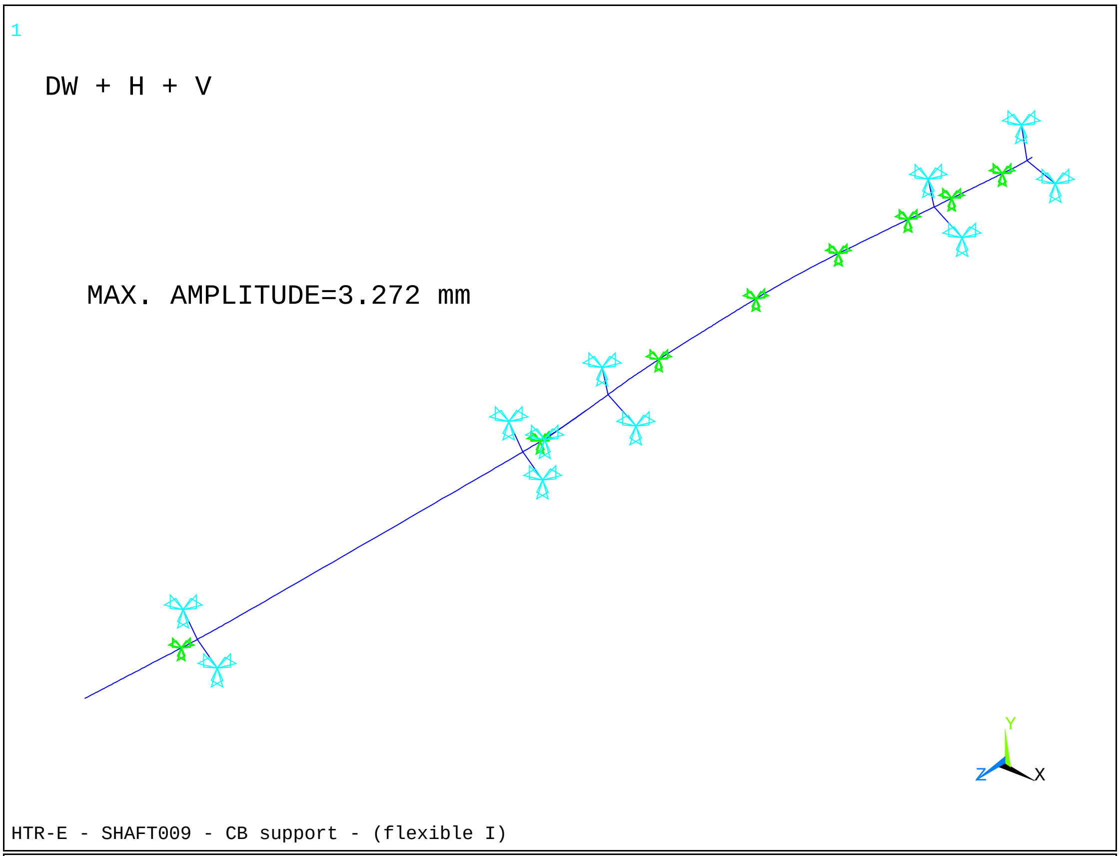


figure 24 CB support (rigid)
Response due to load combination dead weight and seismic



