EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-E

High-Temperature Reactor Components and Systems

CONTRACT N°
FIKI-CT-2001-00177

HTR-E WP 3
Load Analysis

J.H. Fokkens

Nuclear Research and consultancy Group

The Netherlands

Dissemination level : RE
Document N°: HTR-E-04/03-D-3-1-2-1
Status : Preliminary
Deliverable D22

This page is intentionally left blank

Confidential

HTR-E WP 3
Load Analysis

J.H. Fokkens

Petten, 10 March 2004

20793/03.56445/C

Under the contract of the EC and the Netherlands Ministry of Economic Affairs

author :	J.H. Fokkens	reviewed :	F.J. Blom
89 page(s)		approved :	V.A. Wiehers

Acknowledgement

The work reported is carried out for the 5th Framework Programme HTR-E (contract nr. FIKI-CT-2001-00177) with financial support from the European Commision and the Netherlands Ministry of Economic Affairs. The report is a deliverable of NRG to HTR-E WP 3.

Contents

List of Tables **4**

List of Figures **6**

1 Introduction **11**

2 Problem Definition **13**

3 Approach **15**

3.1 Finite Element Model 15

3.2 Material Properties 15

3.3 Boundary Conditions 15

3.4 Loading Conditions 16

3.5 Evaluation Criteria 17

4 Modal Analyses **19**

5 Unbalance in the Exciter **21**

6 Central Unbalance in the Generator **25**

7 Opposite End Unbalances in the Generator **29**

8 Unbalance in the Axial AMB Disk **33**

9 Unbalance in the Hollow Shaft **37**

10 Turbine Unbalance due to Blade Failure **41**

11 LP-Compressor Unbalance due to Blade Failure **45**

12 Summary and Conclusions **49**

References **51**

Figures **53**

List of Tables

1	The frequency dependent stiffnesses of the AMBs with an open loop control system	16
2	The frequency dependent stiffnesses of the AMBs with an closed loop control system	16
3	The applied CB stiffnesses	17
4	The natural frequencies of the GT-MHR rotor shaft for the investigated support variants	19
5	Maximum bearing loads and response displacements for each support variant due to an exciter unbalance	21
6	Harmonic Response Analyses - Active magnetic bearing support - (rigid) Bearing loads at various modes due to an unbalance in the exciter	22
7	Harmonic Response Analyses - Active magnetic bearing support - (open loop) Bearing loads at various modes due to an unbalance in the exciter	22
8	Harmonic Response Analyses - Active magnetic bearing support - (closed loop) Bearing loads at various modes due to an unbalance in the exciter	23
9	Harmonic Response Analyses - Catcher bearing support - (rigid) Bearing loads at various modes due to an unbalance in the exciter	23
10	Harmonic Response Analyses - Catcher bearing support - (flexible I) Bearing loads at various modes due to an unbalance in the exciter	24
11	Harmonic Response Analyses - Catcher bearing support - (flexible II) Bearing loads at various modes due to an unbalance in the exciter	24
12	Maximum bearing loads and response displacements for each support variant due to a central generator unbalance	25
13	Harmonic Response Analyses - Active magnetic bearing support - (rigid) Bearing loads at various modes due to a central unbalance in the generator	26
14	Harmonic Response Analyses - Active magnetic bearing support - (open loop) Bearing loads at various modes due to a central unbalance in the generator	26
15	Harmonic Response Analyses - Active magnetic bearing support - (closed loop) Bearing loads at various modes due to a central unbalance in the generator	27
16	Harmonic Response Analyses - Catcher bearing support - (rigid) Bearing loads at various modes due to a central unbalance in the generator	27
17	Harmonic Response Analyses - Catcher bearing support - (flexible I) Bearing loads at various modes due to a central unbalance in the generator	28
18	Harmonic Response Analyses - Catcher bearing support - (flexible II) Bearing loads at various modes due to a central unbalance in the generator	28
19	Maximum bearing loads and response displacements for each support variant due to opposite end unbalances in the generator	29
20	Harmonic Response Analyses - Active magnetic bearing support - (rigid) Bearing loads at various modes due to opposite end unbalances in the generator	30
21	Harmonic Response Analyses - Active magnetic bearing support - (open loop) Bearing loads at various modes due to opposite end unbalances in the generator	30
22	Harmonic Response Analyses - Active magnetic bearing support - (closed loop) Bearing loads at various modes due to opposite end unbalances in the generator	31
23	Harmonic Response Analyses - Catcher bearing support - (rigid) Bearing loads at various modes due to opposite end unbalances in the generator	31

24 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to opposite end unbalances in the generator 32
25 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to opposite end unbalances in the generator 32
26 Maximum bearing loads and response displacements for each support variant due to an axial AMB disk unbalance 33
27 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 34
28 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 34
29 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 35
30 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 35
31 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 36
32 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB 36
33 Maximum bearing loads and response displacements for each support variant due to a hollow shaft unbalance 37
34 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the hollow shaft 38
35 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the hollow shaft 38
36 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the hollow shaft 39
37 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the hollow shaft 39
38 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the hollow shaft 40
39 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the hollow shaft 40
40 Maximum bearing loads and response displacements for each support variant due to a turbine unbalance 41
41 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the turbine 42
42 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the turbine 42
43 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the turbine 43
44 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the turbine 43
45 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the turbine 44

46 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the turbine 44
47 Maximum bearing loads and response displacements for each support variant due to a LP-compressor unbalance 45
48 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the LP-compressor 46
49 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the LP-compressor 46
50 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the LP-compressor 47
51 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the LP-compressor 47
52 Harmonic Response Analyses - Catcher bearing support - (flexible)
Bearing loads at various modes due to an unbalance in the LP-compressor 48
53 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the LP-compressor 48
54 Summary of maximum bearing loads (in kN) for the AMB support variants under normal operation conditions 49
55 Summary of maximum bearing loads for all support variants under emergency conditions 50

List of Figures

1 Layout of the GT-MHR rotor shaft 53
2 The position of the Active Magnetic Bearings supporting the GT-MHR rotor shaft 54
3 The position of the Catcher Bearings supporting the GT-MHR rotor shaft 54
4 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (rigid stiffness) 55
5 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (flexible stiffness) 55
6 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (rigid stiffness) 56
7 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (flexible stiffness) 56
8 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 1 to 8 57
9 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 9 to 12 58
10 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 1 to 8 59
11 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 9 to 15 60
12 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 1 to 8 61
13 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 9 to 15 62

14 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 1 to 8 63
15 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 9 to 13 64
16 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 1 to 8 65
17 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 9 to 16 66
18 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 1 to 8 67
19 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 9 to 16 68
20 Harmonic Response Analysis
Unbalance of 20 kg mm in the exciter 69
21 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 70
22 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 70
23 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 70
24 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 71
25 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 71
26 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter 71
27 Harmonic Response Analysis
Central unbalance of 20 kg mm in the generator 72
28 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 73
29 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 73
30 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 73
31 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 74
32 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 74
33 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I) 74
34 Harmonic Response Analysis
Opposite end unbalances of 10 kg mm in the generator 75
35 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 76

36 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 76
37 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 76
38 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 77
39 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 77
40 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II) 77
41 Harmonic Response Analysis
Unbalance of 20 kg mm in the disk of the axial AMB 78
42 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 79
43 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 79
44 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 79
45 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 80
46 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 80
47 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB 80
48 Harmonic Response Analysis
Unbalance of 20 kg mm in the hollow shaft 81
49 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 82
50 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 82
51 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 82
52 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 83
53 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 83
54 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft 83
55 Harmonic Response Analysis
Unbalance of 536 kg mm in the turbine 84

56 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 85
57 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 85
58 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 85
59 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 86
60 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 86
61 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine 86
62 Harmonic Response Analysis
Unbalance of 320 kg mm in the LP-compressor 87
63 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 88
64 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 88
65 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 88
66 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 89
67 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 89
68 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor 89

1 Introduction

This report contributes to the 5th Framework Programme HTR-E WP3. The aim of the report 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 load 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 normal and emergency conditions calculated with finite element dynamic analyses are presented in this report. The report focuses on the radial bearing loads caused by unbalance eccentricities in the various components of the rotor shaft.

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).

The radial bearing loads are caused by unbalance eccentricities in the various components of the rotor shaft. 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.

For the load cases 1 to 5 the bearing loads for an unbalance eccentricity of 10 μm [1] are calculated. The load cases 6 and 7 are based on deblading accidents in the turbine and the LP-compressor [2]. For these load cases the calculated bearing loads and the response displacements are compared with the maximum feasible bearing loads and the 10 μm maximal unbalance eccentricity.

3 Approach

The dynamic behaviour of the GT-MHR rotor shaft is investigated by means of finite element calculations. The finite element calculations are performed with the general purpose finite element code ANSYS Release 6.0 [3]. In the finite element model the geometrical and material properties, as well as the boundary and loading conditions are incorporated. Modal analyses are performed to calculate the natural frequencies of the rotor shaft under the various boundary conditions. The response of the rotor shaft to the various unbalance loading conditions is calculated with harmonic response analyses.

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. 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 [4]. 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

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 [4]. For all bearings a damping of 0.05 has been assumed.

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

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

Unbalance eccentricities in the various components of the rotor shaft result in rotating radial forces acting on the rotor shaft at the locations of the unbalances. The magnitude of a rotating radial force depends on the rotational velocity of the rotor shaft:

$$F_{\text{rot}} = m \cdot r \cdot \omega^2$$

where:

$m \cdot r$	: unbalance	[kg m]
ω	: rotational velocity	[rad/s]

The radial deflection of the rotor shaft due to the unbalance forces can be amplified at the rotor shafts natural frequencies. This amplification of the radial deflection will also result in increased bearing forces. For the following unbalance load cases the bearing loads and maximum deflection of the rotor shaft have been calculated at each natural frequency:

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.

For the load cases 1 to 7 the bearing loads and maximum deflection of the rotor shaft have also been determined at normal operation velocity (3000 rpm - 50 Hz) and trip velocity (3600 rpm - 60 Hz).

3.5 Evaluation Criteria

For the GT-MHR rotor shaft and active magnetic bearings the following requirements have been specified in [1]. The maximum load capacity of the radial AMBs is 100 kN and of the axial AMB is 1050 kN. At nominal operation conditions (3000 rpm - 50 Hz) the radial deflection of the rotor shaft should not exceed 10 μm.

4 Modal 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	B	C	D	E	F
	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[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 8 and 9. The Figures 10 and 11 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 12 and 13. For the Catcher Bearing support variant with rigid stiffness (D) the Figures 14 and 15 show the mode shapes and the Figures 16 to 19 show the mode shapes for support variant E and F, CB support with flexible stiffness.

5 Unbalance in the Exciter

In the middle of the exciter an unbalance of 20 kg mm is assumed (Figure 20). The bearing forces and the maximum response displacements as a result of this unbalance have been determined for all the support variants. The results are summarized respectively in Tables 6 to 11 for all support variants. The Figures 21 to 26 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance in the exciter results in high bearing loads in the bearings 1 and 2, if supported by the AMBs. If the shaft is supported by the CBs high bearing loads only occur in bearing 2 and the end of the rotor shaft has a large response displacement. For the support variants A, B, and C the highest bearings loads and responses occur between 30 and 40 Hz, and for the support variants D, E, and F between 5 and 20 Hz. AMB support results in higher bearing loads than CB support, while CB support results in higher response displacements, at the unsupported shaft end, than AMB support. A higher bearing stiffness results in higher bearing loads and lower response displacements.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 5. For each support variant Table 5 also summarizes the magnitude of the maximum allowable unbalance in the exciter if the unbalance eccentricity at 3000 rpm is 10 μm. Finally, the scaled bearing loads and maximum displacement response for the maximum allowable unbalances are given in Table 5.

The 10 μm limit for the shaft eccentricity is the most restrictive criterion for the dynamic behaviour of the rotor shaft. The bearing loads scaled to the 10 μm criterion are for all AMB support variants within acceptable limits. The CB support variants show large response displacements at the unsupported shaft end, which result in combination with the 10 μm criterion in much smaller maximum allowable unbalances in the exciter for the CB support variants than for the AMB support variants.

table 5 Maximum bearing loads and response displacements for each support variant due to an exciter unbalance

Support variant	$F_{bear.max}$ [kN]	$u_{resp.max}$ [μm]	max. unbal. [kg mm]	$F_{bear.scaled}$ [kN]	$u_{resp.scaled}$ [μm]
AMB support - rigid	14.782	46.363	54.2	40.092	125.747
AMB support - open loop	12.683	43.178	52.6	33.359	113.567
AMB support - closed loop	15.630	50.755	41.6	32.508	105.564
CB support - rigid	7.910	107.395	23.4	9.253	125.623
CB support - flexible I	3.510	123.493	11.3	1.987	69.916
CB support - flexible II	5.177	120.622	4.0	1.035	24.110

table 6 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.189	0.633	0.994	0.324	0.109	0.040	3.664
2	24.59	0.398	0.459	0.136	0.067	0.106	0.036	1.304
3	26.20	0.477	0.569	0.307	0.498	0.394	0.134	1.621
4	31.18	0.884	1.187	0.499	0.267	0.086	0.028	3.507
5	38.73	7.870	14.467	8.021	3.565	0.671	0.208	46.363
6	55.74	2.282	14.782	9.306	6.232	0.900	0.248	9.395
7	61.88	0.351	4.657	1.211	1.510	0.232	0.062	4.724
8	67.73	0.895	3.332	0.411	1.510	0.263	0.068	3.921
9	67.87	0.907	3.311	0.437	1.528	0.267	0.069	3.911
10	73.73	1.373	3.988	6.369	4.557	0.964	0.245	5.605
11	78.93	1.727	4.063	3.008	1.076	0.290	0.072	3.839
12	103.94	5.839	3.924	6.925	2.647	2.271	0.556	5.879
3000 rpm	50.00	0.370	0.703	2.281	1.175	0.171	0.049	3.687
3600 rpm	60.00	0.230	5.733	1.956	1.888	0.283	0.076	5.360

table 7 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.074	0.054	0.022	0.001	0.001	0.000	0.461
2	18.55	0.248	0.251	0.005	0.004	0.001	0.000	1.397
3	24.59	0.780	1.212	0.215	0.060	0.009	0.000	5.615
4	30.35	5.079	12.683	2.909	1.013	0.158	0.001	43.178
5	31.18	2.768	8.194	2.633	0.990	0.169	0.001	25.874
6	33.84	1.185	2.891	4.938	2.518	0.550	0.011	10.755
7	36.42	0.706	2.691	4.272	1.813	0.266	0.002	7.602
8	45.61	0.360	1.800	0.965	2.605	0.767	0.059	5.567
9	60.82	1.255	1.706	0.547	0.596	1.812	0.865	3.764
10	66.09	1.813	2.198	0.556	0.394	0.778	0.581	4.158
11	67.73	2.054	2.502	0.751	0.546	0.746	0.669	4.388
12	75.71	3.566	6.537	5.239	5.020	2.834	7.594	9.234
13	78.93	3.337	2.705	2.352	3.166	1.280	7.456	9.573
14	81.90	4.083	5.304	3.135	2.290	0.963	11.166	14.950
15	101.62	36.544	24.418	14.361	21.220	14.656	21.908	53.774
3000 rpm	50.00	0.446	1.066	0.176	0.603	0.268	0.043	3.802
3600 rpm	60.00	1.197	1.721	0.577	0.636	1.415	0.620	3.736

table 8 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.158	0.518	0.675	0.140	0.031	0.007	3.222
2	22.14	0.312	0.361	0.122	0.093	0.073	0.019	1.085
3	24.59	0.421	0.495	0.153	0.049	0.013	0.003	1.559
4	27.01	0.573	0.712	0.202	0.055	0.010	0.002	2.299
5	31.18	1.059	1.503	0.441	0.100	0.008	0.002	4.891
6	36.33	7.890	15.630	4.795	1.064	0.033	0.009	50.755
7	47.36	0.287	4.381	3.522	0.617	0.107	0.032	5.082
8	52.79	0.335	2.622	0.446	0.076	0.041	0.023	4.302
9	56.52	0.481	2.864	0.732	0.432	0.107	0.041	4.159
10	60.79	0.777	2.692	0.435	0.023	0.019	0.012	3.897
11	66.05	1.035	3.048	0.989	0.282	0.021	0.005	3.837
12	67.73	1.166	3.043	0.830	0.177	0.022	0.006	3.818
13	71.20	1.454	3.112	0.684	0.080	0.035	0.013	3.827
14	78.57	2.045	3.482	1.002	0.112	0.007	0.001	3.964
15	78.93	2.083	3.500	1.005	0.109	0.006	0.001	3.979
3000 rpm	50.00	0.148	3.247	0.989	0.187	0.050	0.020	4.808
3600 rpm	60.00	0.722	2.705	0.481	0.041	0.027	0.015	3.928

table 9 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	CB2	CB3	CB4	CB5	CB	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.201	4.054	1.902	0.081	0.033	72.405
2	16.59	7.910	6.763	2.586	0.240	0.093	107.395
3	22.29	0.755	0.468	0.263	0.202	0.073	13.084
4	28.24	0.544	0.372	0.133	0.012	0.004	9.478
5	28.41	0.542	0.373	0.133	0.012	0.004	9.422
6	44.20	3.890	6.547	1.864	0.091	0.027	12.646
7	57.77	2.069	0.894	0.237	0.015	0.004	6.020
8	69.66	9.211	3.410	0.877	0.108	0.027	20.954
9	70.18	10.872	4.044	1.039	0.133	0.033	27.768
10	71.63	15.022	5.695	1.454	0.212	0.052	50.859
11	78.41	2.501	1.160	0.274	0.097	0.023	21.795
12	84.90	0.899	0.660	0.256	0.253	0.061	17.278
13	94.99	0.518	0.533	0.204	0.047	0.011	15.784
3000 rpm	50.00	1.792	1.247	0.342	0.018	0.005	8.549
3600 rpm	60.00	2.343	0.943	0.249	0.017	0.005	5.057

table 10 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.322	0.339	0.050	0.030	0.001	10.253
2	10.22	3.510	0.224	0.205	0.055	0.011	123.493
3	11.94	0.536	0.084	0.134	0.111	0.007	18.195
4	21.01	0.926	1.378	0.859	0.560	0.216	14.722
5	23.05	0.075	0.327	0.258	0.192	0.095	7.761
6	28.37	0.559	0.172	0.673	1.163	1.006	7.764
7	28.41	0.538	0.171	0.670	1.202	1.052	8.724
8	31.18	0.526	0.170	0.663	1.203	1.058	8.971
9	35.67	1.257	0.948	1.093	0.967	1.960	21.433
10	45.87	1.839	0.709	1.367	0.076	2.350	46.473
11	55.96	0.350	0.545	0.137	0.513	1.815	19.625
12	66.17	0.210	0.127	0.210	0.168	0.356	11.341
13	69.66	0.228	0.419	0.521	0.383	0.733	14.665
14	70.06	0.205	0.441	0.537	0.393	0.743	17.270
15	78.93	0.080	0.088	0.084	0.064	0.102	15.221
16	89.96	0.083	0.082	0.098	0.120	0.164	14.854
3000 rpm	50.00	0.458	0.300	0.262	0.096	0.720	17.663
3600 rpm	60.00	0.262	0.050	0.132	0.170	0.466	15.984

table 11 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the exciter

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.495	1.188	0.072	0.103	0.026	27.764
2	12.01	5.177	1.062	0.151	0.194	0.041	120.662
3	14.33	0.714	0.053	0.089	0.080	0.015	17.531
4	25.81	1.181	1.450	0.711	0.242	0.036	8.486
5	28.25	0.170	0.425	0.260	0.110	0.023	6.675
6	28.41	0.183	0.410	0.255	0.110	0.024	6.553
7	30.66	0.339	0.323	0.261	0.143	0.041	5.173
8	35.20	0.869	0.549	1.376	1.528	0.718	6.454
9	42.24	2.193	1.831	1.185	2.633	2.452	20.210
10	49.70	3.378	0.367	2.695	1.576	3.266	48.929
11	61.52	0.468	0.944	0.477	0.145	2.651	16.744
12	66.36	0.401	0.099	0.148	0.147	0.811	14.752
13	69.66	0.404	0.138	0.298	0.216	0.833	12.481
14	72.94	0.403	0.524	0.726	0.475	1.442	16.147
15	78.41	0.120	0.179	0.188	0.123	0.286	15.945
16	92.43	0.110	0.119	0.151	0.168	0.271	15.066
3000 rpm	50.00	3.328	0.399	2.561	1.454	3.127	50.029
3600 rpm	60.00	0.473	0.695	0.476	0.073	1.715	11.584

6 Central Unbalance in the Generator

In the middle of the generator an unbalance of 20 kg mm is assumed (Figure 27). The bearing forces and the maximum response displacements as a result of this unbalance have been determined for all the support variants. The results are summarized respectively in Tables 13 to 18 for all support variants. The Figures 28 to 33 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance in the middle of the generator results in high bearing loads in the bearings 2 and 3. For all support variants high bearing loads and large response displacements occur for the first mode shapes and the mode shapes around 40 Hz. A higher stiffness of the supports results for this load case in higher bearing loads and response displacements.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 12. For each support variant Table 12 also summarizes the magnitude of the maximum allowable central unbalance in the generator if the unbalance eccentricity at 3000 rpm is 10 μm. Finally, the scaled bearing loads and maximum displacement response for the maximum allowable unbalances are given in Table 12.