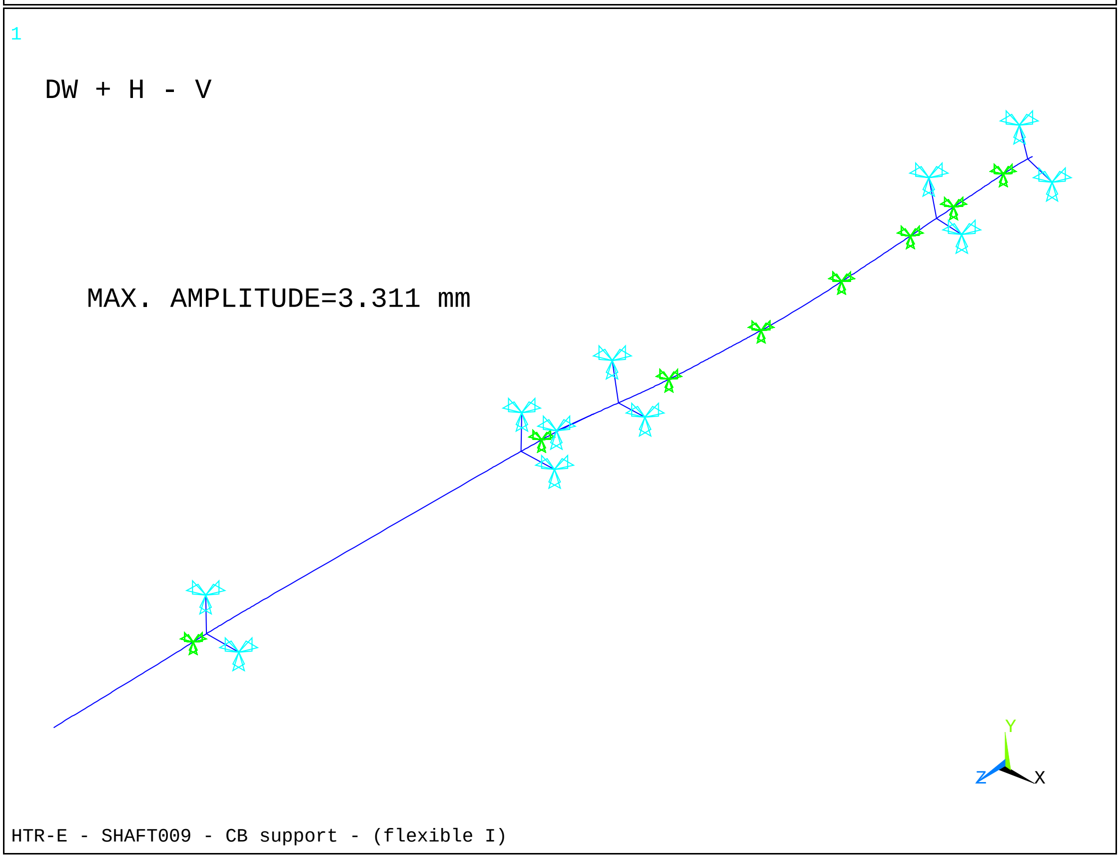
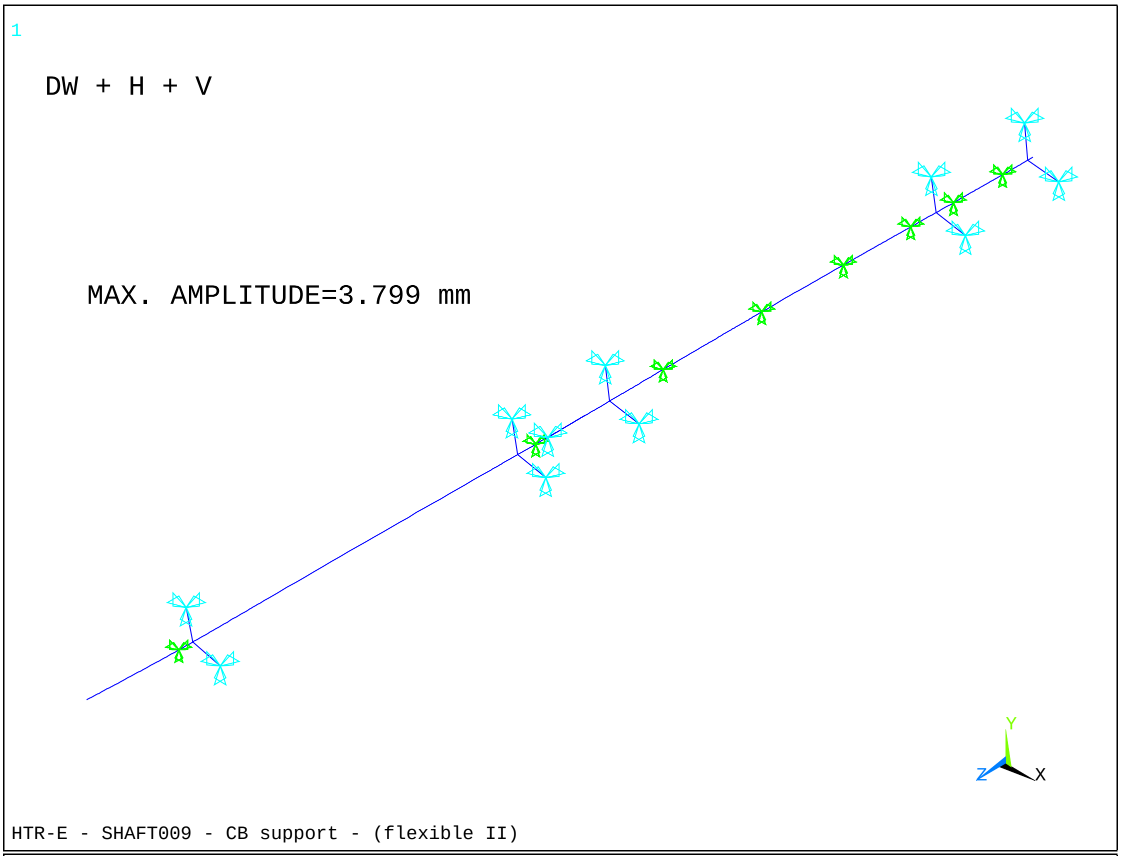