The 10 μm limit for the shaft eccentricity is the most restrictive criterion for the dynamic behaviour of the rotor shaft. The bearing loads scaled to the 10 μm criterion are for all AMB support variants within acceptable limits. The CB support variants with flexible support stiffness show large response displacements at the unsupported shaft end, which result in combination with the 10 μm criterion in much smaller maximum allowable unbalances in the exciter for the these support variants than for the AMB support variants and the CB rigid support variant.

table 12 Maximum bearing loads and response displacements for each support variant due to a central generator unbalance

Support variant	$F_{bear.max}$ [kN]	$u_{resp.max}$ [μm]	max. unbal. [kg mm]	$F_{bear.scaled}$ [kN]	$u_{resp.scaled}$ [μm]
AMB support - rigid	4.336	15.976	194.0	42.056	154.956
AMB support - open loop	2.450	13.527	148.4	18.175	100.349
AMB support - closed loop	3.300	15.748	122.2	20.171	96.259
CB support - rigid	3.824	38.290	155.0	29.643	296.822
CB support - flexible I	1.309	15.738	28.3	1.851	22.251
CB support - flexible II	1.844	22.176	19.6	1.808	21.741

table 13 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.537	2.727	4.336	1.415	0.477	0.174	15.976
2	24.59	0.068	0.180	0.203	0.129	0.204	0.070	1.002
3	26.20	0.081	0.178	0.435	0.773	0.612	0.209	2.512
4	31.18	0.137	0.087	0.214	0.159	0.051	0.017	1.013
5	38.73	1.665	3.085	1.743	0.783	0.147	0.046	9.870
6	55.74	0.445	2.971	1.883	1.290	0.186	0.051	1.942
7	61.88	0.072	0.497	0.700	1.064	0.164	0.044	1.213
8	67.73	0.151	1.197	0.559	1.805	0.314	0.082	2.128
9	67.87	0.154	1.220	0.604	1.843	0.322	0.084	2.175
10	73.73	0.387	3.329	10.391	7.461	1.579	0.401	9.177
11	78.93	0.048	0.382	5.633	2.077	0.559	0.140	2.695
12	103.94	1.017	5.977	12.982	5.034	4.319	1.058	4.751
3000 rpm	50.00	0.239	1.226	0.301	0.223	0.032	0.009	1.031
3600 rpm	60.00	0.048	0.310	0.916	1.029	0.154	0.042	1.162

table 14 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.121	1.496	1.610	0.059	0.090	0.017	13.527
2	18.55	0.015	0.170	0.178	0.128	0.107	0.022	0.999
3	24.59	0.005	0.204	0.158	0.021	0.002	0.001	0.743
4	30.35	0.052	0.221	0.226	0.045	0.005	0.000	0.686
5	31.18	0.052	0.144	0.256	0.062	0.009	0.000	0.652
6	33.84	0.067	0.220	0.331	0.149	0.032	0.001	0.780
7	36.42	0.071	0.329	0.540	0.208	0.030	0.000	0.907
8	45.61	0.218	1.201	0.934	2.450	0.722	0.055	5.235
9	60.82	0.148	0.730	0.969	1.020	3.105	1.482	3.725
10	66.09	0.229	1.003	0.976	0.661	1.305	0.974	1.531
11	67.73	0.314	1.301	1.267	0.890	1.218	1.092	1.815
12	75.71	2.312	7.955	7.250	6.946	3.921	10.507	12.777
13	78.93	0.979	2.984	2.794	3.797	1.534	8.941	11.479
14	81.90	2.094	5.709	3.176	2.335	0.982	11.381	15.238
15	101.62	4.045	2.963	1.602	2.390	1.650	2.467	6.014
3000 rpm	50.00	0.016	0.119	0.285	0.772	0.345	0.055	1.348
3600 rpm	60.00	0.150	0.760	1.029	1.087	2.421	1.060	3.002

table 15 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.459	2.500	3.300	0.683	0.152	0.034	15.748
2	22.14	0.058	0.204	0.276	0.266	0.211	0.054	1.179
3	24.59	0.063	0.176	0.244	0.106	0.030	0.007	0.977
4	27.01	0.075	0.154	0.214	0.086	0.016	0.004	0.889
5	31.18	0.131	0.074	0.156	0.066	0.006	0.001	0.965
6	36.33	1.062	2.131	0.686	0.166	0.005	0.001	6.855
7	47.36	0.170	2.979	2.711	0.493	0.084	0.025	3.049
8	52.79	0.011	0.135	1.396	0.757	0.360	0.204	1.248
9	56.52	0.022	0.306	2.115	1.627	0.400	0.153	2.240
10	60.79	0.024	0.427	1.785	0.264	0.244	0.151	1.126
11	66.05	0.037	0.478	2.927	0.990	0.075	0.017	1.241
12	67.73	0.043	0.609	2.692	0.706	0.092	0.024	1.217
13	71.20	0.053	0.868	2.641	0.402	0.195	0.071	1.245
14	78.57	0.100	1.369	3.447	0.446	0.025	0.005	1.412
15	78.93	0.103	1.408	3.489	0.438	0.024	0.005	1.425
3000 rpm	50.00	0.017	0.597	1.381	0.495	0.123	0.050	1.636
3600 rpm	60.00	0.024	0.382	1.799	0.364	0.275	0.155	1.133

table 16 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.064	1.722	0.808	0.034	0.014	30.553
2	16.59	2.830	2.430	0.930	0.086	0.033	38.290
3	22.29	0.315	0.334	0.211	0.163	0.059	1.979
4	28.24	0.286	0.258	0.112	0.010	0.004	1.149
5	28.41	0.287	0.256	0.111	0.010	0.003	1.141
6	44.20	2.239	3.824	1.092	0.053	0.016	5.971
7	57.77	0.097	1.445	0.406	0.026	0.007	1.110
8	69.66	2.506	3.127	0.826	0.102	0.025	10.910
9	70.18	3.346	3.359	0.883	0.113	0.028	13.471
10	71.63	6.394	3.316	0.861	0.125	0.031	21.181
11	78.41	4.117	2.577	0.629	0.222	0.054	7.183
12	84.90	5.928	5.159	2.038	2.015	0.483	6.954
13	94.99	35.131	33.478	12.832	2.982	0.712	27.254
3000 rpm	50.00	0.115	1.423	0.412	0.021	0.006	1.290
3600 rpm	60.00	0.090	1.555	0.432	0.030	0.008	1.206

table 17 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.584	0.757	0.109	0.066	0.002	12.099
2	10.22	0.119	0.085	0.014	0.010	0.000	3.468
3	11.94	0.064	0.062	0.020	0.016	0.001	0.882
4	21.01	0.075	0.082	0.047	0.030	0.012	0.958
5	23.05	0.088	0.048	0.030	0.021	0.010	1.118
6	28.37	0.257	0.086	0.298	0.515	0.445	3.718
7	28.41	0.246	0.086	0.301	0.540	0.473	3.606
8	31.18	0.240	0.086	0.299	0.543	0.478	3.629
9	35.67	0.826	0.633	0.729	0.645	1.309	13.825
10	45.87	0.633	0.249	0.481	0.027	0.827	15.738
11	55.96	0.162	0.337	0.085	0.317	1.123	9.454
12	66.17	0.065	0.254	0.413	0.332	0.703	8.781
13	69.66	0.367	1.039	1.292	0.951	1.818	25.267
14	70.06	0.403	1.119	1.363	0.997	1.888	26.328
15	78.93	0.127	0.330	0.319	0.243	0.386	4.056
16	89.96	0.422	0.463	0.554	0.677	0.923	8.378
3000 rpm	50.00	0.216	0.027	0.024	0.009	0.067	7.073
3600 rpm	60.00	0.020	0.053	0.147	0.191	0.522	3.725

table 18 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to a central unbalance in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.389	1.003	0.061	0.087	0.022	22.176
2	12.01	0.775	0.187	0.026	0.034	0.007	18.044
3	14.33	0.146	0.099	0.131	0.120	0.022	1.297
4	25.81	0.198	0.220	0.103	0.034	0.005	0.954
5	28.25	0.119	0.182	0.099	0.040	0.009	0.634
6	28.41	0.123	0.181	0.100	0.041	0.009	0.630
7	30.66	0.180	0.200	0.146	0.078	0.023	0.967
8	35.20	0.585	0.421	1.033	1.147	0.539	4.048
9	42.24	1.470	1.274	0.824	1.832	1.706	13.419
10	49.70	0.672	0.073	0.573	0.335	0.695	9.571
11	61.52	0.123	1.224	0.618	0.188	3.438	11.974
12	66.36	0.057	0.198	0.302	0.300	1.658	5.820
13	69.66	0.261	0.361	0.768	0.558	2.149	8.291
14	72.94	1.032	1.636	2.269	1.485	4.506	22.803
15	78.41	0.422	0.718	0.763	0.498	1.158	6.305
16	92.43	0.693	0.813	1.040	1.154	1.864	6.728
3000 rpm	50.00	0.698	0.070	0.483	0.274	0.590	10.200
3600 rpm	60.00	0.171	0.754	0.512	0.079	1.844	10.069

7 Opposite End Unbalances in the Generator

At the ends of the generator two opposite acting unbalances of 10 kg mm each are assumed (Figure 34). The bearing forces and the maximum response displacements as a result of these unbalances have been determined for all the support variants. The results are summarized respectively in Tables 20 to 25 for all support variants. The Figures 35 to 40 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

Opposite end unbalances in the generator result in high bearing loads in the bearings 2 and 3. For the support variants A, B, C, and D the highest bearing loads and displacements responses occur between 35 and 60 Hz, and for the support variants E and F between 20 and 30 Hz.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 19. For each support variant Table 19 also summarizes the magnitude of the maximum allowable opposite end unbalances in the generator if the unbalance eccentricity at 3000 rpm is 10 μm, as well as the scaled bearing loads and maximum displacement response for these maximum allowable unbalances.

The 10 μm limit for the shaft eccentricity is the most restrictive criterion for the dynamic behaviour of the rotor shaft. The bearing loads scaled to the 10 μm criterion are for all AMB support variants within acceptable limits.

table 19 Maximum bearing loads and response displacements for each support variant due to opposite end unbalances in the generator

Support variant	$F_{bear.max}$ [kN]	$u_{resp.max}$ [μm]	max. unbal. [kg mm]	$F_{bear.scaled}$ [kN]	$u_{resp.scaled}$ [μm]
AMB support - rigid	10.555	6.729	59.5	62.790	40.029
AMB support - open loop	9.987	14.550	62.5	62.419	90.938
AMB support - closed loop	11.499	11.687	23.3	26.748	27.185
CB support - rigid	11.703	18.135	30.8	36.031	55.834
CB support - flexible I	2.132	20.957	50.0	10.655	104.733
CB support - flexible II	4.240	16.697	8.7	3.698	14.561

table 20 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.098	0.504	0.795	0.258	0.087	0.032	2.914
2	24.59	0.008	0.136	0.309	0.051	0.081	0.028	0.343
3	26.20	0.014	0.155	0.421	0.364	0.288	0.098	1.183
4	31.18	0.043	0.203	0.599	0.147	0.047	0.015	0.329
5	38.73	1.133	2.155	1.459	0.548	0.103	0.032	6.714
6	55.74	1.564	10.555	6.799	4.470	0.645	0.178	6.729
7	61.88	0.203	1.162	0.390	1.320	0.203	0.054	1.506
8	67.73	0.048	0.300	1.602	1.416	0.246	0.064	1.669
9	67.87	0.046	0.316	1.644	1.434	0.250	0.065	1.691
10	73.73	0.222	1.951	5.981	4.258	0.901	0.229	5.237
11	78.93	0.054	0.334	0.932	0.964	0.260	0.065	1.250
12	103.94	0.535	4.005	1.745	1.807	1.550	0.380	1.705
3000 rpm	50.00	0.389	2.422	1.892	0.568	0.082	0.024	1.681
3600 rpm	60.00	0.323	2.031	0.699	1.579	0.236	0.064	1.954

table 21 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.011	0.146	0.153	0.015	0.009	0.002	1.252
2	18.55	0.011	0.136	0.183	0.071	0.051	0.011	0.376
3	24.59	0.103	0.581	0.552	0.184	0.031	0.000	1.351
4	30.35	1.224	3.245	1.570	0.597	0.096	0.001	10.503
5	31.18	0.986	1.678	1.424	0.600	0.106	0.001	7.854
6	33.84	1.229	1.842	7.551	3.853	0.841	0.017	14.550
7	36.42	1.060	3.551	9.987	4.244	0.621	0.006	13.867
8	45.61	0.291	1.666	1.483	3.285	0.967	0.074	7.035
9	60.82	0.004	0.272	0.340	0.156	0.459	0.219	0.993
10	66.09	0.037	0.120	0.260	0.121	0.221	0.165	0.927
11	67.73	0.049	0.080	0.225	0.148	0.191	0.171	0.921
12	75.71	0.161	0.302	0.085	0.307	0.169	0.453	0.984
13	78.93	0.281	0.620	0.093	0.463	0.185	1.075	1.380
14	81.90	0.464	1.195	0.498	0.561	0.235	2.718	3.639
15	101.62	6.926	5.087	3.221	4.930	3.405	5.090	10.296
3000 rpm	50.00	0.081	0.721	0.500	0.336	0.156	0.025	1.600
3600 rpm	60.00	0.008	0.316	0.308	0.157	0.330	0.144	1.030

table 22 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.063	0.351	0.458	0.094	0.021	0.005	2.160
2	22.14	0.003	0.119	0.265	0.006	0.003	0.001	0.238
3	24.59	0.009	0.159	0.326	0.004	0.003	0.001	0.254
4	27.01	0.016	0.199	0.405	0.010	0.001	0.000	0.290
5	31.18	0.053	0.256	0.596	0.014	0.002	0.000	0.412
6	36.33	0.633	1.404	0.982	0.092	0.003	0.001	4.091
7	47.36	0.637	11.499	10.644	1.809	0.310	0.093	11.687
8	52.79	0.109	2.002	3.781	3.441	1.611	0.913	4.841
9	56.52	0.125	1.541	5.923	5.216	1.277	0.489	7.224
10	60.79	0.088	0.904	2.236	1.297	1.384	0.856	1.961
11	66.05	0.102	0.749	2.484	1.904	0.165	0.037	2.304
12	67.73	0.089	0.523	1.713	1.416	0.215	0.056	1.617
13	71.20	0.073	0.209	0.938	0.896	0.550	0.202	1.015
14	78.57	0.048	0.396	0.285	0.659	0.105	0.022	0.879
15	78.93	0.047	0.424	0.256	0.637	0.112	0.025	0.875
3000 rpm	50.00	0.209	3.894	2.657	1.714	0.405	0.166	4.299
3600 rpm	60.00	0.094	1.009	2.298	1.616	1.348	0.760	1.970

table 23 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.034	0.457	0.213	0.009	0.004	8.096
2	16.59	0.144	0.193	0.052	0.005	0.002	1.680
3	22.29	0.151	0.303	0.101	0.078	0.028	0.491
4	28.24	0.293	0.529	0.123	0.011	0.004	0.722
5	28.41	0.298	0.538	0.125	0.011	0.004	0.732
6	44.20	6.827	11.703	3.325	0.163	0.047	18.135
7	57.77	0.096	0.352	0.249	0.016	0.004	1.857
8	69.66	0.818	0.419	0.107	0.013	0.003	2.446
9	70.18	0.899	0.457	0.106	0.014	0.003	2.617
10	71.63	0.934	0.466	0.140	0.020	0.005	2.581
11	78.41	0.888	0.478	0.113	0.040	0.010	0.983
12	84.90	1.703	0.425	0.261	0.258	0.062	1.578
13	94.99	7.791	7.473	2.768	0.643	0.154	6.009
3000 rpm	50.00	0.844	1.538	0.548	0.028	0.008	3.248
3600 rpm	60.00	0.095	0.193	0.213	0.015	0.004	1.762

table 24 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.054	0.057	0.012	0.005	0.001	0.886
2	10.22	0.267	0.040	0.028	0.006	0.001	9.286
3	11.94	0.014	0.052	0.096	0.081	0.005	1.732
4	21.01	1.376	2.132	1.329	0.867	0.335	20.957
5	23.05	0.302	0.493	0.373	0.275	0.135	4.127
6	28.37	0.432	0.190	0.634	1.092	0.944	7.292
7	28.41	0.472	0.187	0.622	1.113	0.975	7.436
8	31.18	0.480	0.185	0.612	1.110	0.976	7.414
9	35.67	0.277	0.190	0.202	0.178	0.360	4.439
10	45.87	0.627	0.249	0.466	0.026	0.801	15.493
11	55.96	0.047	0.114	0.022	0.089	0.317	2.473
12	66.17	0.018	0.023	0.025	0.019	0.039	0.866
13	69.66	0.013	0.030	0.046	0.033	0.063	0.878
14	70.06	0.010	0.034	0.044	0.031	0.059	0.880
15	78.93	0.029	0.029	0.061	0.045	0.072	1.442
16	89.96	0.345	0.386	0.467	0.571	0.778	6.868
3000 rpm	50.00	0.047	0.132	0.084	0.032	0.238	2.001
3600 rpm	60.00	0.015	0.035	0.005	0.008	0.022	0.905

table 25 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to opposite end unbalances in the generator

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.046	0.089	0.009	0.008	0.002	1.927
2	12.01	0.209	0.068	0.015	0.009	0.002	4.715
3	14.33	0.032	0.088	0.027	0.015	0.002	0.777
4	25.81	3.241	4.240	2.081	0.707	0.105	16.967
5	28.25	0.756	1.008	0.583	0.243	0.052	3.932
6	28.41	0.715	0.956	0.561	0.237	0.052	3.721
7	30.66	0.406	0.593	0.431	0.231	0.066	2.126
8	35.20	0.628	0.462	1.039	1.152	0.541	4.170
9	42.24	0.360	0.190	0.088	0.179	0.167	2.896
10	49.70	0.867	0.160	0.697	0.408	0.844	12.192
11	61.52	0.037	0.111	0.030	0.009	0.169	0.861
12	66.36	0.033	0.082	0.025	0.021	0.115	0.849
13	69.66	0.021	0.059	0.038	0.025	0.095	0.875
14	72.94	0.031	0.025	0.085	0.053	0.161	0.911
15	78.41	0.033	0.059	0.140	0.089	0.207	1.003
16	92.43	0.646	0.815	1.057	1.173	1.894	6.838
3000 rpm	50.00	0.786	0.170	0.658	0.374	0.805	11.467
3600 rpm	60.00	0.032	0.087	0.018	0.003	0.068	0.895

8 Unbalance in the Axial AMB Disk

In the disk of the axial AMB an unbalance of 20 kg mm is assumed (Figure 41). The bearing forces and the maximum response displacements as a result of this unbalance have been determined for all the support variants. The results are summarized respectively in Tables 27 to 32 for all support variants. The Figures 42 to 47 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance in the disk of the axial AMB results in high bearing loads in the bearings 3 and 4. For all support variants the highest bearing loads and response displacements occur between 30 and 60 Hz. The bearing loads for the AMB support variants are substantially higher than for the CB support variants.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 26. For each support variant Table 26 also summarizes the magnitude of the maximum allowable unbalances in the disk of the axial AMB if the unbalance eccentricity at 3000 rpm is 10 μm, as well as the scaled bearing loads and maximum displacement response for these maximum allowable unbalances. The maximum allowable unbalance for the support variants with rigid stiffness is much larger than for the support variants with flexible stiffness.

The 10 μm limit for the shaft eccentricity is the most restrictive criterion for the dynamic behaviour of the rotor shaft. The bearing loads scaled to the 10 μm criterion are for all AMB support variants within acceptable limits.

table 26 Maximum bearing loads and response displacements for each support variant due to an axial AMB disk unbalance

Support variant	$F_{bear.max}$ [kN]	$u_{resp.max}$ [μm]	max. unbal. [kg mm]	$F_{bear.scaled}$ [kN]	$u_{resp.scaled}$ [μm]
AMB support - rigid	16.249	10.418	56.6	45.979	29.479
AMB support - open loop	19.578	41.833	19.0	18.617	39.780
AMB support - closed loop	48.999	62.894	11.4	27.867	35.770
CB support - rigid	2.399	2.546	347.2	41.649	44.201
CB support - flexible I	4.110	39.284	25.7	5.285	50.513
CB support - flexible II	5.361	45.483	4.7	1.268	10.757

table 27 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.102	0.519	0.834	0.289	0.097	0.035	3.044
2	24.59	0.030	0.092	0.636	0.304	0.482	0.166	2.032
3	26.20	0.055	0.143	1.107	2.344	1.857	0.633	7.620
4	31.18	0.032	0.029	0.389	1.007	0.324	0.106	1.217
5	38.73	0.792	1.469	1.147	1.451	0.273	0.085	4.691
6	55.74	2.415	16.249	10.890	7.995	1.154	0.319	10.418
7	61.88	0.683	5.298	9.768	4.430	0.681	0.182	5.052
8	67.73	0.786	6.578	17.905	11.600	2.018	0.524	13.674
9	67.87	0.798	6.685	18.311	11.914	2.080	0.540	14.056
10	73.73	2.747	23.725	77.388	56.334	11.921	3.026	69.290
11	78.93	0.745	6.412	21.818	16.480	4.438	1.109	21.381
12	103.94	0.638	3.789	2.156	19.502	16.731	4.098	18.405
3000 rpm	50.00	0.389	2.098	1.234	3.327	0.483	0.138	3.534
3600 rpm	60.00	0.815	6.102	9.169	3.062	0.459	0.124	3.811

table 28 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.011	0.141	0.165	0.071	0.009	0.003	1.276
2	18.55	0.001	0.047	0.221	0.421	0.303	0.064	2.241
3	24.59	0.035	0.281	0.691	0.494	0.149	0.008	2.247
4	30.35	0.673	1.812	2.016	1.377	0.285	0.009	5.754
5	31.18	0.682	0.979	2.392	1.666	0.355	0.008	5.932
6	33.84	1.834	2.642	11.408	5.943	1.304	0.028	22.241
7	36.42	1.294	4.320	12.422	5.566	0.832	0.012	17.743
8	45.61	1.671	9.132	6.899	19.578	5.756	0.441	41.833
9	60.82	0.307	1.450	2.767	3.445	9.948	4.750	11.935
10	66.09	0.345	1.458	2.625	1.467	2.409	1.795	4.493
11	67.73	0.376	1.522	2.583	1.523	1.751	1.566	4.058
12	75.71	1.047	3.601	3.473	3.320	1.786	4.783	5.816
13	78.93	0.895	2.745	2.018	3.927	1.501	8.738	11.218
14	81.90	2.551	6.972	3.303	3.557	1.432	16.590	22.212
15	101.62	3.423	2.517	1.675	4.903	3.280	4.903	7.914
3000 rpm	50.00	0.335	1.780	2.676	5.369	2.258	0.363	10.516
3600 rpm	60.00	0.182	0.874	1.715	3.984	8.349	3.657	10.351

table 29 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.063	0.344	0.467	0.133	0.028	0.006	2.169
2	22.14	0.012	0.045	0.406	0.780	0.608	0.155	3.398
3	24.59	0.011	0.033	0.379	0.513	0.129	0.032	0.713
4	27.01	0.015	0.036	0.485	0.564	0.088	0.022	0.807
5	31.18	0.033	0.027	0.713	0.765	0.057	0.014	1.237
6	36.33	0.392	0.790	1.168	1.189	0.033	0.009	2.531
7	47.36	0.200	3.575	6.580	5.737	0.832	0.256	9.672
8	52.79	0.016	0.977	31.039	32.675	15.340	8.693	45.882
9	56.52	0.172	3.924	48.999	45.496	11.154	4.268	62.894
10	60.79	0.011	0.425	16.068	13.554	14.109	8.729	20.755
11	66.05	0.138	2.406	21.662	19.218	1.452	0.332	24.148
12	67.73	0.087	1.592	15.963	14.832	1.934	0.508	17.954
13	71.20	0.044	0.881	10.884	9.923	5.057	1.856	12.265
14	78.57	0.065	0.985	8.804	7.998	0.674	0.140	9.500
15	78.93	0.064	0.961	8.633	7.925	0.584	0.127	9.322
3000 rpm	50.00	0.054	1.502	12.944	11.004	2.495	1.025	17.583
3600 rpm	60.00	0.017	0.574	15.503	16.523	13.533	7.634	20.460

table 30 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	CB2	CB3	CB4	CB5	CB	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.002	0.072	0.076	0.003	0.001	1.232
2	16.59	0.147	0.140	0.168	0.016	0.006	1.993
3	22.29	0.027	0.132	0.486	0.374	0.136	1.822
4	28.24	0.028	0.160	0.572	0.053	0.018	0.222
5	28.41	0.028	0.162	0.578	0.053	0.018	0.219
6	44.20	0.957	1.698	1.461	0.072	0.021	2.546
7	57.77	0.089	1.049	2.399	0.153	0.040	0.693
8	69.66	0.806	1.210	3.742	0.460	0.115	3.541
9	70.18	1.067	1.232	3.809	0.489	0.122	4.321
10	71.63	1.997	1.762	3.887	0.566	0.140	6.604
11	78.41	1.244	2.099	4.398	1.554	0.377	2.150
12	84.90	1.781	1.953	8.924	8.821	2.114	10.814
13	94.99	9.589	9.882	11.260	2.617	0.625	7.439
3000 rpm	50.00	0.183	0.958	1.692	0.088	0.024	0.576
3600 rpm	60.00	0.067	1.103	2.621	0.183	0.048	0.765

table 31 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.110	0.147	0.043	0.014	0.002	2.292
2	10.22	0.067	0.036	0.085	0.035	0.005	2.299
3	11.94	0.014	0.149	0.513	0.437	0.026	7.244
4	21.01	1.488	2.319	1.455	0.952	0.368	22.664
5	23.05	0.441	0.500	0.237	0.138	0.070	6.514
6	28.37	0.736	0.102	0.881	1.542	1.333	10.833
7	28.41	0.708	0.099	0.908	1.632	1.429	10.899
8	31.18	0.692	0.098	0.908	1.646	1.448	11.000
9	35.67	2.347	1.808	2.105	1.860	3.772	39.284
10	45.87	0.889	0.387	0.751	0.040	1.248	22.079
11	55.96	0.529	1.217	0.365	1.161	4.110	30.596
12	66.17	0.070	0.547	0.174	0.102	0.217	9.711
13	69.66	0.252	0.795	0.816	0.592	1.132	17.389
14	70.06	0.263	0.753	0.961	0.686	1.298	17.126
15	78.93	0.042	0.048	0.665	0.460	0.731	5.299
16	89.96	1.160	1.326	1.655	2.009	2.738	22.980
3000 rpm	50.00	0.071	0.044	0.459	0.147	1.105	7.777
3600 rpm	60.00	0.091	0.613	0.323	0.344	0.939	11.196

table 32 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the disk of the axial AMB

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.030	0.086	0.040	0.007	0.002	1.731
2	12.01	0.059	0.060	0.097	0.024	0.007	1.384
3	14.33	0.043	0.104	0.444	0.392	0.072	4.243
4	25.81	2.675	3.531	1.777	0.615	0.091	14.001
5	28.25	0.863	0.620	0.130	0.095	0.018	4.830
6	28.41	0.838	0.571	0.134	0.107	0.021	4.710
7	30.66	0.753	0.155	0.492	0.350	0.098	4.508
8	35.20	2.542	1.672	4.825	5.361	2.518	18.916
9	42.24	4.053	3.566	2.352	5.168	4.813	36.997
10	49.70	3.205	0.738	2.779	1.604	3.322	45.483
11	61.52	0.203	2.121	1.150	0.326	5.937	20.679
12	66.36	0.174	1.289	0.267	0.139	0.765	10.742
13	69.66	0.399	1.339	0.326	0.261	1.006	12.873
14	72.94	1.019	1.671	2.349	1.511	4.584	22.488
15	78.41	0.203	0.103	1.534	0.916	2.131	7.597
16	92.43	1.936	2.513	3.379	3.717	6.004	21.675
3000 rpm	50.00	2.912	0.667	2.916	1.617	3.477	42.284
3600 rpm	60.00	0.144	0.824	1.291	0.180	4.191	14.555

9 Unbalance in the Hollow Shaft

In the middle of the hollow shaft an unbalance of 20 kg mm is assumed (Figure 48). The bearing forces and the maximum response displacements as a result of this unbalance have been determined for all the support variants. The results are summarized respectively in Tables 34 to 39 for all support variants. The Figures 49 to 54 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance in the middle of the hollow shaft results in high bearing loads in the bearings 4 and 5. Because the unbalance is nearer to bearing 5 the highest bearing loads occur in bearing 5. For support variants A and C the highest bearing loads and response displacements occur between 10 and 30 Hz, for support variant B and C between 45 and 60 Hz. The highest bearing loads for the CB support variants (D, E, and F) occur between 10 and 25.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 33. For each support variant Table 33 also summarizes the magnitude of the maximum allowable unbalances in the middle of the hollow shaft if the unbalance eccentricity at 3000 rpm is 10 μm, as well as the scaled bearing loads and maximum displacement response for these maximum allowable unbalances.

The 10 μm limit for the shaft eccentricity is the most restrictive criterion for the dynamic behaviour of the rotor shaft. The bearing loads scaled to the 10 μm criterion are for all AMB support variants within acceptable limits. The CB support variants with flexible stiffness show large response displacements at the unsupported shaft end, which result in combination with the 10 μm criterion in much smaller maximum allowable unbalances in the exciter for the CB support variants than for the AMB support variants and the CB rigid support variant.

table 33 Maximum bearing loads and response displacements for each support variant due to a hollow shaft unbalance

Support variant	$F_{bear.max}$ [kN]	$u_{resp.max}$ [μm]	max. unbal. [kg mm]	$F_{bear.scaled}$ [kN]	$u_{resp.scaled}$ [μm]
AMB support - rigid	12.838	42.197	98.8	63.429	208.483
AMB support - open loop	12.941	33.905	55.6	35.987	94.285
AMB support - closed loop	8.797	40.090	65.4	28.786	131.185
CB support - rigid	8.062	39.210	102.2	41.196	200.358
CB support - flexible I	2.908	41.851	16.5	2.402	34.570
CB support - flexible II	5.163	34.872	5.9	1.522	10.277

table 34 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.072	0.368	0.590	0.287	0.279	0.094	2.154
2	24.59	0.075	0.232	1.598	3.470	2.974	1.008	12.032
3	26.20	0.283	0.734	5.676	12.838	10.288	3.506	42.197
4	31.18	0.064	0.059	0.783	1.971	1.235	0.431	5.485
5	38.73	0.526	0.976	0.762	1.353	0.489	0.185	3.116
6	55.74	0.744	5.008	3.357	2.675	0.484	0.109	3.211
7	61.88	0.192	1.488	2.743	1.983	0.723	0.139	2.045
8	67.73	0.214	1.789	4.870	1.055	1.588	0.355	3.719
9	67.87	0.217	1.818	4.980	1.032	1.619	0.363	3.823
10	73.73	0.764	6.600	21.528	16.183	3.888	0.962	19.276
11	78.93	0.222	1.910	6.500	11.009	1.686	0.361	6.370
12	103.94	1.231	7.314	4.162	91.551	81.458	19.956	89.617
3000 rpm	50.00	0.140	0.754	0.443	1.170	0.073	0.036	2.024
3600 rpm	60.00	0.234	1.751	2.631	2.190	0.534	0.092	2.017

table 35 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.008	0.102	0.109	0.110	0.121	0.019	1.171
2	18.55	0.010	0.202	0.036	5.506	4.570	0.961	33.905
3	24.59	0.004	0.023	0.118	0.750	0.331	0.072	2.885
4	30.35	0.082	0.222	0.289	0.910	0.173	0.059	2.114
5	31.18	0.093	0.138	0.373	0.975	0.135	0.055	2.080
6	33.84	0.339	0.490	2.107	1.391	0.276	0.049	4.134
7	36.42	0.159	0.531	1.522	1.262	0.139	0.053	2.225
8	45.61	0.463	2.528	1.891	5.527	1.683	0.138	11.563
9	60.82	0.402	1.896	3.450	4.422	16.836	8.027	20.200
10	66.09	0.056	0.237	0.398	0.595	6.730	4.908	7.830
11	67.73	0.089	0.359	0.568	0.900	5.757	5.029	7.024
12	75.71	2.581	8.880	8.348	8.756	5.748	15.239	18.524
13	78.93	2.551	7.823	5.436	3.249	1.525	8.410	10.789
14	81.90	3.476	9.500	4.464	4.582	2.247	25.013	33.496
15	101.62	8.838	6.500	4.099	8.141	7.905	11.762	18.994
3000 rpm	50.00	0.141	0.746	1.025	0.371	0.393	0.116	3.596
3600 rpm	60.00	0.359	1.724	3.157	3.922	12.941	5.705	15.950

table 36 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.027	0.149	0.204	0.245	0.257	0.061	1.626
2	22.14	0.066	0.249	2.458	8.797	7.178	1.824	40.090
3	24.59	0.012	0.038	0.507	2.015	1.447	0.363	8.157
4	27.01	0.009	0.021	0.328	1.364	0.864	0.220	4.886
5	31.18	0.008	0.006	0.217	1.062	0.501	0.128	3.103
6	36.33	0.039	0.079	0.171	1.056	0.291	0.078	2.371
7	47.36	0.035	0.631	0.692	2.224	0.562	0.236	2.371
8	52.79	0.007	0.300	7.345	8.391	4.610	2.614	10.953
9	56.52	0.025	0.570	6.982	7.052	3.056	1.204	8.969
10	60.79	0.002	0.073	4.614	1.581	10.610	6.552	12.671
11	66.05	0.005	0.082	1.106	4.980	5.721	1.243	6.325
12	67.73	0.005	0.091	1.438	6.519	9.113	2.350	9.470
13	71.20	0.006	0.131	2.900	12.932	30.049	11.047	26.938
14	78.57	0.002	0.034	0.975	25.974	47.974	10.533	40.441
15	78.93	0.002	0.029	1.000	24.800	47.894	10.925	39.756
3000 rpm	50.00	0.013	0.341	1.828	3.556	1.416	0.647	3.056
3600 rpm	60.00	0.004	0.124	5.299	1.472	8.144	4.623	9.594

table 37 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.001	0.044	0.062	0.104	0.038	0.777
2	16.59	0.171	0.155	0.321	0.433	0.156	2.314
3	22.29	0.334	1.305	8.062	8.050	2.919	39.210
4	28.24	0.034	0.136	1.095	0.733	0.271	3.957
5	28.41	0.033	0.133	1.082	0.715	0.265	3.878
6	44.20	0.378	0.661	1.180	0.048	0.031	1.906
7	57.77	0.032	0.303	2.063	0.924	0.208	2.312
8	69.66	0.375	0.435	4.127	3.495	0.833	5.235
9	70.18	0.508	0.457	4.289	3.716	0.887	5.535
10	71.63	1.018	0.764	4.859	4.422	1.057	6.481
11	78.41	1.058	1.483	10.188	12.089	2.895	16.237
12	84.90	5.343	4.667	40.761	62.965	15.091	77.199
13	94.99	4.763	4.809	7.104	15.608	3.765	16.426
3000 rpm	50.00	0.066	0.290	1.481	0.301	0.050	1.957
3600 rpm	60.00	0.024	0.324	2.305	1.194	0.275	2.480

table 38 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.047	0.061	0.051	0.059	0.005	0.981
2	10.22	0.050	0.048	0.182	0.180	0.013	2.962
3	11.94	0.021	0.504	1.843	1.589	0.093	26.293
4	21.01	0.697	1.086	0.706	0.453	0.173	10.615
5	23.05	0.213	0.220	0.065	0.128	0.036	3.137
6	28.37	0.543	0.048	0.744	1.243	1.076	8.300
7	28.41	0.538	0.048	0.739	1.322	1.152	8.830
8	31.18	0.531	0.048	0.730	1.336	1.167	8.925
9	35.67	1.219	0.937	1.100	0.989	1.994	20.403
10	45.87	1.686	0.692	1.283	0.091	2.236	41.851
11	55.96	0.368	0.842	0.159	0.826	2.908	21.307
12	66.17	0.022	0.163	0.158	0.558	1.162	8.344
13	69.66	0.202	0.620	0.742	0.776	1.471	13.953
14	70.06	0.232	0.655	0.801	0.719	1.351	15.154
15	78.93	0.190	0.057	0.123	0.470	0.735	5.969
16	89.96	1.458	1.657	2.072	2.570	3.503	28.881
3000 rpm	50.00	0.376	0.128	0.371	0.066	0.378	12.106
3600 rpm	60.00	0.023	0.145	0.060	0.516	1.378	9.833

table 39 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the hollow shaft

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.036	0.094	0.061	0.077	0.016	2.080
2	12.01	0.146	0.038	0.250	0.268	0.052	3.407
3	14.33	0.218	0.350	3.011	2.740	0.500	29.650
4	25.81	0.759	1.004	0.638	0.187	0.035	3.973
5	28.25	0.291	0.167	0.368	0.039	0.034	1.805
6	28.41	0.286	0.152	0.382	0.044	0.036	1.830
7	30.66	0.304	0.037	0.606	0.227	0.096	2.362
8	35.20	1.802	1.187	3.503	3.926	1.839	13.856
9	42.24	0.750	0.657	0.430	1.147	1.035	6.847
10	49.70	2.457	0.498	2.042	1.258	2.582	34.872
11	61.52	0.313	3.233	1.514	0.533	9.352	32.574
12	66.36	0.102	0.705	0.612	0.608	3.242	11.389
13	69.66	0.116	0.365	0.405	0.657	2.453	8.658
14	72.94	0.154	0.249	0.341	0.714	2.111	7.481
15	78.41	0.227	0.076	0.161	0.893	2.041	7.278
16	92.43	2.477	3.194	4.306	4.874	7.871	28.415
3000 rpm	50.00	2.337	0.464	2.003	1.098	2.359	33.932
3600 rpm	60.00	0.350	2.082	0.676	0.245	5.163	19.955

10 Turbine Unbalance due to Blade Failure

A major cause for unbalances in the turbine is deblading. In [2] it is estimated that blade failure in the turbine results in an unbalance of 536 kg mm. For this load case it is assumed that an unbalance of 536 kg mm acts at the inlet stage of the turbine (Figure 55). This is a worst case assumption.

The bearing forces and the maximum response displacements have been determined for all the support variants. For each support variant the results are summarized in the Tables 41 to 46 respectively. The Figures 56 to 61 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance at the inlet stage of the turbine gives the highest bearing loads in the bearings 4 and 5. Because the inlet stage is nearer to bearing 4 the highest bearing loads occur in bearing 4. The highest bearing loads and response displacements occur between 10 and 30 Hz.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 40. For all support variants the maximum response displacement is very large. The 10 μm eccentricity criterion at operational velocity (3000 rpm) is exceeded for all support variants. For the support variants with CB support with flexible stiffness it should be noted that the highest displacement response occurs at the unsupported end of the rotor shaft. The maximum bearing loads for the support variants with AMBs are in excess of the maximum load capacity of the radial AMBs. Blade failure in the inlet stage of the turbine will result in an activation of the CBs. Table 40 gives an indication of the required load capacity for the CBs.

table 40 Maximum bearing loads and response displacements for each support variant due to a turbine unbalance

Support variant	Maximum bearing force [kN]	Maximum response [μm]
AMB support - rigid	338.868	1113.415
AMB support - open loop	145.316	894.429
AMB support - closed loop	226.683	1032.388
CB support - rigid	213.634	1038.727
CB support - flexible I	48.873	696.905
CB support - flexible II	79.594	783.439

table 41 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	2.034	10.319	16.562	8.639	6.206	2.177	60.465
2	24.59	2.005	6.181	42.669	94.242	75.391	25.805	313.474
3	26.20	7.482	19.367	149.814	338.868	271.359	92.479	1113.415
4	31.18	1.626	1.490	19.880	47.456	38.034	12.774	149.046
5	38.73	12.428	23.070	18.007	28.367	22.077	7.229	79.607
6	55.74	14.216	95.634	64.092	47.703	19.195	5.850	61.317
7	61.88	3.314	25.716	47.415	26.758	18.778	5.651	47.952
8	67.73	3.309	27.692	75.376	11.188	15.233	4.639	57.564
9	67.87	3.349	28.060	76.857	11.340	15.070	4.595	58.996
10	73.73	10.319	89.137	290.757	216.335	51.606	13.482	260.332
11	78.93	2.590	22.301	75.880	118.269	42.477	11.386	74.359
12	103.94	2.240	13.309	7.573	154.800	97.326	24.291	109.310
3000 rpm	50.00	2.898	15.619	9.182	18.672	17.722	5.592	55.275
3600 rpm	60.00	4.174	31.255	46.962	31.885	19.486	5.874	50.927

table 42 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.217	2.683	2.879	3.266	2.818	0.523	29.294
2	18.55	0.267	5.310	0.691	145.316	120.503	25.358	894.429
3	24.59	0.033	0.168	1.688	16.668	11.790	1.914	78.751
4	30.35	0.848	2.311	3.377	17.245	10.401	1.602	57.307
5	31.18	1.046	1.572	4.533	17.831	9.998	1.471	54.358
6	33.84	4.221	6.103	26.189	20.634	10.455	1.059	51.485
7	36.42	1.503	5.035	14.284	19.429	11.299	1.527	49.814
8	45.61	4.916	26.868	20.031	59.683	22.236	1.036	122.760
9	60.82	1.783	8.415	15.225	23.563	54.995	25.840	67.325
10	66.09	2.846	12.031	20.131	34.135	11.548	6.818	55.555
11	67.73	3.584	14.491	22.887	38.061	16.044	12.133	58.689
12	75.71	32.826	112.939	106.174	112.119	62.860	167.429	203.669
13	78.93	21.277	65.248	45.370	26.131	13.568	83.118	107.091
14	81.90	15.716	42.947	20.214	21.878	10.614	108.009	144.907
15	101.62	293.097	215.544	135.922	270.591	194.060	289.681	467.637
3000 rpm	50.00	1.305	6.920	9.352	4.262	21.504	2.119	49.589
3600 rpm	60.00	1.068	5.132	9.313	15.572	53.903	22.424	70.115

table 43 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.652	3.546	4.903	7.154	5.816	1.477	39.410
2	22.14	1.692	6.421	63.303	226.683	184.769	46.970	1032.388
3	24.59	0.323	0.991	13.077	49.126	39.910	9.684	214.095
4	27.01	0.237	0.562	8.430	31.591	25.668	6.075	130.042
5	31.18	0.225	0.178	5.620	22.179	17.978	3.811	83.544
6	36.33	1.259	2.537	4.603	18.874	15.517	2.390	63.514
7	47.36	0.149	2.671	2.107	18.554	21.299	4.475	50.873
8	52.79	0.022	1.117	22.686	37.302	42.845	22.395	68.270
9	56.52	0.034	0.769	6.924	24.525	40.220	13.238	61.972
10	60.79	0.029	0.897	45.705	32.786	114.336	70.755	136.464
11	66.05	0.077	1.332	10.692	40.124	46.097	7.782	60.398
12	67.73	0.045	0.818	6.869	34.493	60.530	13.469	70.949
13	71.20	0.025	0.500	10.456	72.934	127.719	46.974	115.585
14	78.57	0.039	0.582	3.044	89.595	117.312	25.686	100.613
15	78.93	0.037	0.558	2.307	99.047	109.588	25.354	91.465
3000 rpm	50.00	0.040	1.012	1.402	18.008	28.325	9.514	55.990
3600 rpm	60.00	0.032	1.011	34.084	27.106	100.301	55.240	120.166

table 44 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.042	1.300	2.045	2.250	0.849	22.721
2	16.59	4.786	4.352	9.574	10.118	3.753	64.770
3	22.29	8.849	34.578	213.634	213.168	77.318	1038.727
4	28.24	0.828	3.353	25.572	23.855	8.412	108.147
5	28.41	0.816	3.282	25.178	23.438	8.258	106.016
6	44.20	7.356	12.847	20.145	14.605	4.706	51.048
7	57.77	0.468	4.483	26.694	14.956	4.475	40.172
8	69.66	3.891	4.507	38.126	13.377	3.888	45.289
9	70.18	5.161	4.641	38.862	13.108	3.815	45.759
10	71.63	9.724	7.294	41.630	12.244	3.585	47.225
11	78.41	6.825	9.568	60.529	8.461	1.998	61.177
12	84.90	15.585	13.612	116.578	168.466	40.513	207.728
13	94.99	29.852	30.142	38.089	88.505	21.718	96.054
3000 rpm	50.00	1.149	5.065	22.610	14.646	4.564	45.685
3600 rpm	60.00	0.339	4.535	28.296	14.999	4.444	40.341

table 45 Harmonic Response Analyses - Catcher bearing support - (flexible I)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	1.102	1.424	1.497	1.407	0.158	24.841
2	10.22	1.471	1.367	5.054	4.492	0.387	76.932
3	11.94	0.515	13.363	48.873	42.092	2.464	696.905
4	21.01	10.860	16.925	11.173	7.643	2.735	165.330
5	23.05	2.851	2.879	1.372	5.073	1.928	44.784
6	28.37	2.388	0.261	3.871	6.494	5.090	43.512
7	28.41	2.701	0.299	4.329	6.041	4.808	40.428
8	31.18	2.798	0.313	4.473	5.846	4.673	41.231
9	35.67	29.241	22.486	26.435	23.400	47.372	489.454
10	45.87	20.115	8.252	15.320	1.201	27.412	499.406
11	55.96	2.611	5.961	1.408	6.118	21.316	151.385
12	66.17	1.468	10.745	10.482	8.978	18.689	204.778
13	69.66	8.509	26.088	31.275	23.627	45.091	586.833
14	70.06	9.449	26.604	32.581	24.178	45.742	615.954
15	78.93	5.046	1.507	3.131	1.969	3.049	158.127
16	89.96	28.425	32.313	40.385	49.739	67.817	563.226
3000 rpm	50.00	2.779	0.926	2.422	2.393	15.881	111.908
3600 rpm	60.00	0.938	5.932	2.985	2.822	7.194	115.738

table 46 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the turbine

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.992	2.562	1.835	1.803	0.416	56.722
2	12.01	3.908	1.112	7.015	6.608	1.362	90.993
3	14.33	5.759	9.267	79.594	72.378	13.221	783.439
4	25.81	10.654	14.091	9.977	5.666	0.303	55.756
5	28.25	3.772	2.014	6.146	5.503	0.500	36.383
6	28.41	3.679	1.813	6.285	5.460	0.516	35.932
7	30.66	3.467	0.424	8.181	4.844	0.714	36.312
8	35.20	10.574	6.983	21.005	23.159	10.537	82.591
9	42.24	41.509	36.403	24.347	54.015	50.196	378.937
10	49.70	46.239	9.339	38.450	22.961	47.683	656.265
11	61.52	1.759	18.152	8.654	3.174	50.364	175.466
12	66.36	0.928	6.403	6.255	7.790	41.116	144.435
13	69.66	4.270	13.453	15.853	13.926	52.436	185.040
14	72.94	18.321	29.498	41.480	28.044	84.954	404.357
15	78.41	10.081	3.371	7.005	3.824	8.678	149.246
16	92.43	55.085	71.017	95.712	107.278	173.294	625.600
3000 rpm	50.00	43.101	8.522	36.791	22.271	48.409	625.755
3600 rpm	60.00	2.685	15.920	5.638	1.183	17.296	152.913

11 LP-Compressor Unbalance due to Blade Failure

A major cause for unbalances in the LP-compressor is deblading. In [2] it is estimated that blade failure in a compressor results in an unbalance of 320 kg mm. For this load case it is assumed that an unbalance of 320 kg mm acts at the inlet stage of the LP-compressor (Figure 62). This is a worst case assumption for the LP-compressor.

The bearing forces and the maximum response displacements have been determined for all the support variants. The results are summarized in the Tables 48 to 53 for each support variant respectively. The Figures 63 to 68 show for each support variant the response of the GT-MHR rotor shaft at 3000 and 3600 rpm.

An unbalance at the inlet stage of the LP-compressor yields the highest bearing loads in the bearings 5 and 6. Because the inlet stage is nearer to bearing 6 the highest bearing loads occur in bearing 6. For the support variants A and D with rigid bearing stiffness the bearing loads increase with increasing frequency. For the support variants B, C, E, and F with flexible bearing stiffness the highest bearing loadsoccur between 45 and 60 Hz.

For the operational range of rotational speeds up to 3600 rpm (60 Hz) the maximum bearing loads and response displacements are summarized in Table 47. For the rigid AMB and CB support variants (A and D) the maximum bearing loads and response displacements are small and within acceptable limits. For the support variants with flexible stiffnesses (B, C, E, and F) the maximum bearing loads and response displacements are very large. The maximum bearing loads for the support variants B and C are in excess of the maximum load capacity of the radial AMBs. Blade failure in the inlet stage of the LP-compressor will in these cases result in activation of the CBs. Table 47 gives an indiation of the required load capacity for the radial CBs.

table 47 Maximum bearing loads and response displacements for each support variant due to a LP-compressor unbalance