figure 25 CB support (flexible I)
Response due to load combination dead weight and seismic



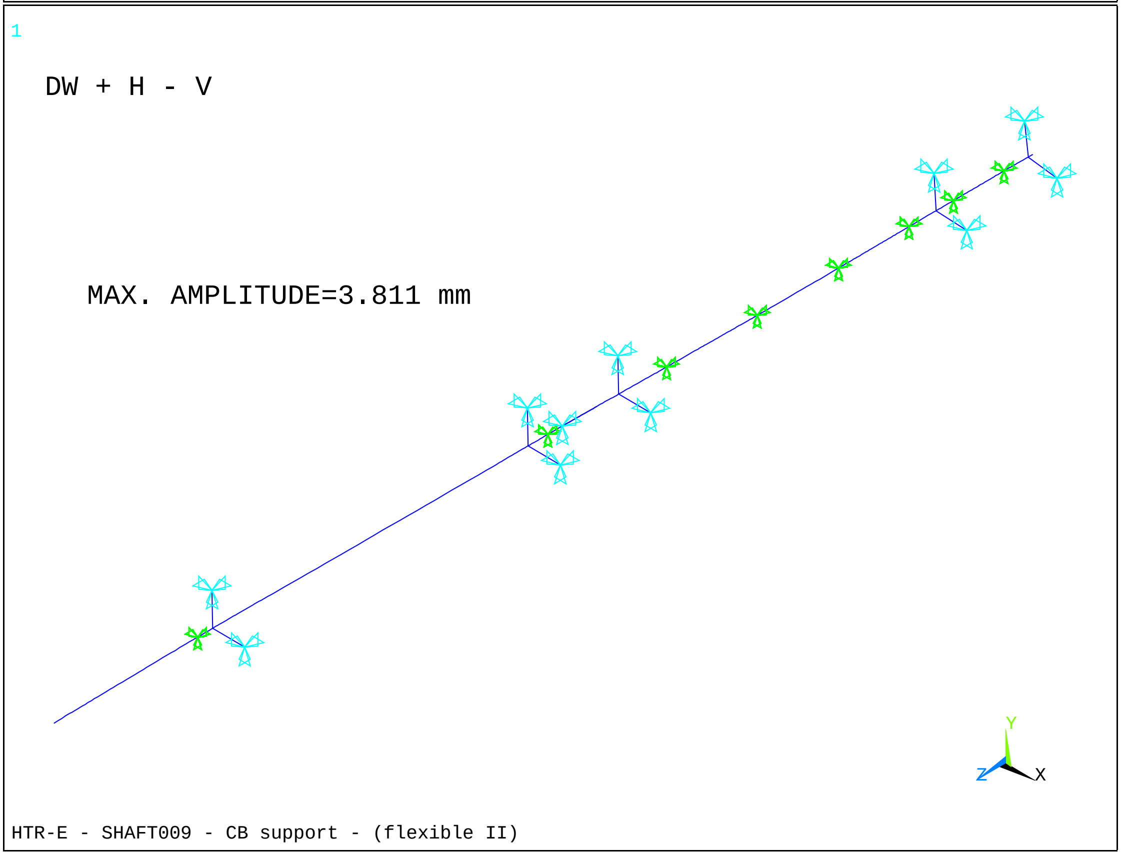


figure 26 CB support (flexible II)
Response due to load combination dead weight and seismic