Support variant	Maximum bearing force [kN]	Maximum response [μm]
AMB support - rigid	41.089	7.420
AMB support - open loop	263.737	303.971
AMB support - closed loop	345.811	425.802
CB support - rigid	34.967	12.657
CB support - flexible I	116.113	946.900
CB support - flexible II	161.238	907.189

table 48 Harmonic Response Analyses - Active magnetic bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	15.78	0.012	0.061	0.098	0.047	0.355	2.799	0.359
2	24.59	0.013	0.040	0.278	0.601	0.503	6.942	2.103
3	26.20	0.050	0.129	0.998	2.257	2.087	7.740	7.420
4	31.18	0.012	0.011	0.143	0.364	1.814	10.835	0.988
5	38.73	0.102	0.189	0.148	0.270	2.585	16.855	0.953
6	55.74	0.174	1.171	0.785	0.635	5.325	35.340	2.038
7	61.88	0.049	0.378	0.698	0.524	6.602	43.780	2.548
8	67.73	0.059	0.498	1.355	0.313	7.859	52.767	3.106
9	67.87	0.061	0.507	1.389	0.306	7.888	52.994	3.120
10	73.73	0.235	2.034	6.634	4.995	9.602	62.887	5.940
11	78.93	0.075	0.649	2.209	3.776	11.220	72.458	4.350
12	103.94	0.801	4.758	2.708	59.563	58.819	129.917	58.507
3000 rpm	50.00	0.030	0.164	0.097	0.268	4.260	28.315	1.622
3600 rpm	60.00	0.058	0.434	0.652	0.561	6.208	41.089	2.384

table 49 Harmonic Response Analyses - Active magnetic bearing support - (open loop)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	11.11	0.003	0.037	0.040	0.076	0.425	1.307	4.983
2	18.55	0.004	0.086	0.012	2.357	2.265	3.958	14.472
3	24.59	0.004	0.028	0.073	0.059	2.809	7.509	16.983
4	30.35	0.064	0.171	0.200	0.244	4.468	12.155	21.624
5	31.18	0.075	0.108	0.276	0.356	4.872	13.042	23.173
6	33.84	0.340	0.491	2.117	1.240	6.402	16.285	28.823
7	36.42	0.118	0.393	1.133	0.648	6.830	18.508	26.158
8	45.61	0.777	4.245	3.181	9.265	16.287	35.333	46.139
9	60.82	7.451	35.170	63.987	81.821	328.219	179.956	390.275
10	66.09	4.921	20.803	34.944	51.850	92.099	74.220	155.454
11	67.73	5.680	22.965	36.384	54.003	68.798	101.944	153.940
12	75.71	66.752	229.661	215.903	226.427	137.346	424.903	536.454
13	78.93	66.826	204.927	142.372	85.999	112.612	277.618	385.209
14	81.90	102.110	279.027	131.103	135.209	86.935	747.440	996.205
15	101.62	236.446	173.884	109.648	217.678	172.526	224.102	356.346
3000 rpm	50.00	0.433	2.296	3.171	1.502	26.690	49.912	63.970
3600 rpm	60.00	5.357	25.756	47.178	57.691	263.737	178.672	303.971

table 50 Harmonic Response Analyses - Active magnetic bearing support - (closed loop)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	AMB1	AMB2	AMB3	AMB4	AMB5	AMB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	14.77	0.015	0.081	0.112	0.178	0.568	2.401	4.613
2	22.14	0.037	0.139	1.375	4.926	4.231	5.749	22.432
3	24.59	0.007	0.021	0.275	1.020	2.863	6.860	9.177
4	27.01	0.005	0.012	0.172	0.630	3.038	8.555	10.878
5	31.18	0.004	0.003	0.104	0.363	4.062	12.039	15.350
6	36.33	0.023	0.047	0.066	0.058	6.698	18.082	25.526
7	47.36	0.252	4.499	5.427	13.999	39.558	58.675	106.506
8	52.79	0.152	6.972	172.994	197.506	159.622	143.185	258.089
9	56.52	0.300	6.800	83.181	83.391	103.296	114.426	154.393
10	60.79	0.083	2.864	170.643	61.546	435.254	284.344	522.485
11	66.05	0.034	0.595	7.134	22.377	101.664	119.023	103.291
12	67.73	0.041	0.752	11.027	41.186	151.781	145.358	132.937
13	71.20	0.090	1.838	40.339	179.712	437.630	206.764	386.754
14	78.57	0.010	0.150	6.103	169.942	326.070	166.082	268.081
15	78.93	0.009	0.133	6.592	174.016	315.886	154.235	271.205
3000 rpm	50.00	0.148	3.940	22.356	39.083	72.478	87.593	154.040
3600 rpm	60.00	0.107	3.598	148.559	43.618	345.811	262.667	425.802

table 51 Harmonic Response Analyses - Catcher bearing support - (rigid)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	10.49	0.000	0.013	0.017	0.412	0.986	0.270
2	16.59	0.052	0.048	0.095	0.982	2.495	0.708
3	22.29	0.108	0.421	2.602	3.235	4.572	12.657
4	28.24	0.012	0.047	0.387	3.533	7.087	1.942
5	28.41	0.011	0.046	0.384	3.568	7.177	1.966
6	44.20	0.165	0.288	0.532	8.326	18.084	4.949
7	57.77	0.018	0.170	1.187	14.313	32.157	8.794
8	69.66	0.277	0.321	3.091	19.901	49.184	13.438
9	70.18	0.380	0.342	3.255	20.083	50.062	13.677
10	71.63	0.792	0.594	3.826	20.515	52.584	14.364
11	78.41	1.002	1.404	9.704	18.679	66.566	19.130
12	84.90	6.300	5.502	48.062	83.862	78.613	91.283
13	94.99	8.631	8.715	12.764	71.670	96.665	26.429
3000 rpm	50.00	0.032	0.140	0.737	10.697	23.505	6.431
3600 rpm	60.00	0.014	0.190	1.387	15.416	34.967	9.561

table 52 Harmonic Response Analyses - Catcher bearing support - (flexible)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.10	0.088	0.114	0.032	0.374	0.563	3.795
2	10.22	0.040	0.043	0.189	0.753	0.922	6.161
3	11.94	0.039	0.770	2.818	2.566	1.329	40.229
4	21.01	5.949	9.271	5.976	5.398	6.175	90.574
5	23.05	2.559	2.682	0.584	4.777	8.164	55.248
6	28.37	25.569	2.337	34.769	65.993	60.260	442.372
7	28.41	26.714	2.463	36.565	67.802	60.515	453.366
8	31.18	26.848	2.506	36.824	67.748	59.995	452.730
9	35.67	43.652	33.574	39.379	36.290	71.848	730.671
10	45.87	38.140	15.667	29.049	11.856	51.797	946.910
11	55.96	14.552	33.284	6.522	33.405	116.113	841.812
12	66.17	1.454	10.654	10.100	8.232	16.124	202.805
13	69.66	6.599	20.237	24.194	18.812	34.757	455.145
14	70.06	7.156	20.149	24.673	18.751	40.997	466.483
15	78.93	2.653	0.790	1.760	2.747	21.276	148.390
16	89.96	11.825	13.442	16.813	21.035	34.198	246.629
3000 rpm	50.00	9.486	3.242	9.539	13.476	6.759	305.404
3600 rpm	60.00	1.884	11.948	5.347	2.759	41.464	290.565

table 53 Harmonic Response Analyses - Catcher bearing support - (flexible II)
Bearing loads at various modes due to an unbalance in the LP-compressor

Mode	Frequency	CB2	CB3	CB4	CB5	CB6	max. disp.
	[Hz]	[kN]	[kN]	[kN]	[kN]	[kN]	[μm]
1	8.97	0.012	0.033	0.005	0.396	0.696	2.339
2	12.01	0.075	0.014	0.091	0.829	1.267	4.242
3	14.33	0.146	0.234	2.003	2.110	1.917	19.718
4	25.81	3.442	4.551	2.731	5.349	8.060	26.971
5	28.25	1.726	1.027	1.867	7.663	10.739	36.166
6	28.41	1.728	0.957	1.990	7.899	10.957	36.941
7	30.66	2.468	0.307	4.549	12.563	14.865	51.343
8	35.20	31.867	20.995	61.948	71.863	39.123	251.423
9	42.24	74.584	65.431	43.329	97.990	93.516	680.877
10	49.70	63.919	12.990	53.151	39.635	69.219	907.189
11	61.52	8.970	92.615	43.455	24.212	273.020	951.011
12	66.36	4.524	31.359	27.681	21.452	64.397	278.992
13	69.66	9.543	30.118	34.202	29.168	29.815	308.080
14	72.94	26.237	42.247	59.387	42.207	129.356	579.068
15	78.41	9.149	3.051	6.759	8.022	61.910	214.503
16	92.43	29.394	37.895	51.099	58.397	101.831	365.225
3000 rpm	50.00	59.923	11.927	51.507	43.313	64.068	869.982
3600 rpm	60.00	9.271	55.092	17.736	26.946	161.238	564.587

12 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 radial bearing loads caused by unbalance eccentricities in various parts of the rotor shaft. For the following load cases the bearing loads and response displacements of the rotor shaft 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.

The load cases 1 to 5 are representative for normal operation conditions. Under normal operation conditions the rotor shaft is supported by the AMBs only. Table 54 summarizes the maximum bearing loads that occur for the load cases 1 to 5. These are bearing loads, which occur as a result of the maximum allowable unbalance in the various parts of the rotor shaft. The maximum allowable unbalance results in an unbalance eccentricity of 10 μm in the rotor shaft at 3000 rpm (50 Hz). For the investigated load cases 1 to 5 the bearing loads are below the maximum load capacity of the radial AMBs (100 kN).

table 54 Summary of maximum bearing loads (in kN) for the AMB support variants under normal operation conditions

Support variant	Load case				
	1	2	3	4	5
AMB support - rigid	40.092	42.056	62.790	45.979	63.429
AMB support - open loop	33.359	18.175	62.419	18.617	35.987
AMB support - closed loop	32.508	20.171	26.748	27.867	28.787

Load case 6 and 7 represent emergency conditions for the rotor shaft. Table 55 summarizes the maximum bearing loads that occur for the load cases 6 and 7. For the AMB support variants the bearing loads are, with the exception of the combination of load case 7 with rigid

supports, well in excess of the maximum load capacity of the radial AMBs (100 kN). This implies that as a result of a deblading accident in the turbine or LP-compressor the rotor support will be transferred from the AMBs to the CBs. The load capacity required for the CBs is given in Table 55.

table 55 Summary of maximum bearing loads for all support variants under emergency conditions

Support variant	turbine unbalance	LP-compressor unbalance
AMB support - rigid	338.868	41.089
AMB support - open loop	145.316	263.737
AMB support - closed loop	226.683	345.811
CB support - rigid	213.634	34.967
CB support - flexible I	48.873	116.113
CB support - flexible II	79.594	161.238

It should be noted that for the CB support variants large response displacements occur at the unsupported shaft end. These response displacements limit in combination with the 10 μm eccentricity criterion the maximum allowable unbalances in the various parts of the rotor shaft. An additional CB near AMB1 would improve the dynamic behaviour of the CB support variants.

References

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

[2] I. Pierre. *Rotordynamics analysis: Estimation of the mass unbalance induced by deblading.* Personal communication, E-mail message 22-7-2003.

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

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

Figures

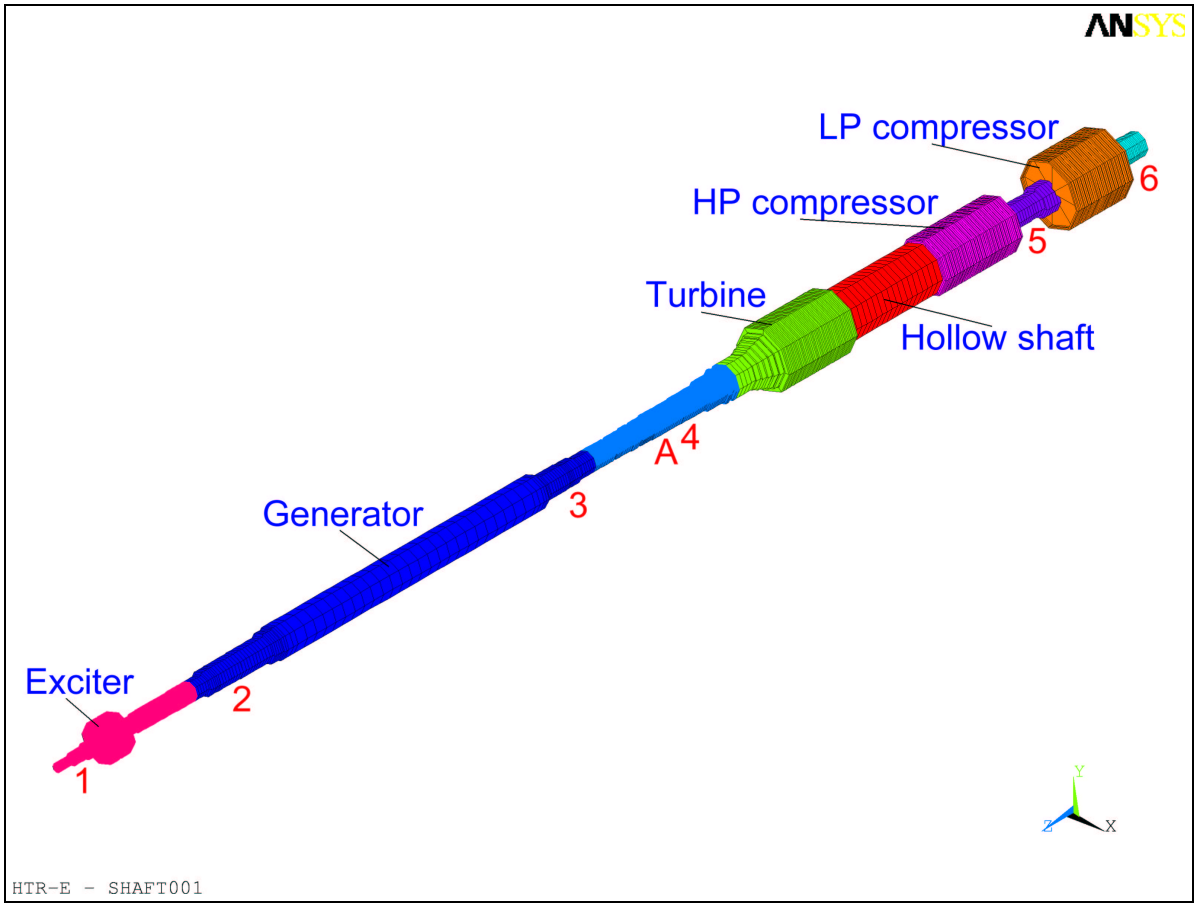


figure 1 Layout of the GT-MHR rotor shaft

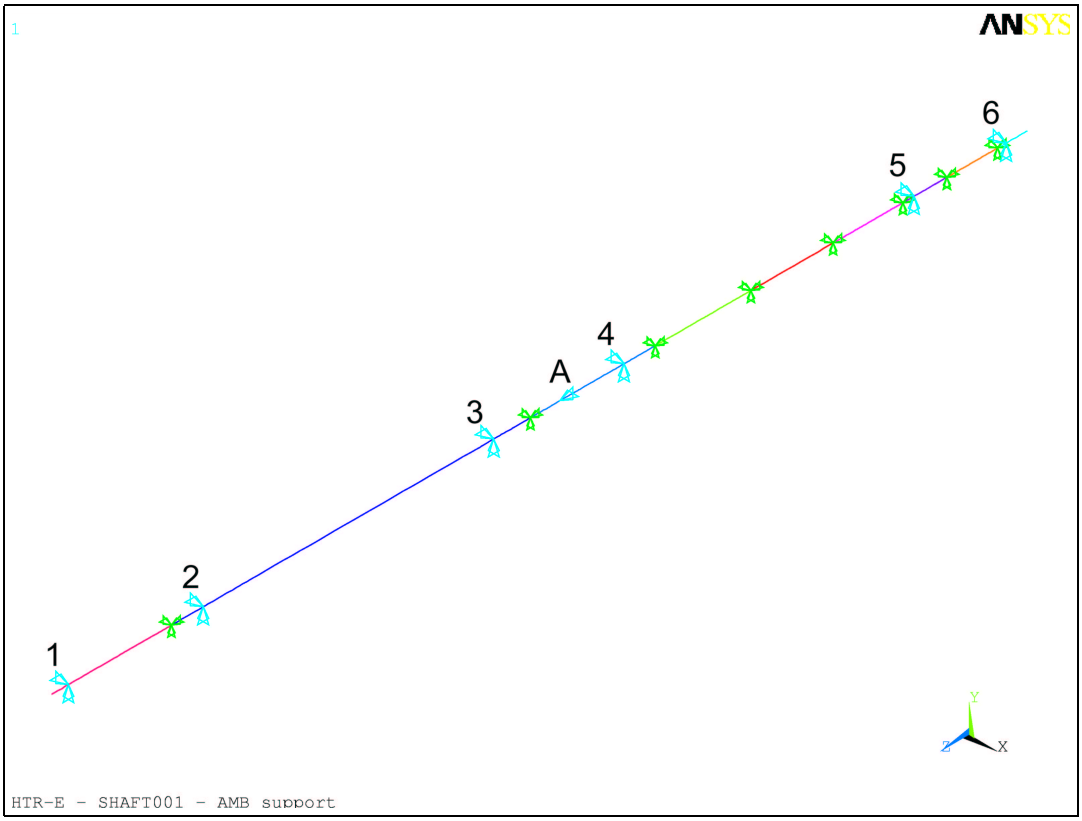


figure 2 The position of the Active Magnetic Bearings supporting the GT-MHR rotor shaft

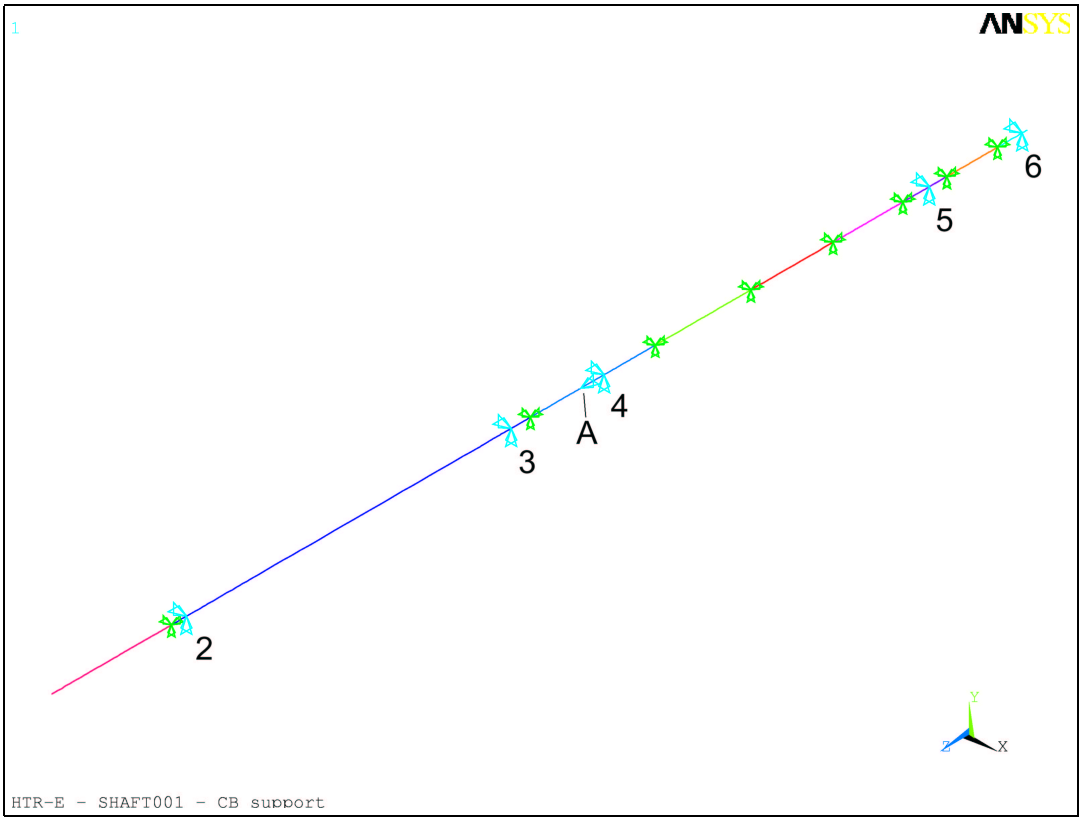


figure 3 The position of the Catcher Bearings supporting the GT-MHR rotor shaft

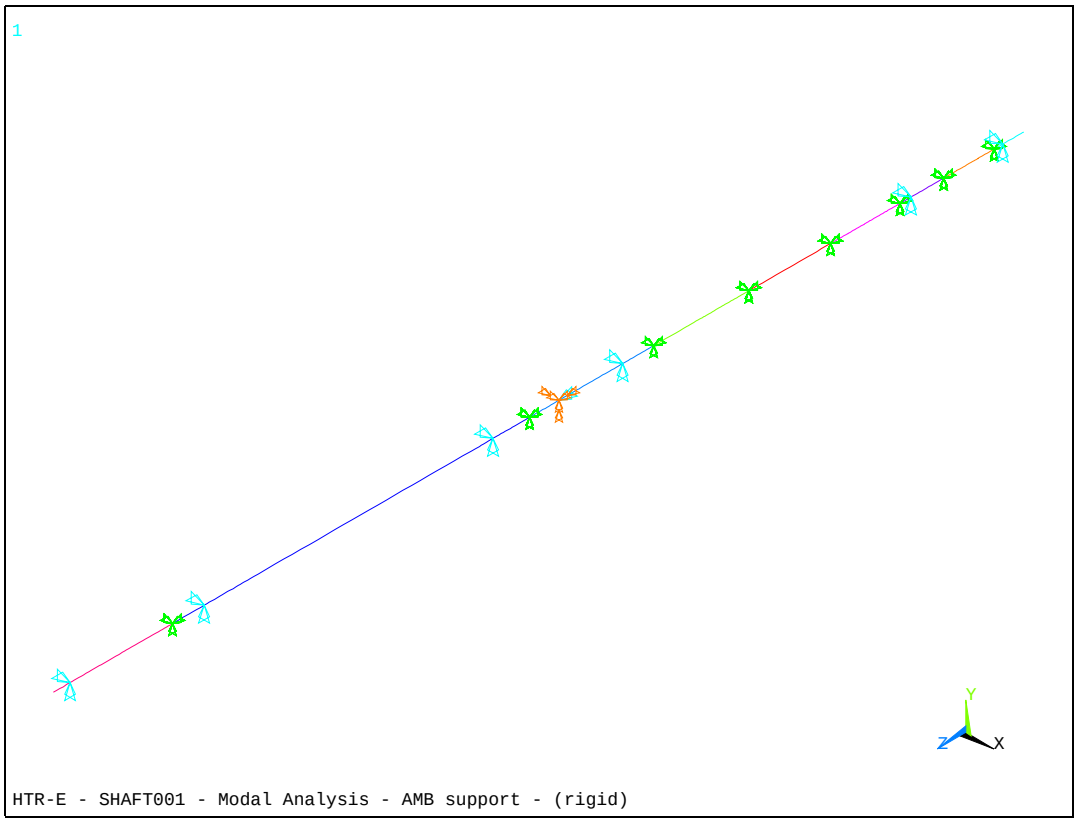


figure 4 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (rigid stiffness)

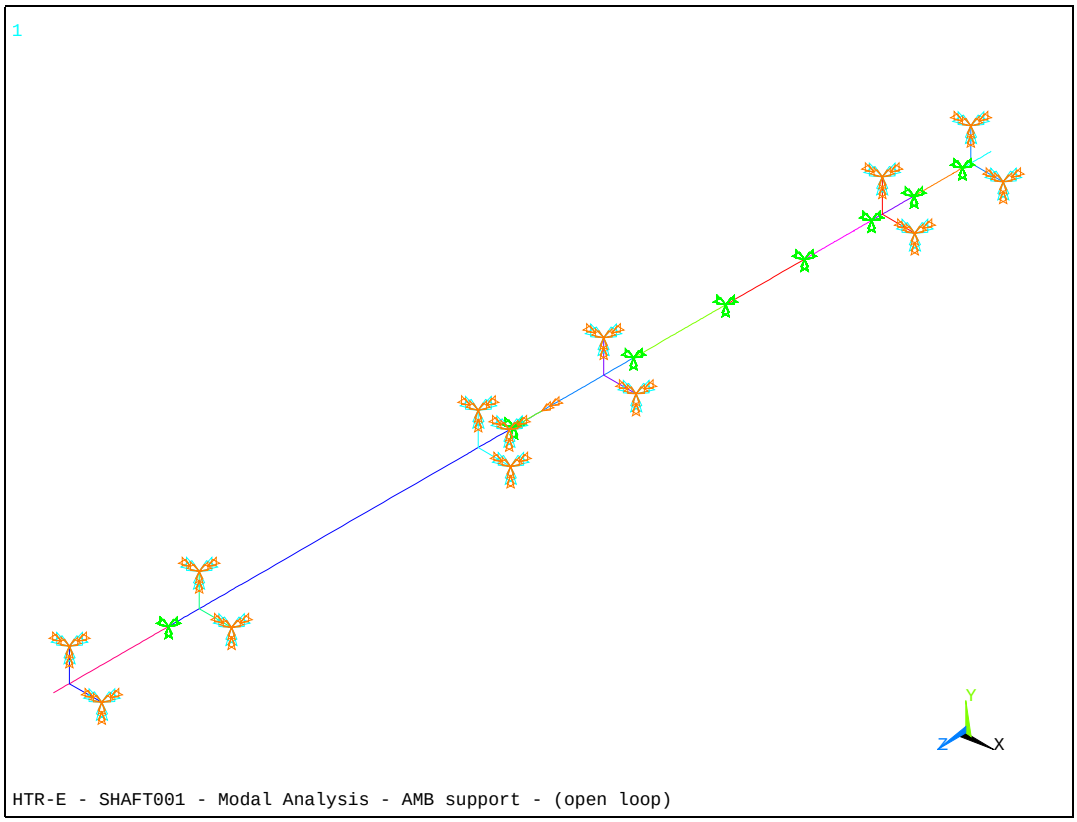


figure 5 Applied boundary conditions for the GT-MHR rotor shaft resting on the active magnetic bearings (flexible stiffness)

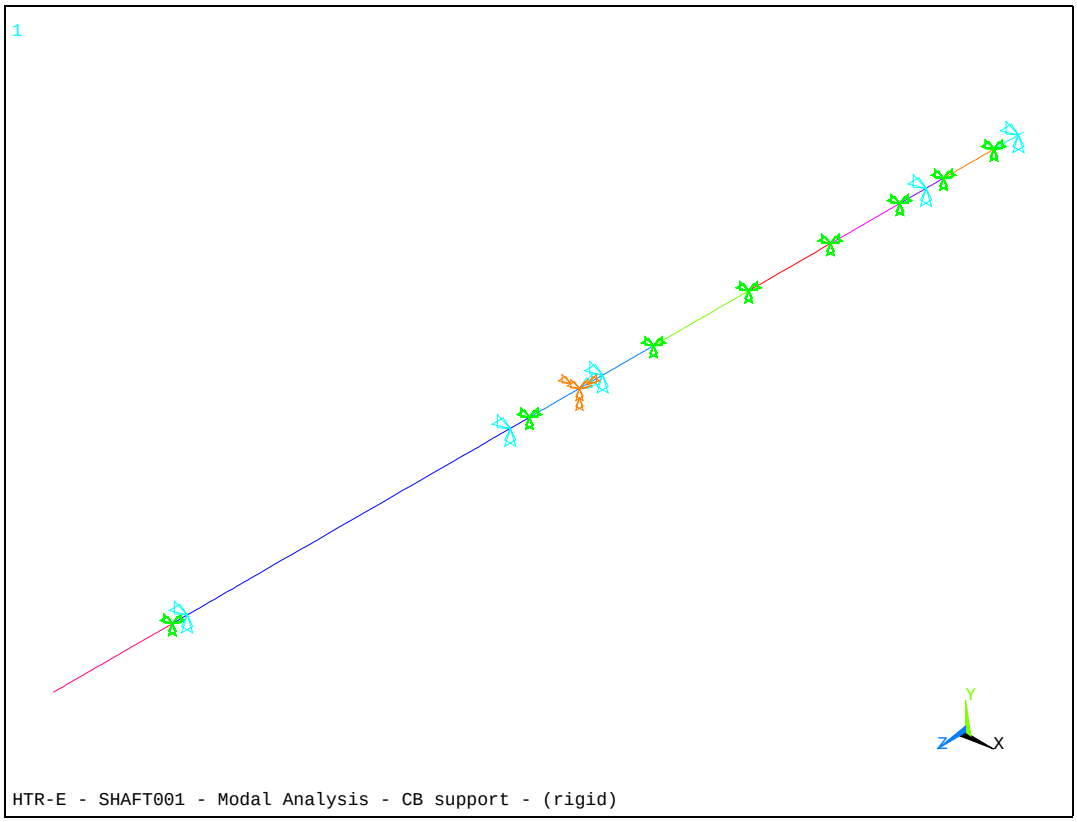


figure 6 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (rigid stiffness)

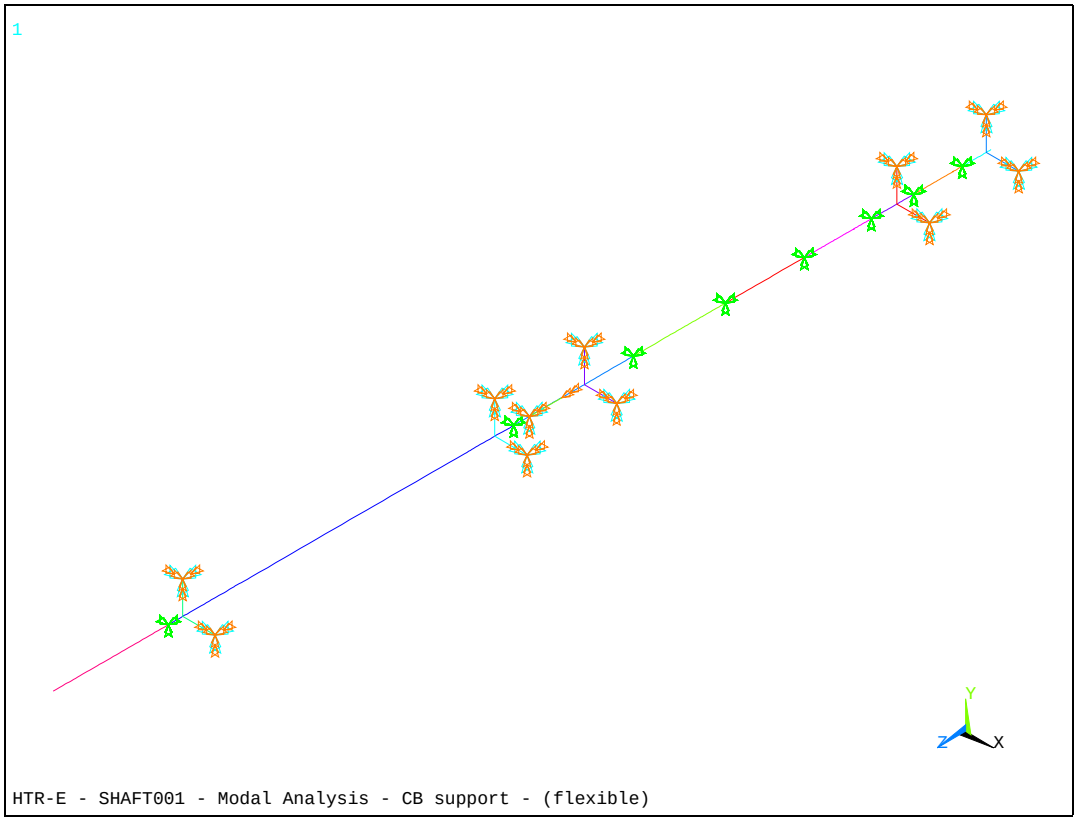


figure 7 Applied boundary conditions for the GT-MHR rotor shaft resting on the catcher bearings (flexible stiffness)

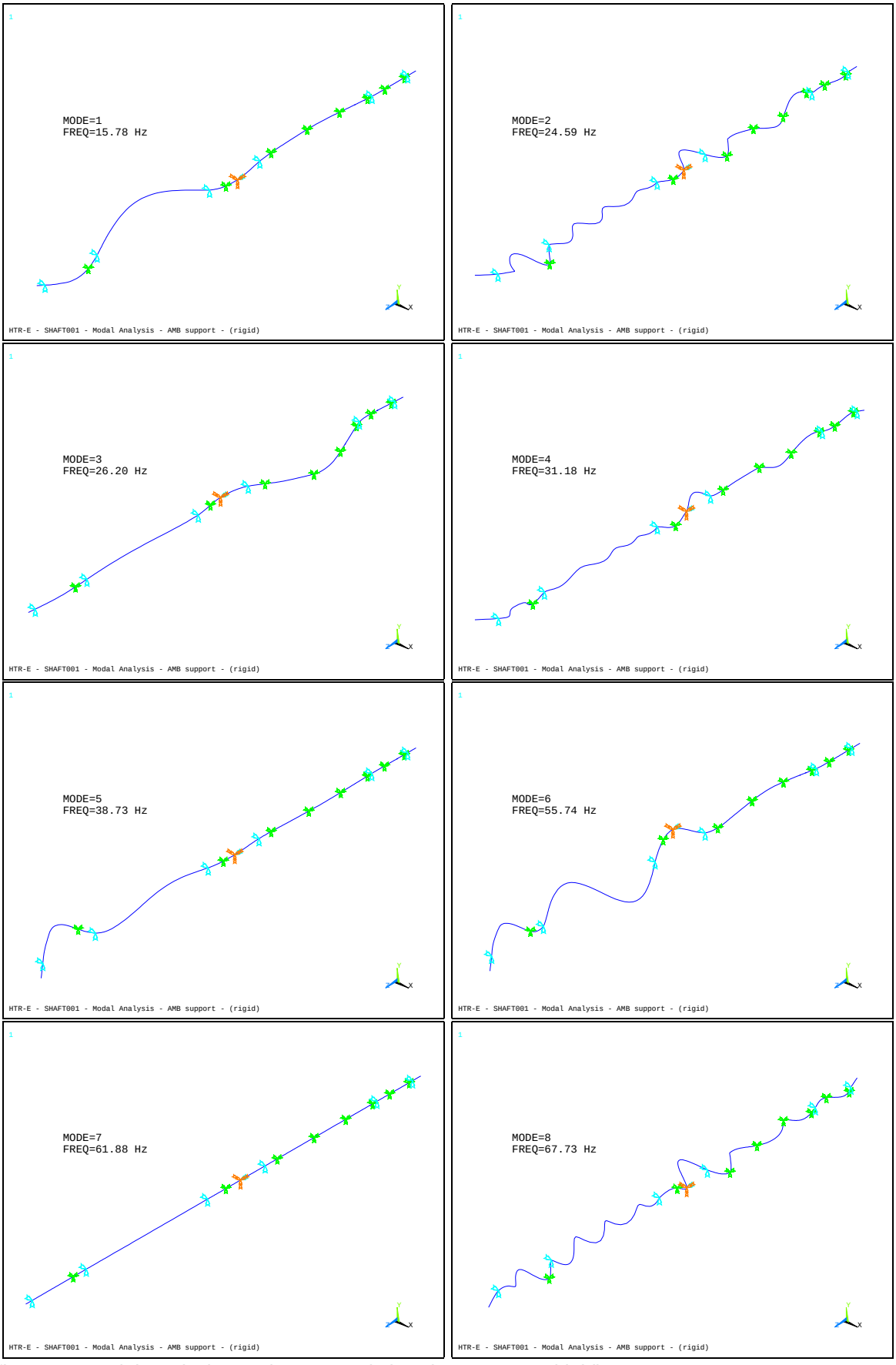


figure 8 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 1 to 8

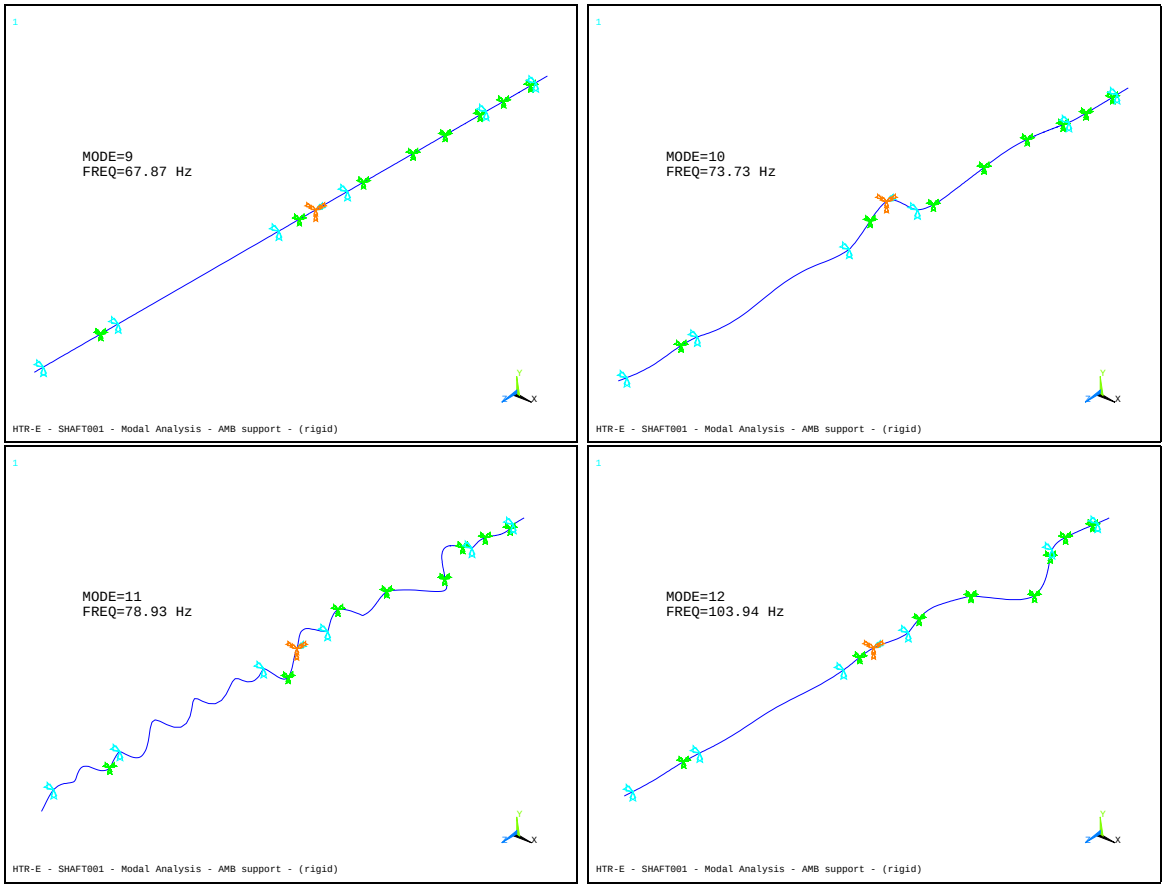


figure 9 Modal Analysis - Active magnetic bearing support - (rigid)
Mode shape 9 to 12

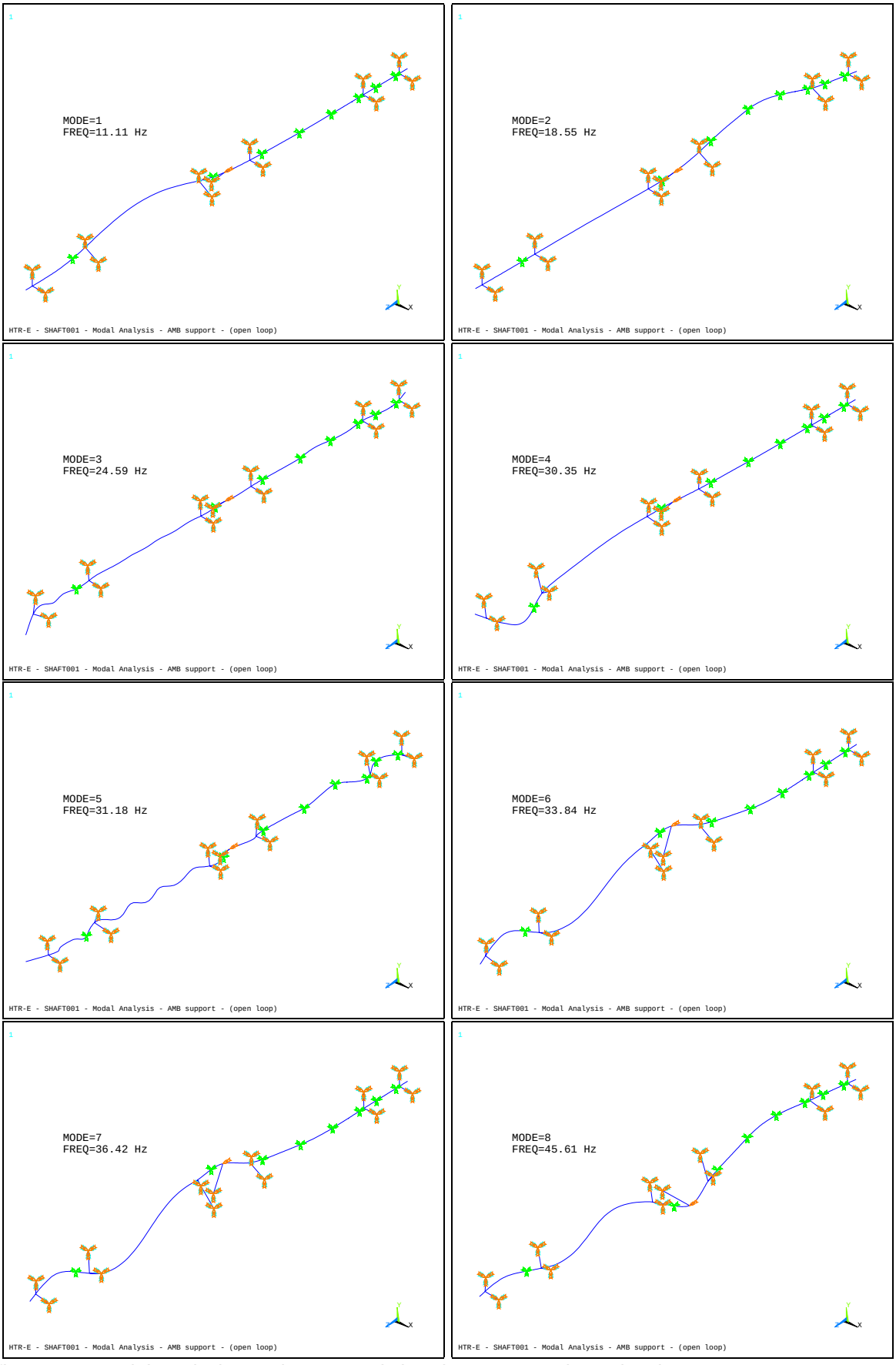


figure 10 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 1 to 8

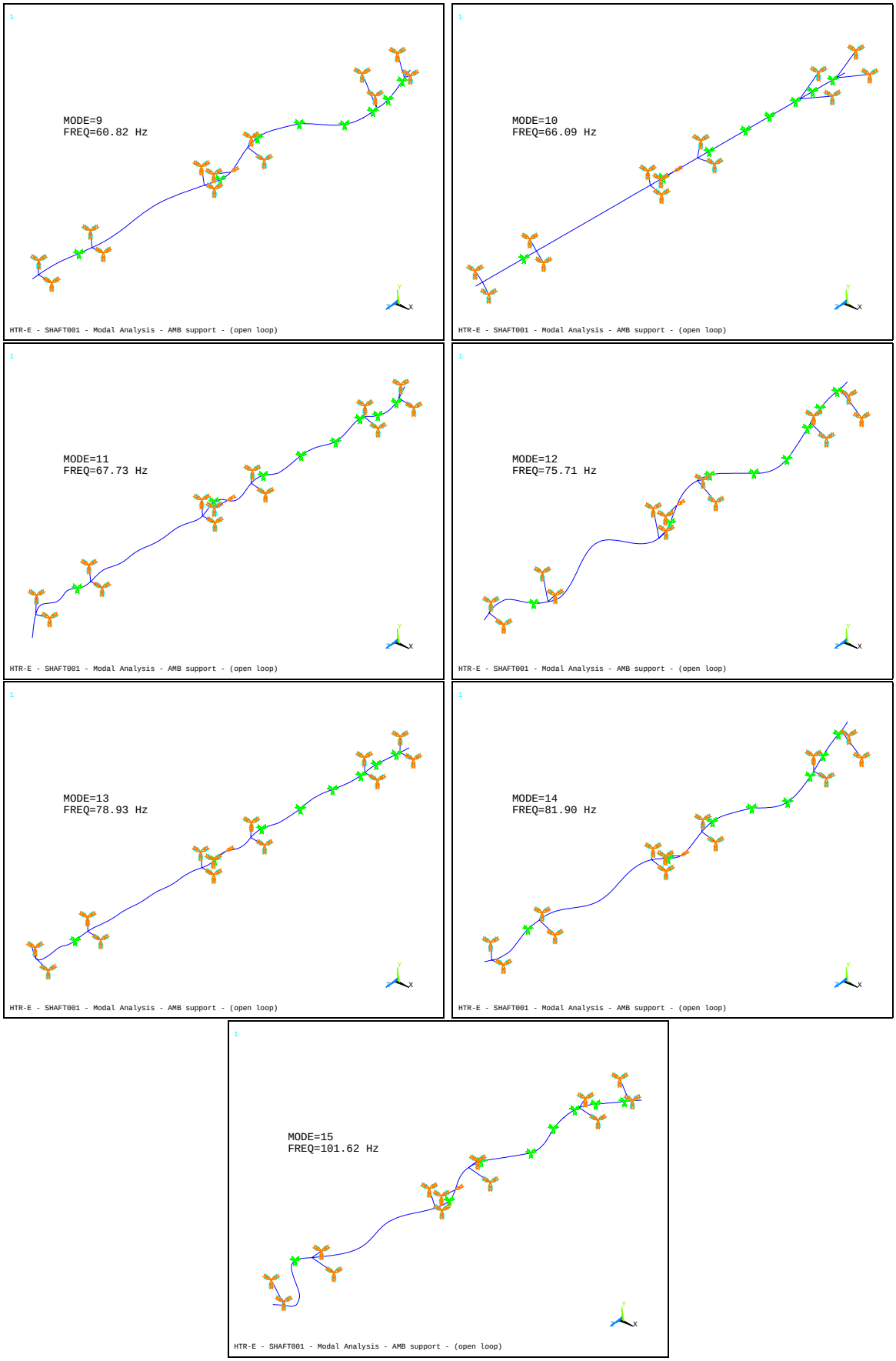


figure 11 Modal Analysis - Active magnetic bearing support - (open loop)
Mode shape 9 to 15

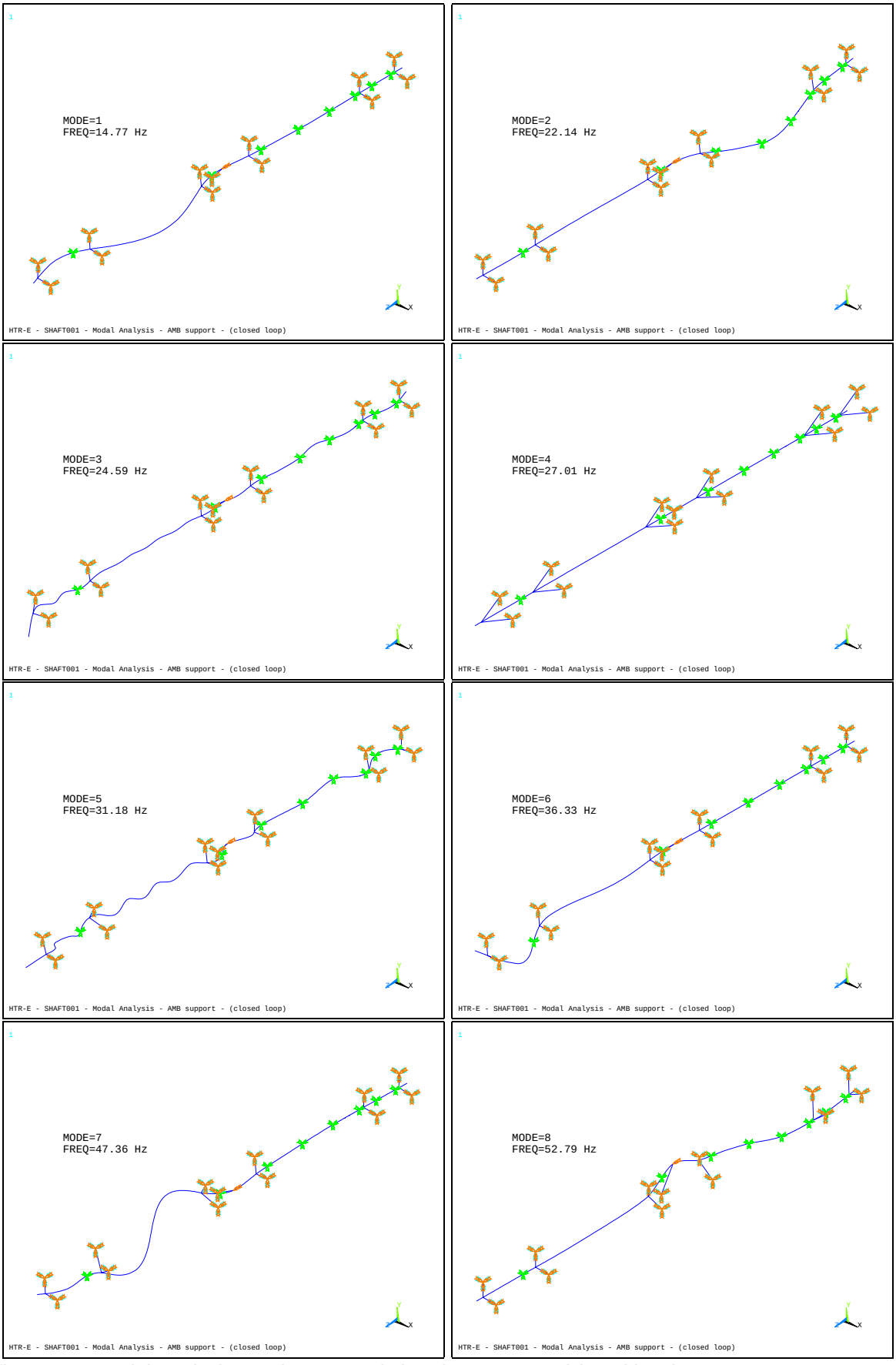


figure 12 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 1 to 8

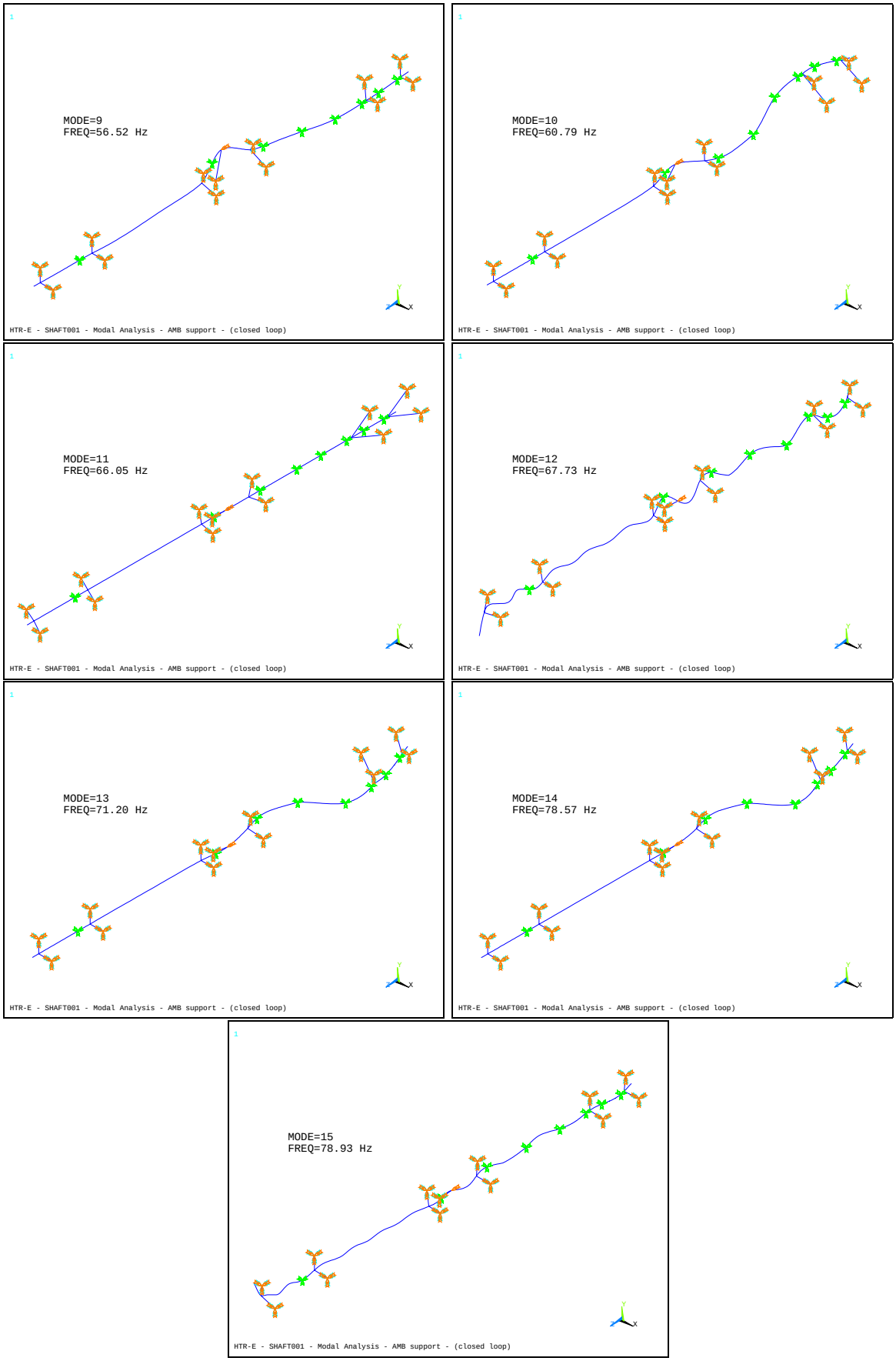


figure 13 Modal Analysis - Active magnetic bearing support - (closed loop)
Mode shape 9 to 15

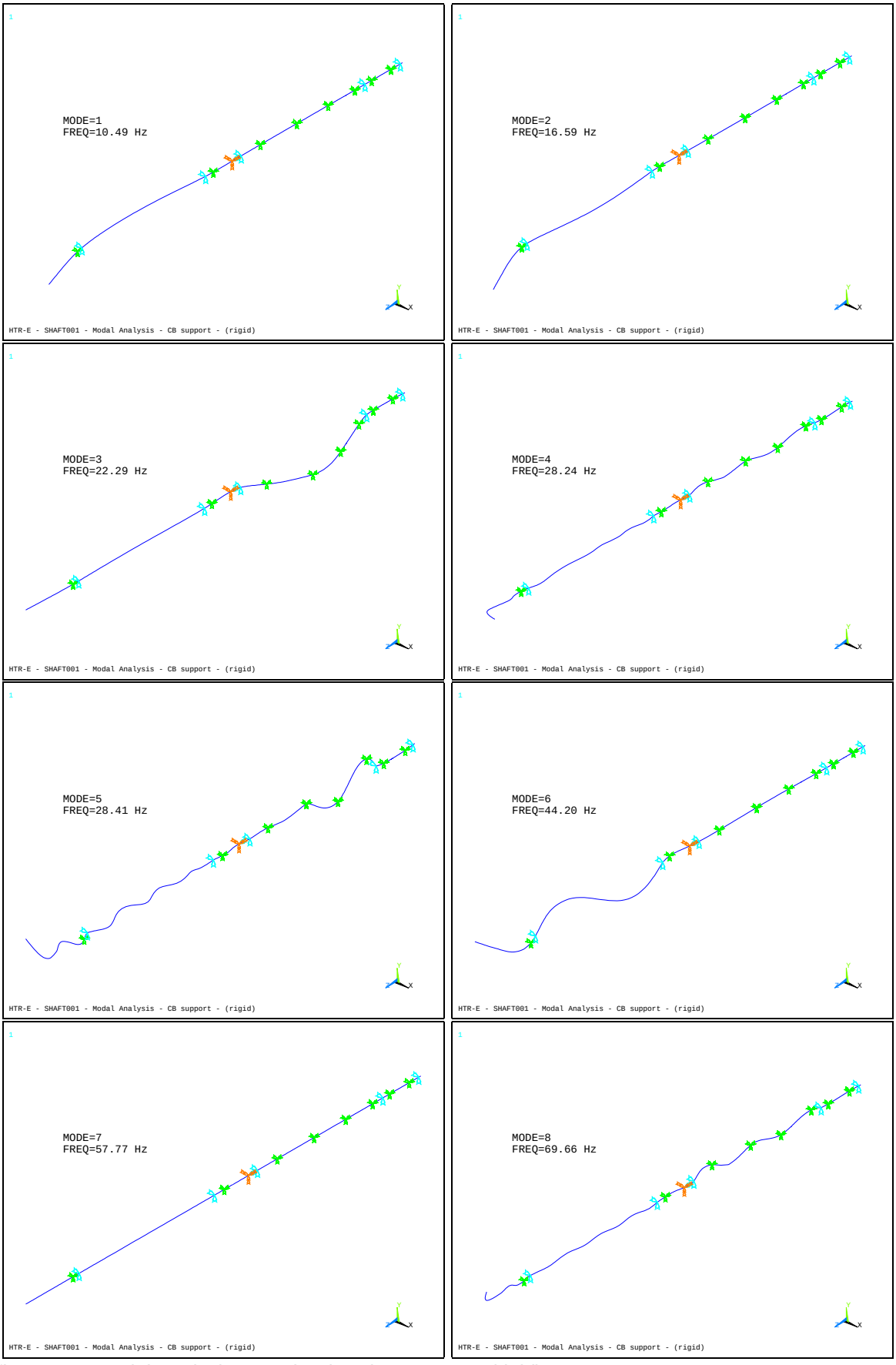


figure 14 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 1 to 8

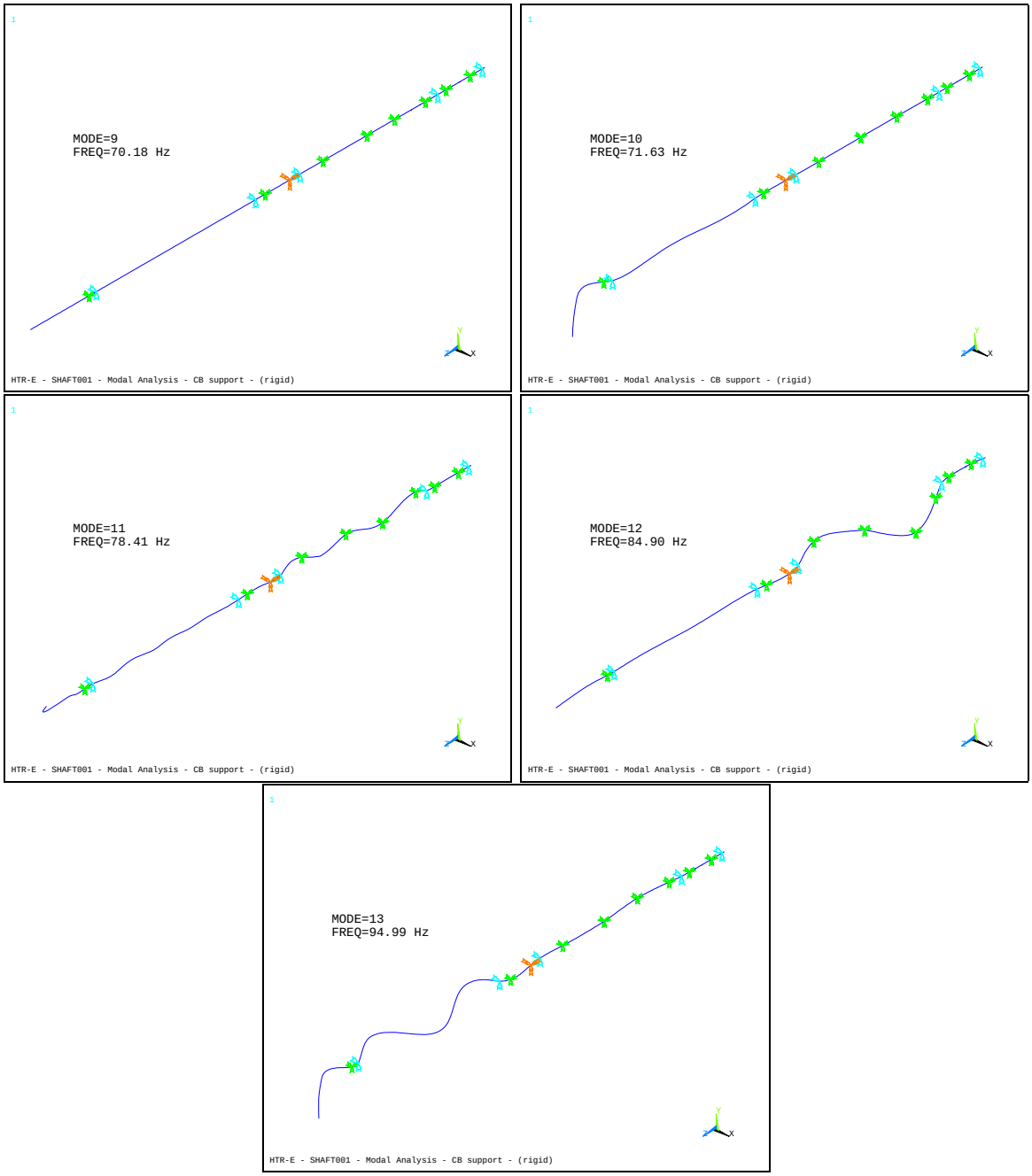


figure 15 Modal Analysis - Catcher bearing support - (rigid)
Mode shape 9 to 13

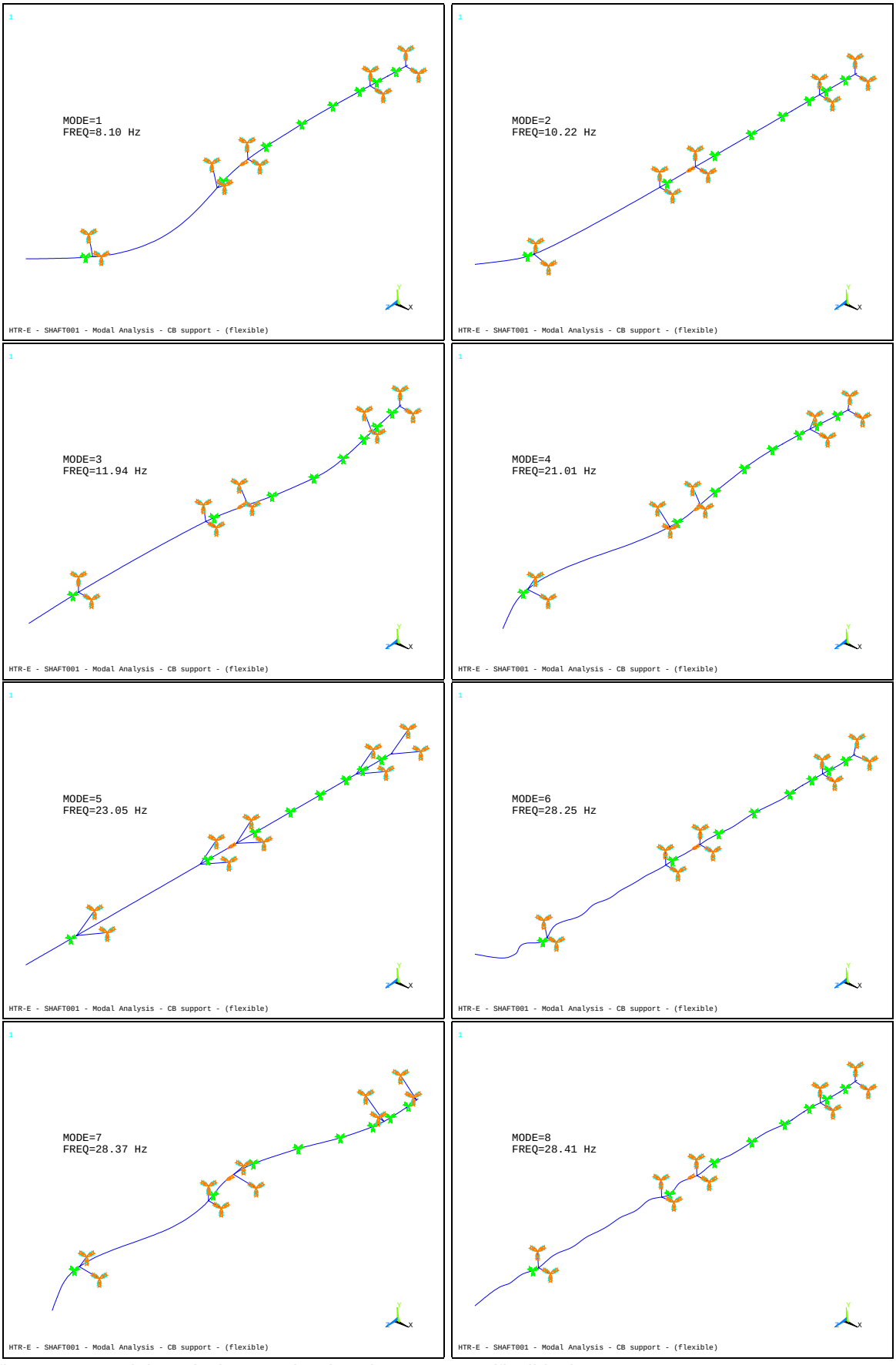


figure 16 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 1 to 8

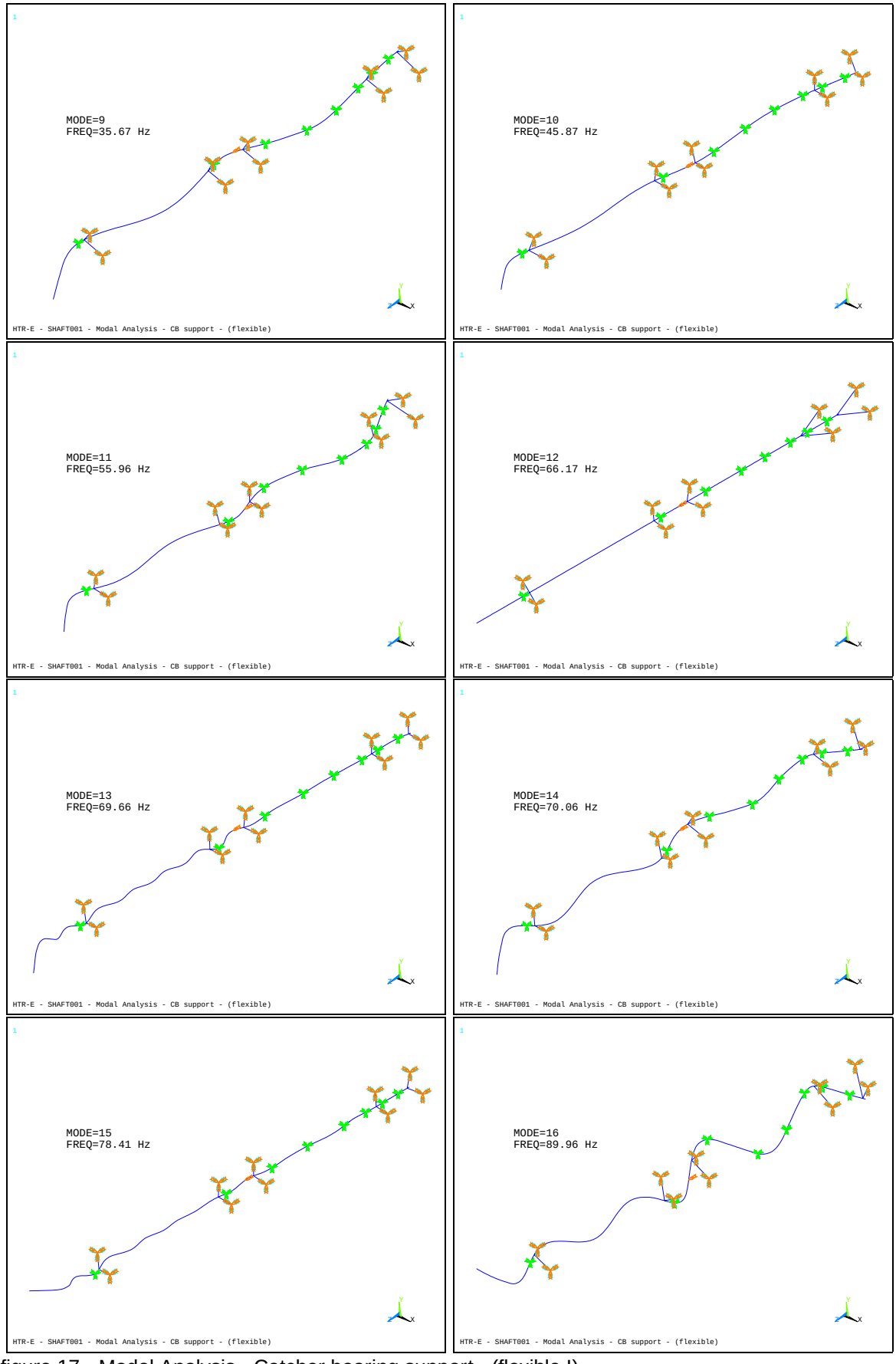


figure 17 Modal Analysis - Catcher bearing support - (flexible I)
Mode shape 9 to 16

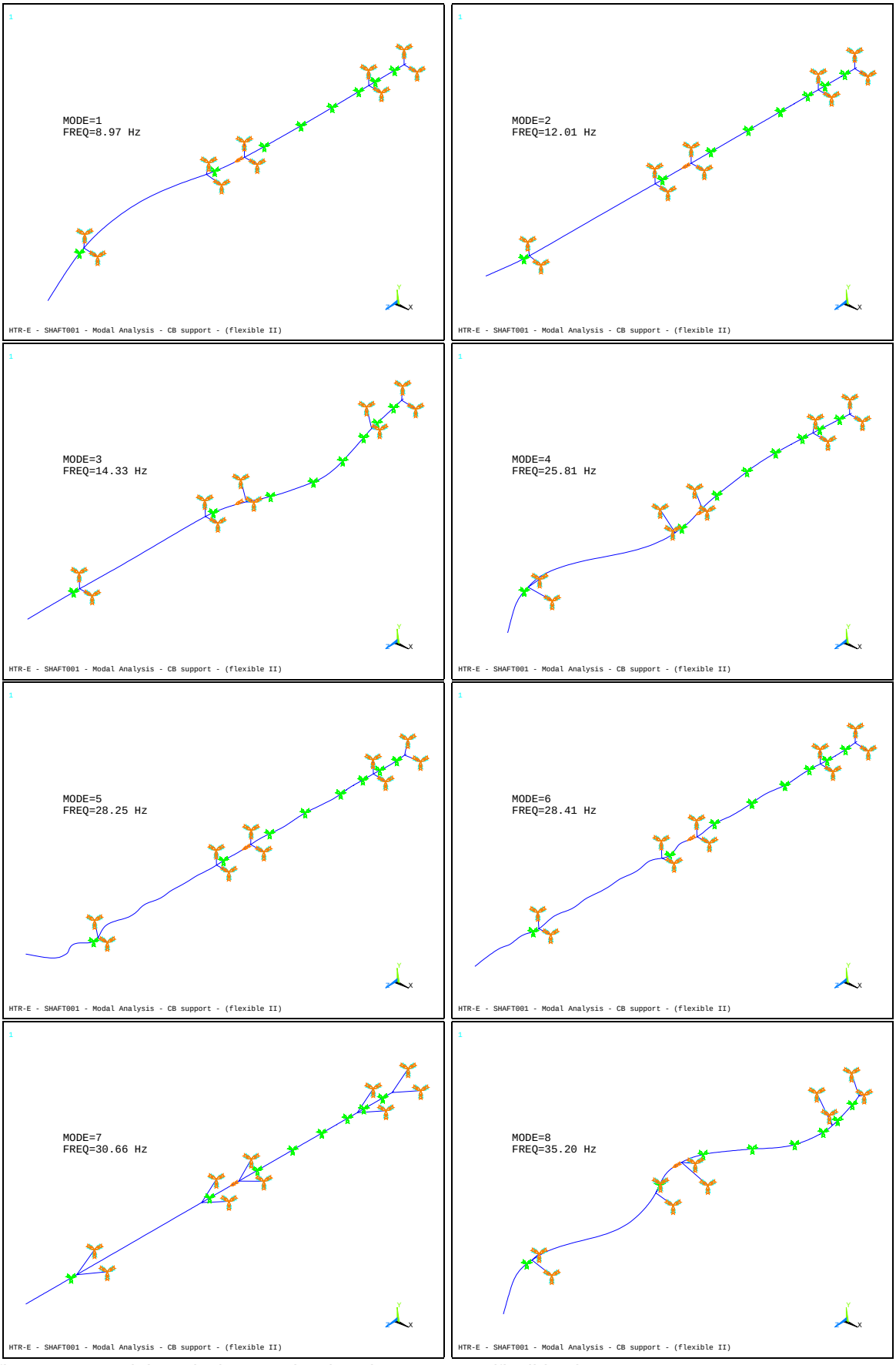


figure 18 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 1 to 8

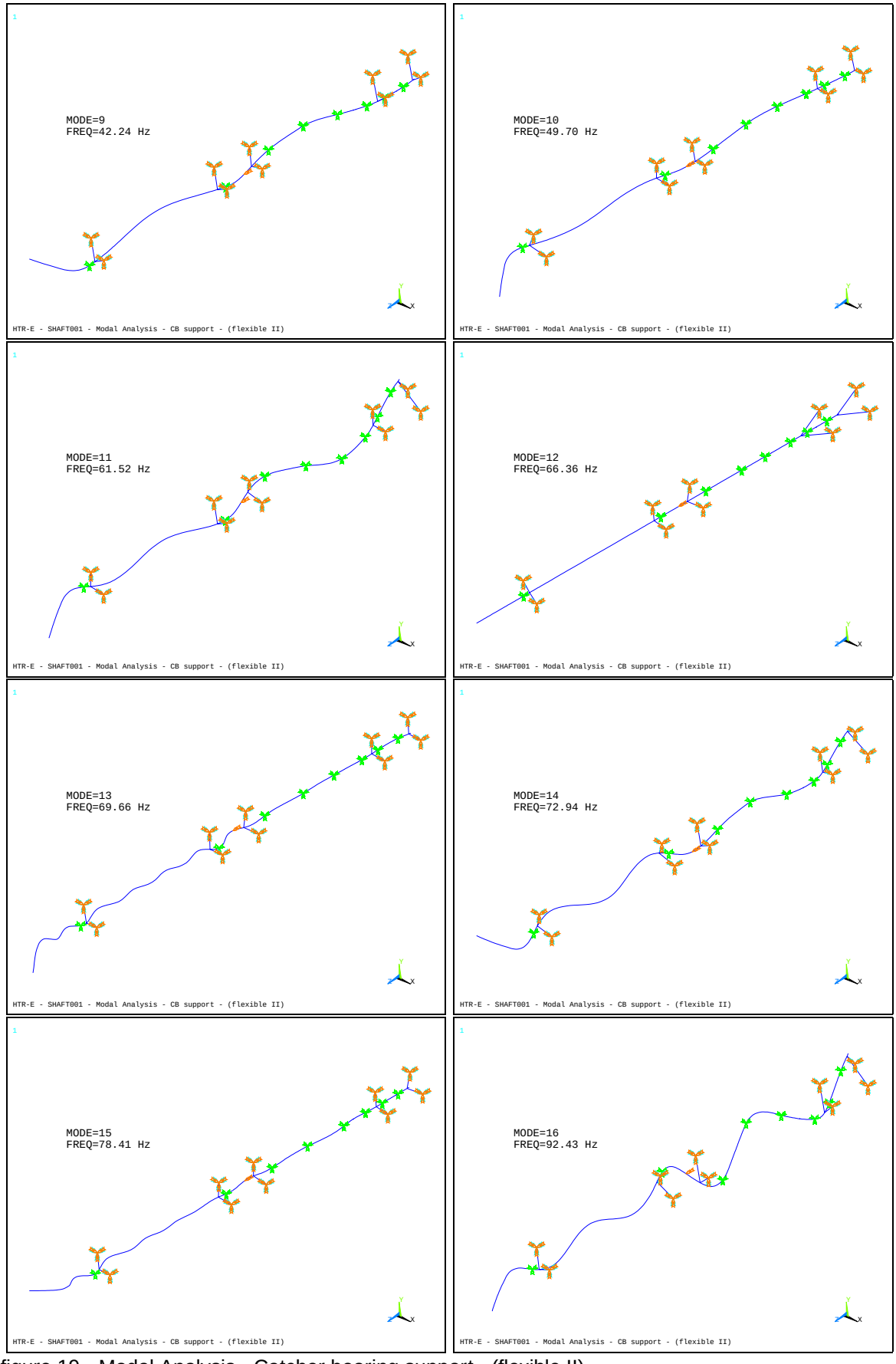


figure 19 Modal Analysis - Catcher bearing support - (flexible II)
Mode shape 9 to 16

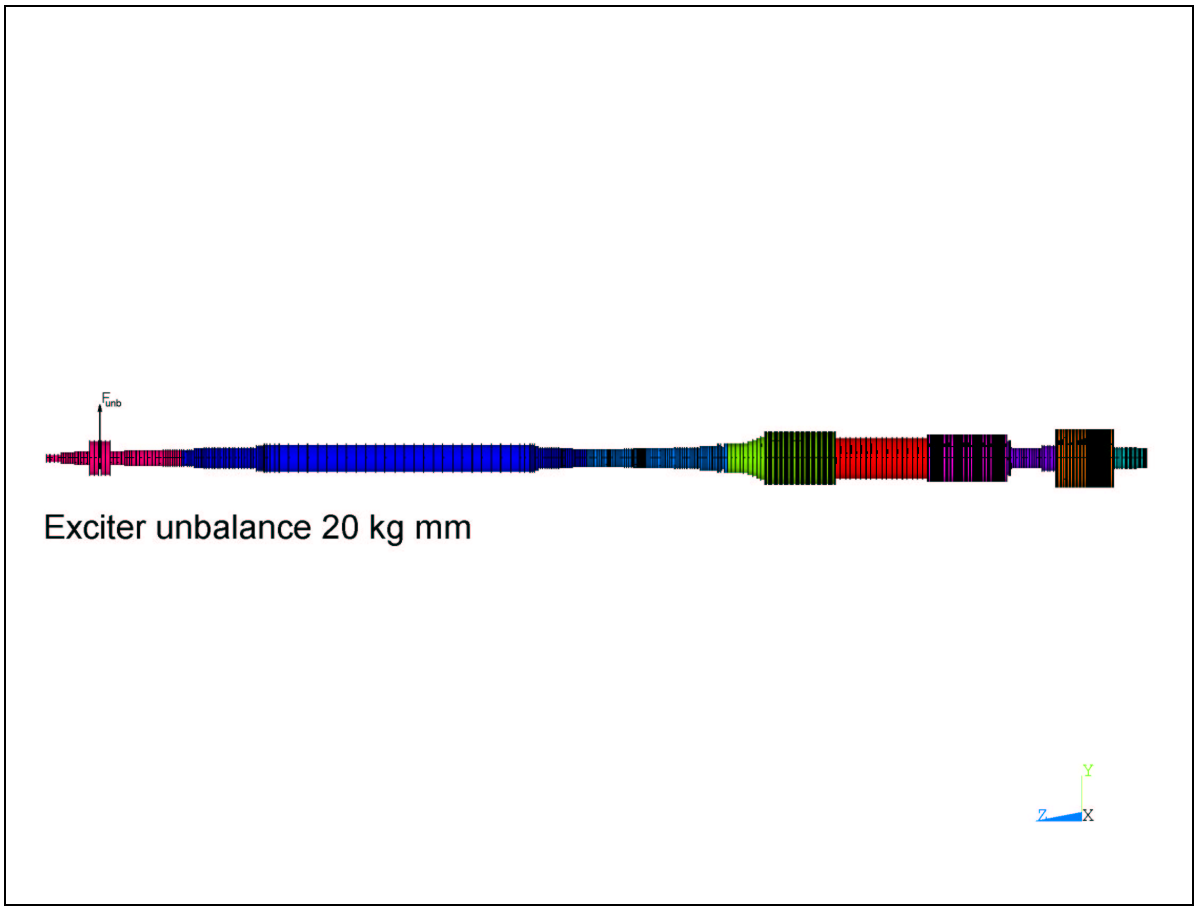


figure 20 Harmonic Response Analysis
Unbalance of 20 kg mm in the exciter

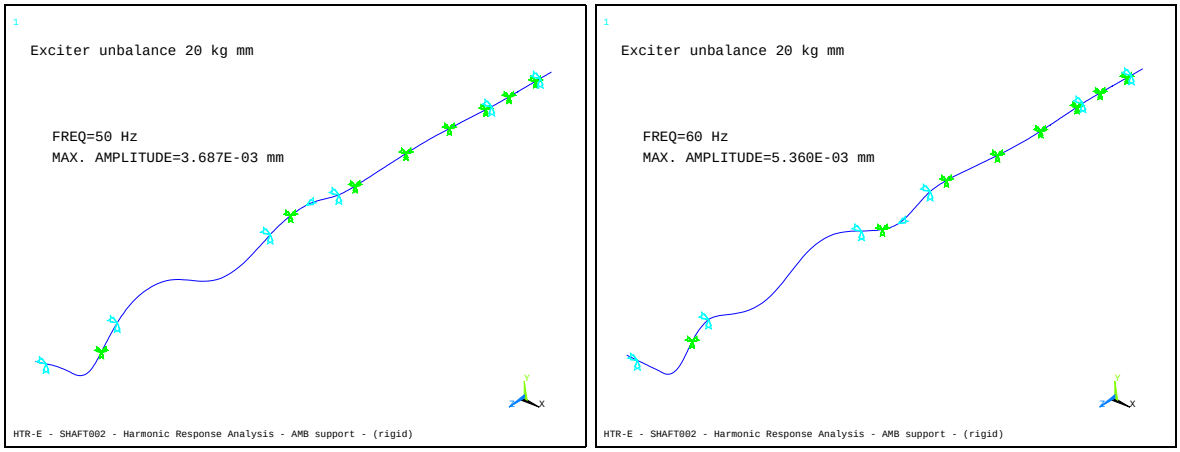


figure 21 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter

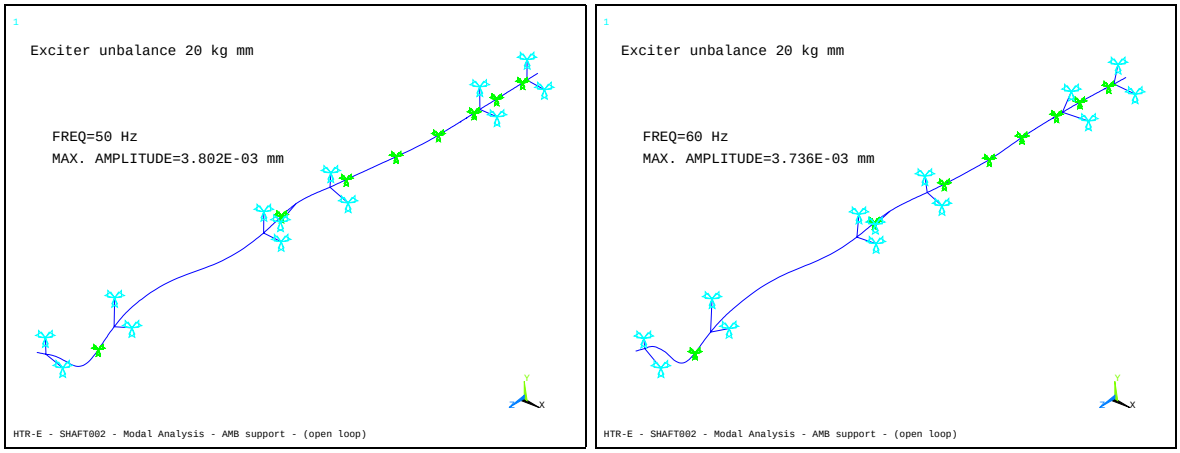


figure 22 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter

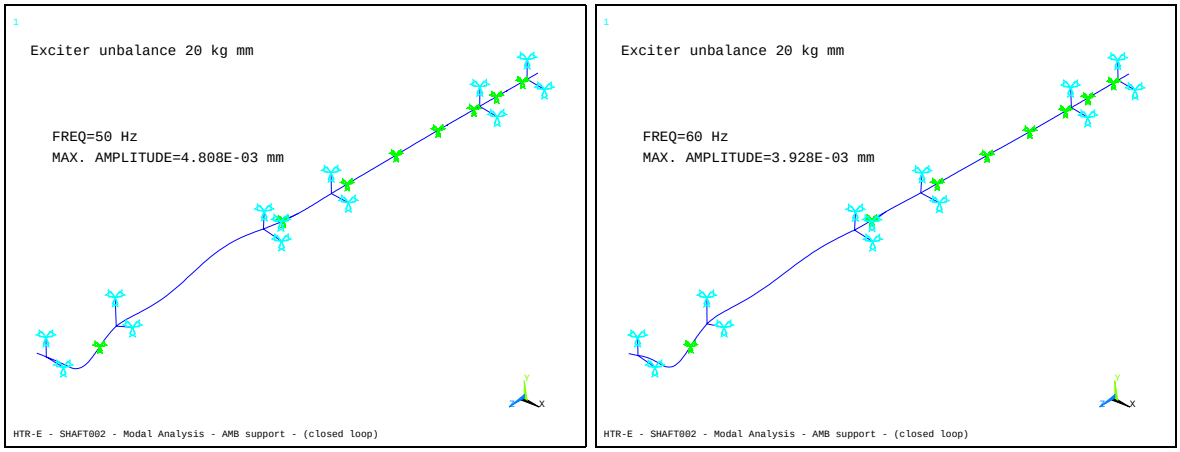
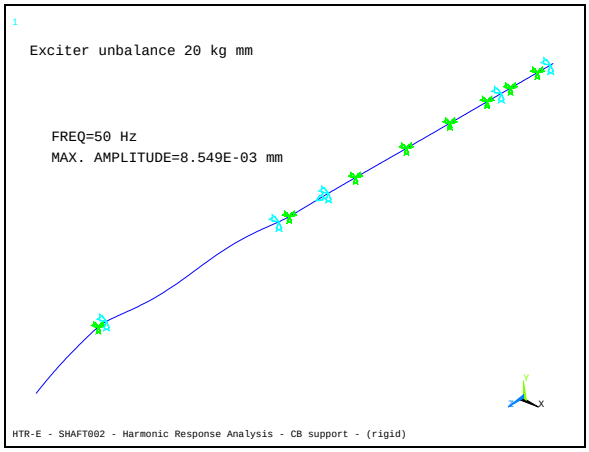


figure 23 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter



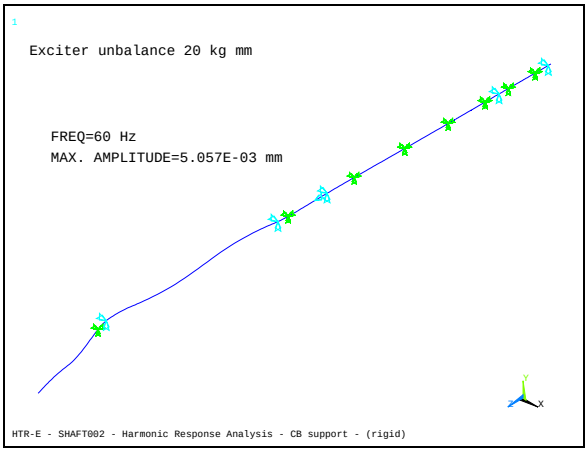
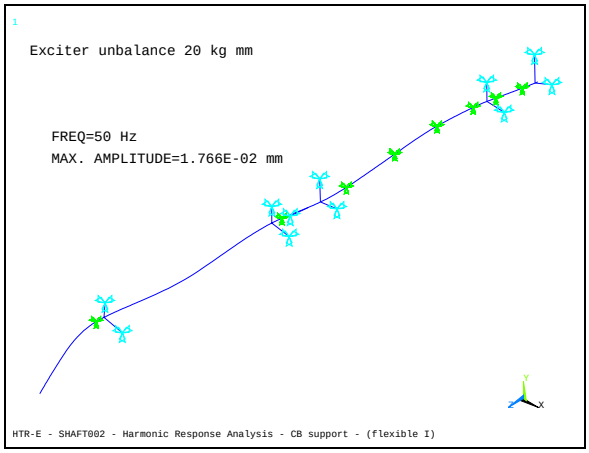


figure 24 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter



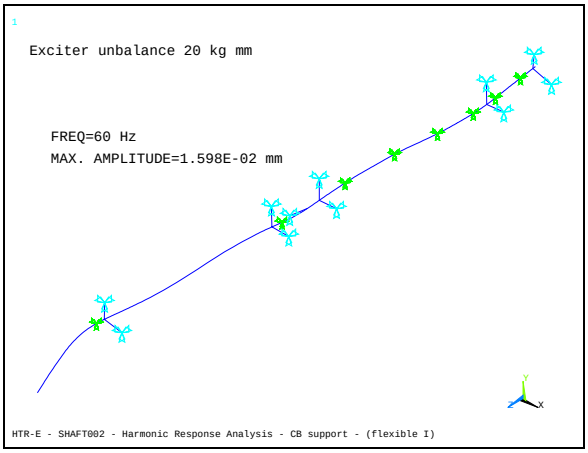
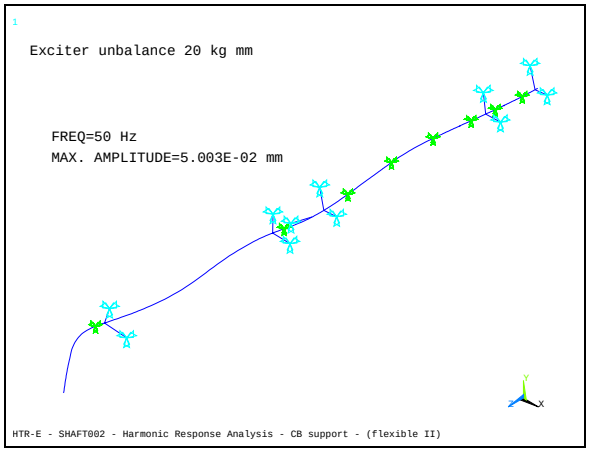


figure 25 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter



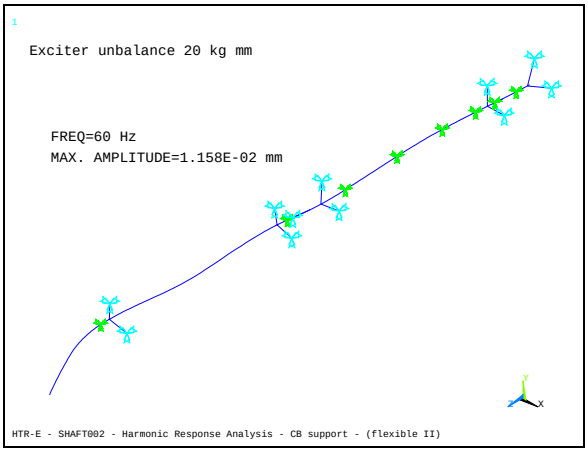


figure 26 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the exciter

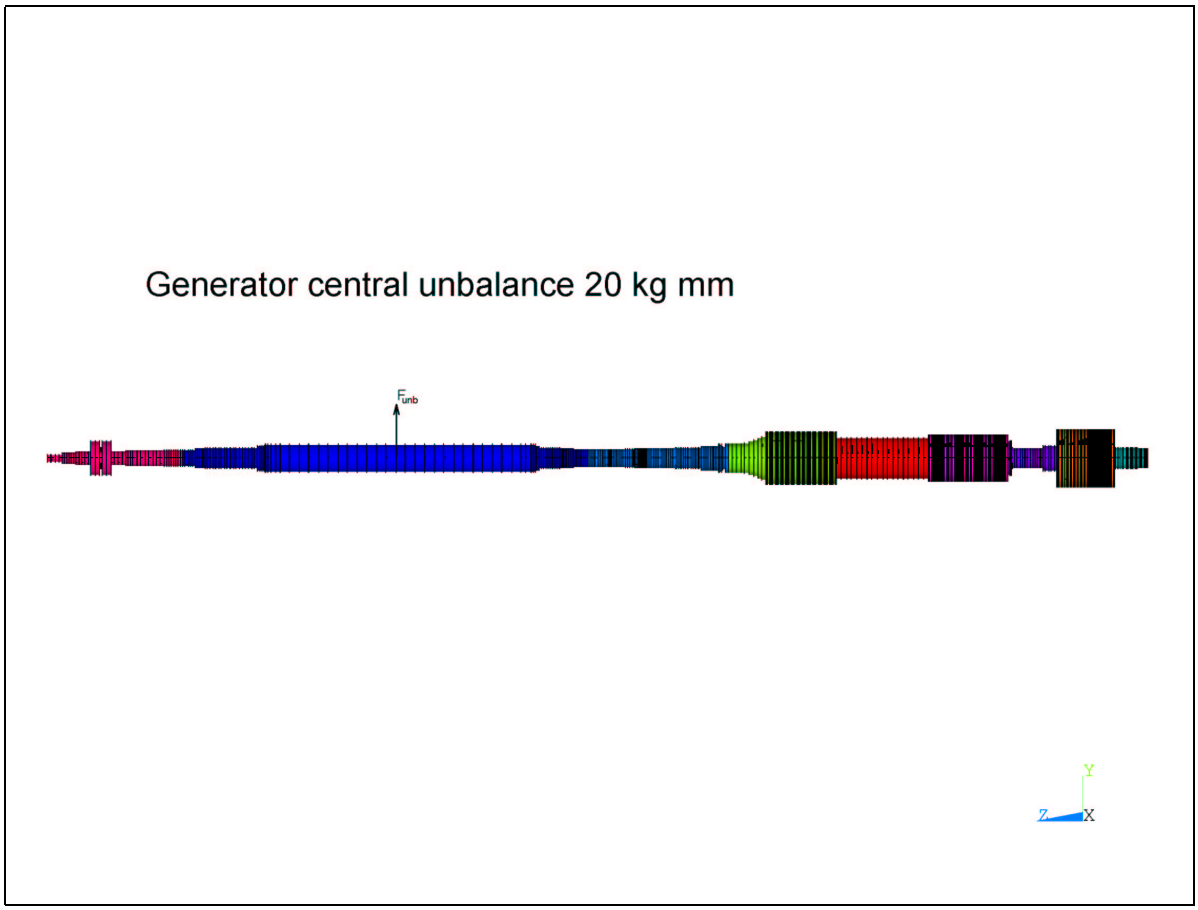
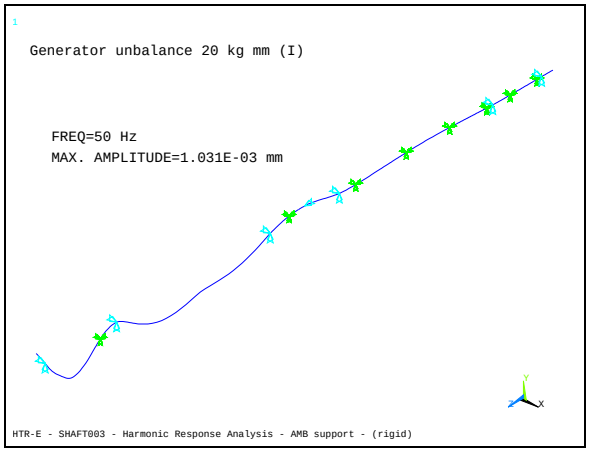


figure 27 Harmonic Response Analysis
Central unbalance of 20 kg mm in the generator



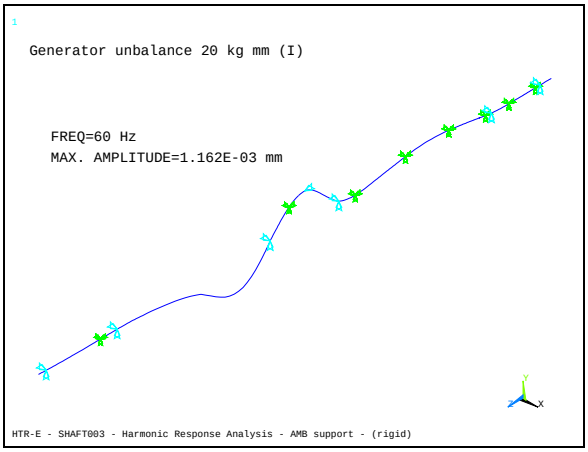
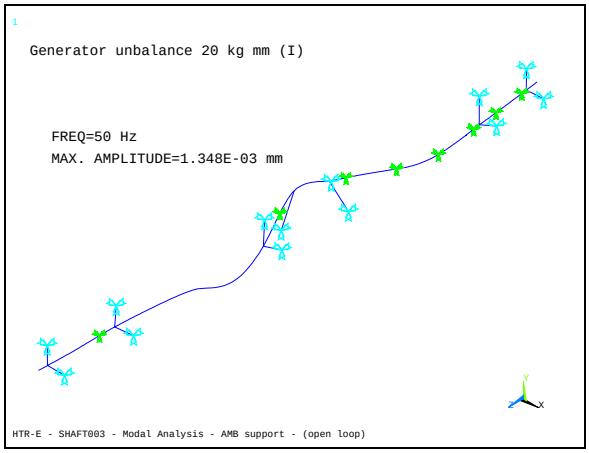


figure 28 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)



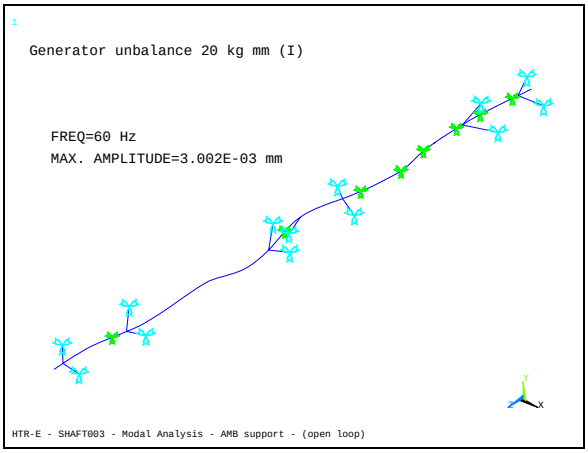
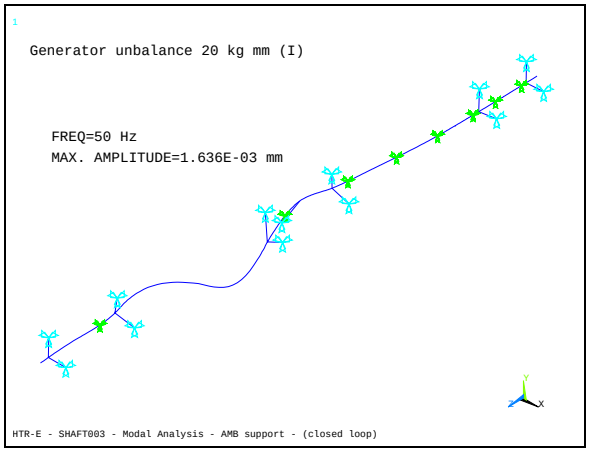


figure 29 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)



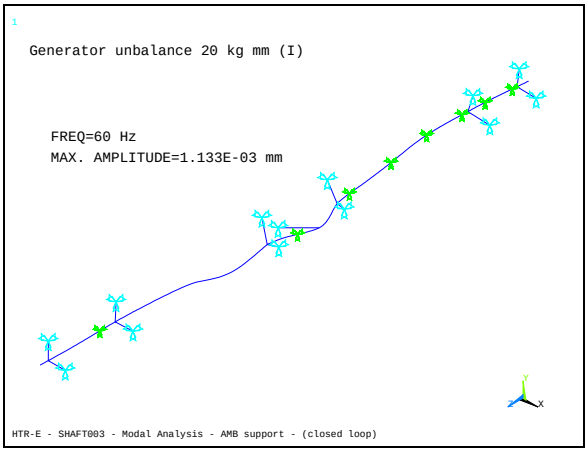
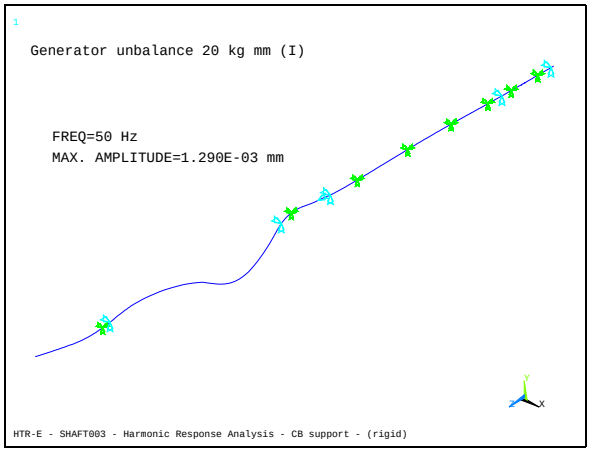


figure 30 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)



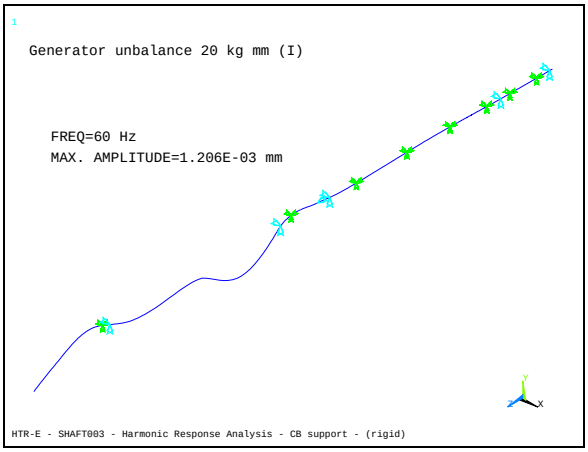
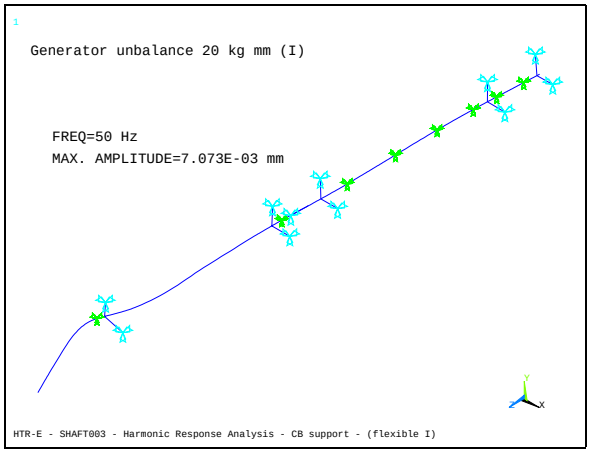


figure 31 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)



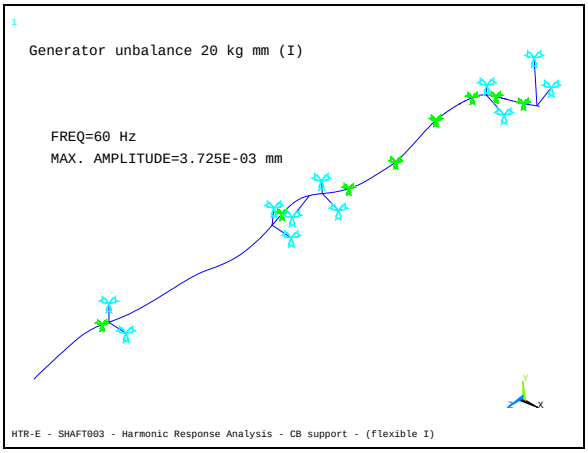
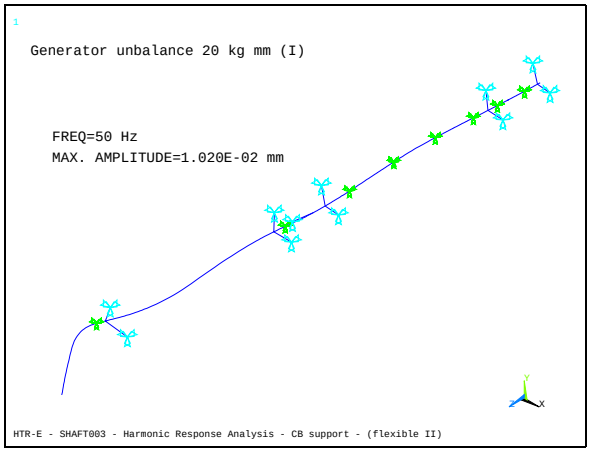


figure 32 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)



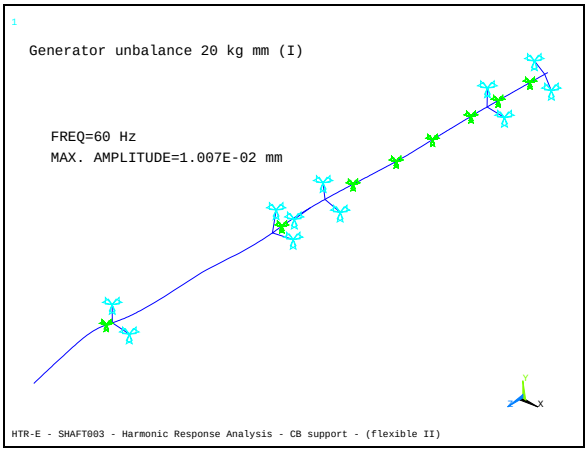


figure 33 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 20 kg mm in the generator (I)

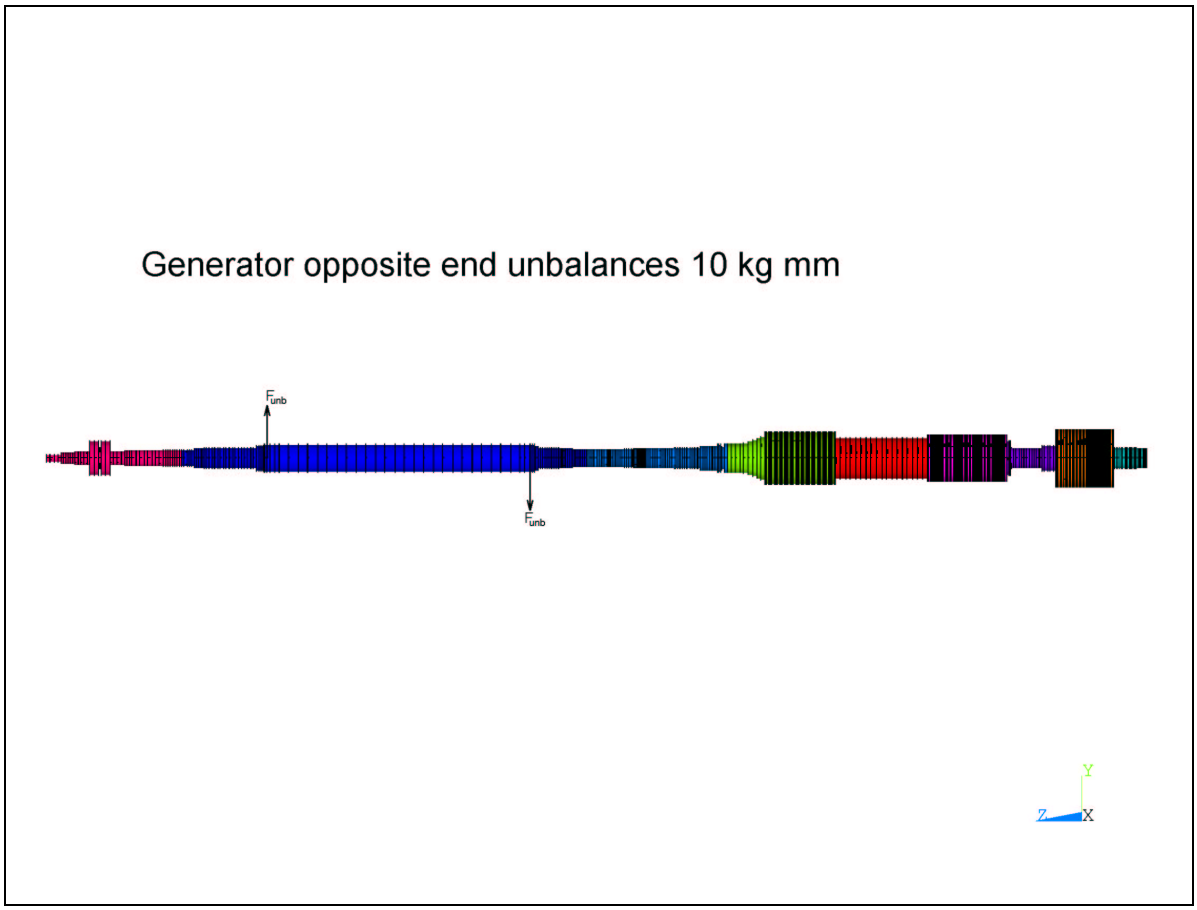


figure 34 Harmonic Response Analysis
Opposite end unbalances of 10 kg mm in the generator

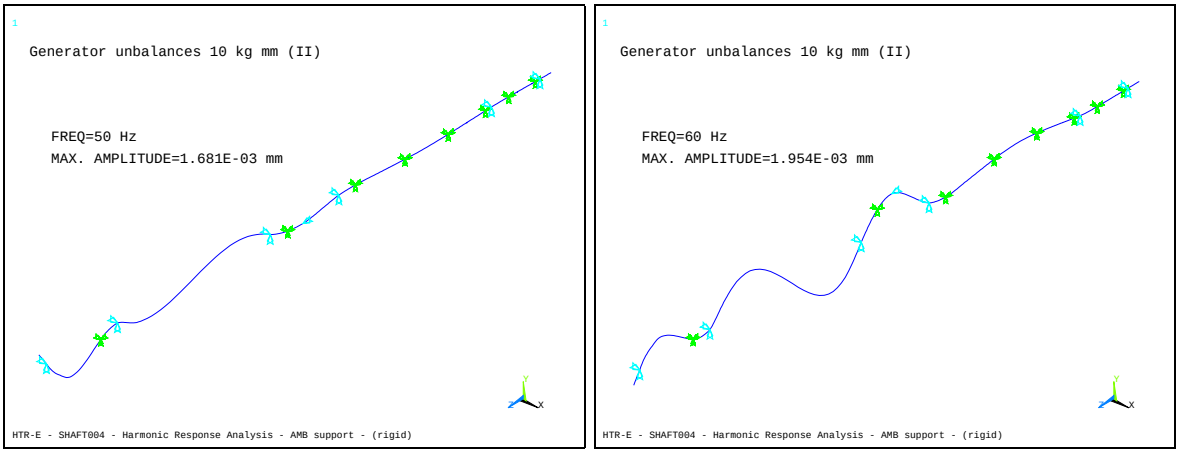


figure 35 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)

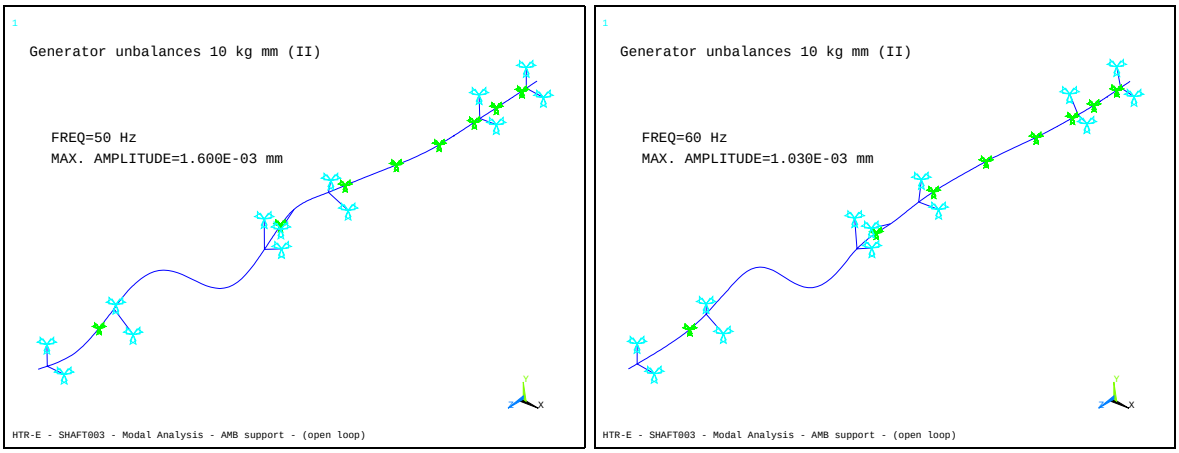


figure 36 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)

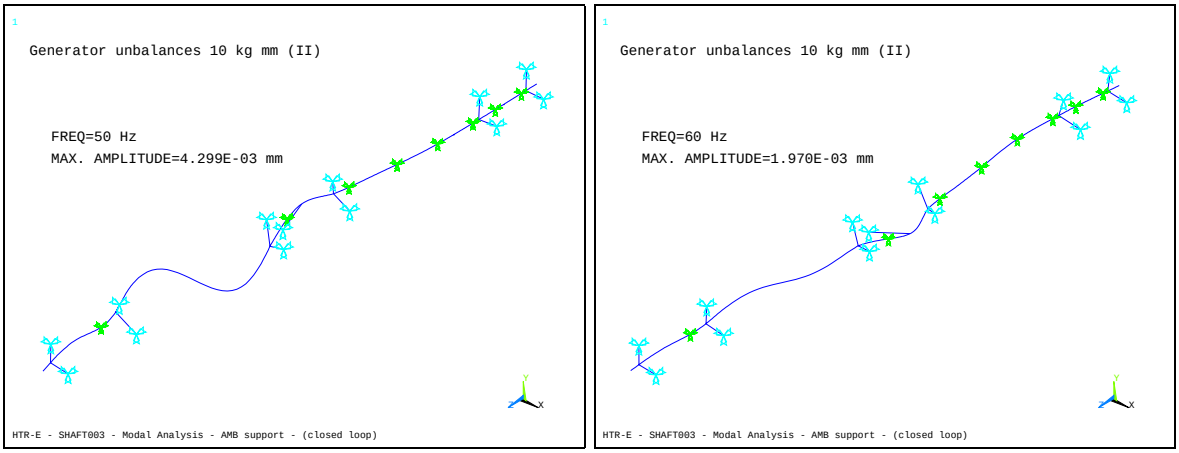
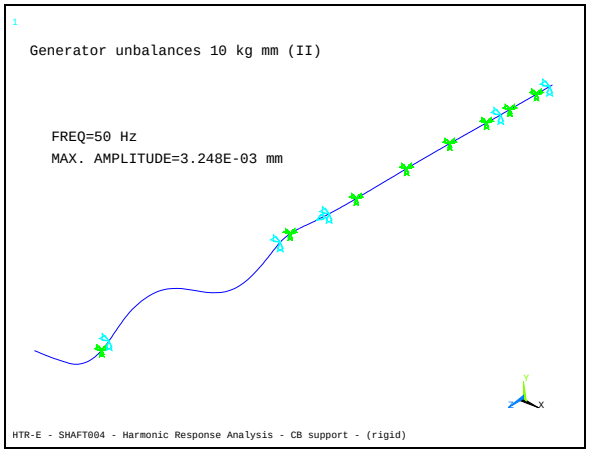


figure 37 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)



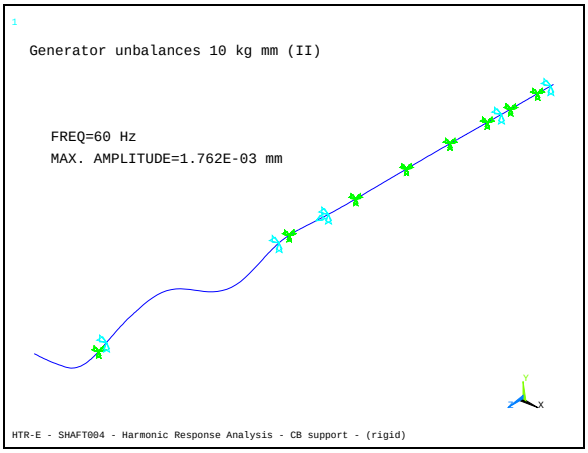
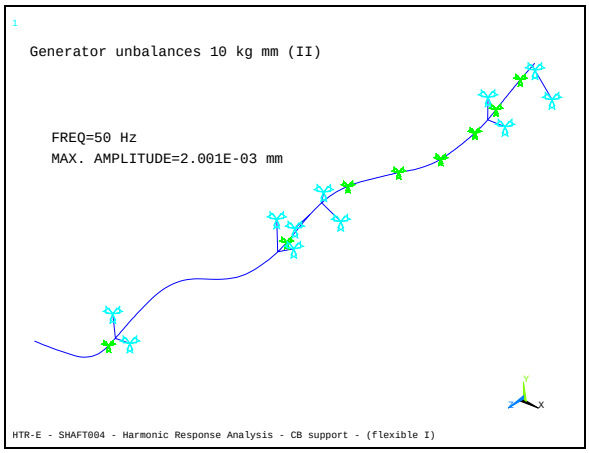


figure 38 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)



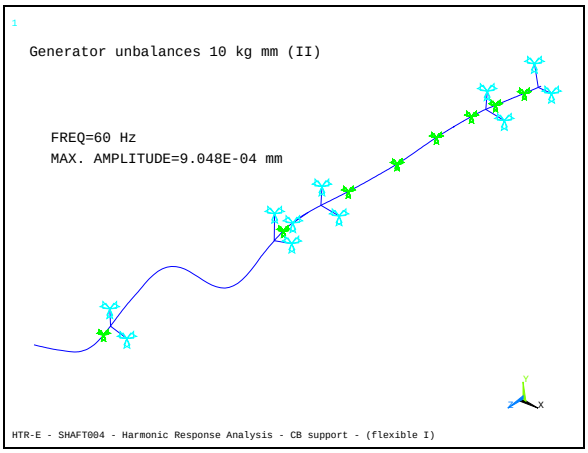
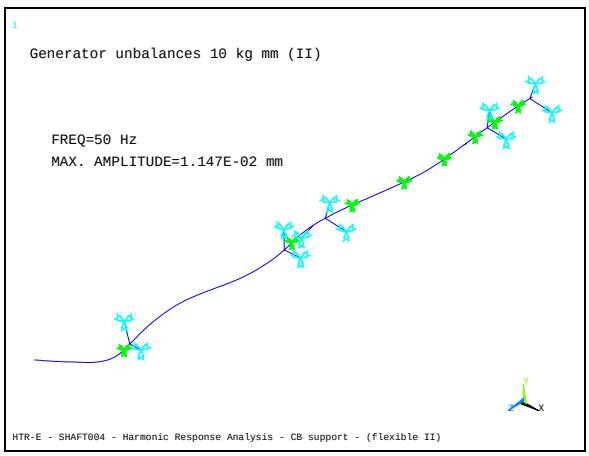


figure 39 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)



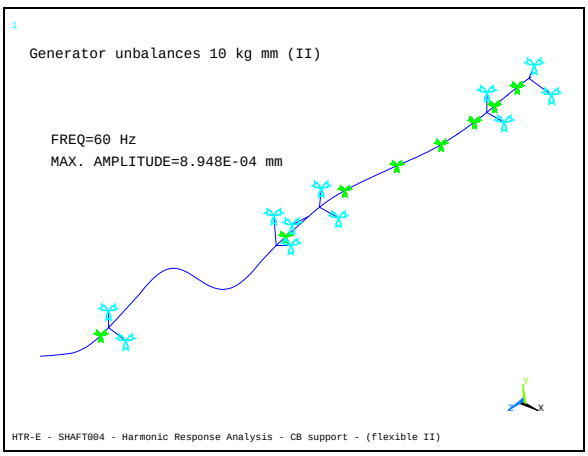


figure 40 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with opposite end unbalances of 10 kg mm in the generator (II)

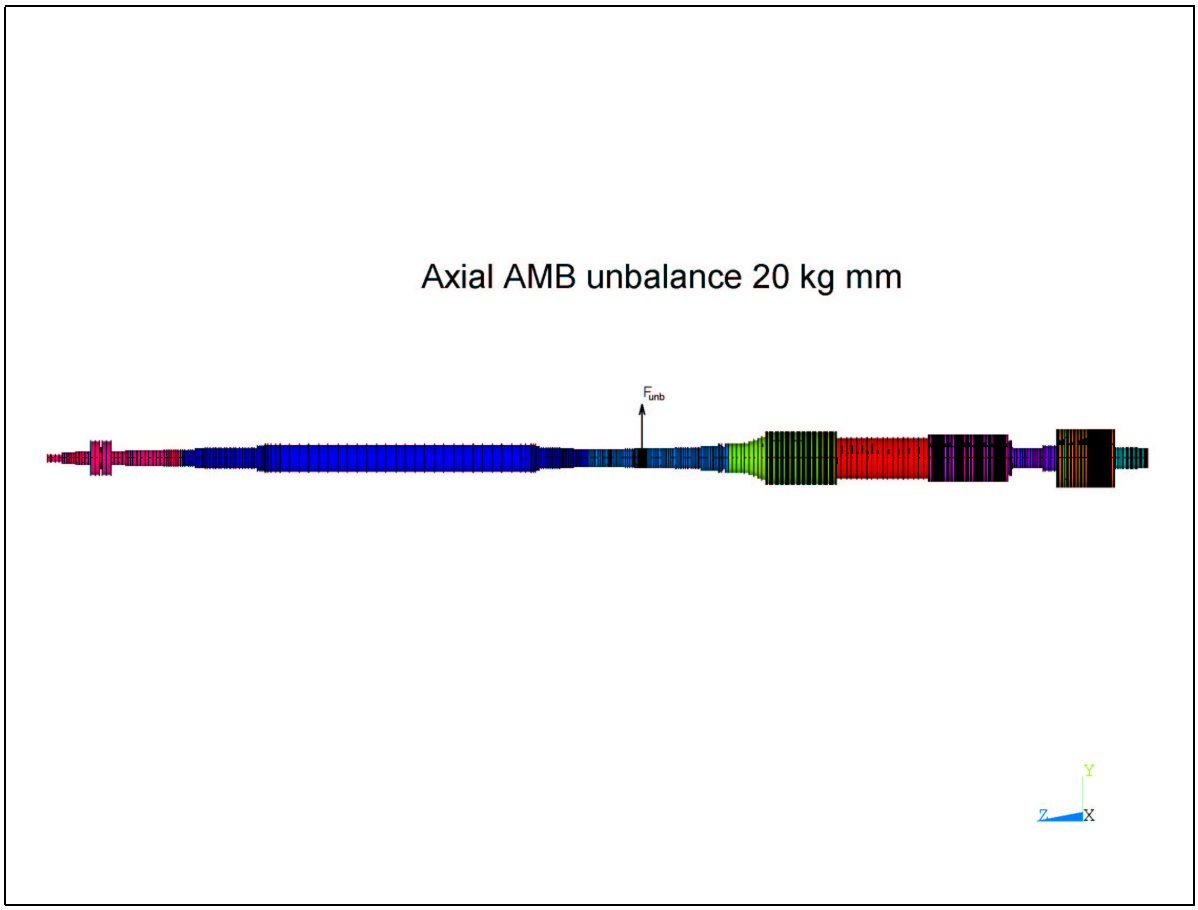


figure 41 Harmonic Response Analysis
Unbalance of 20 kg mm in the disk of the axial AMB

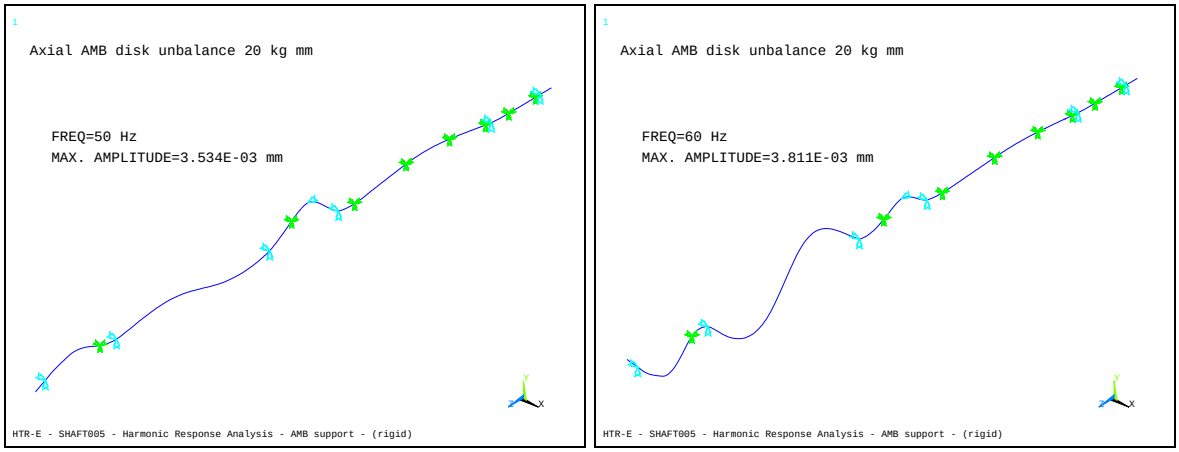


figure 42 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

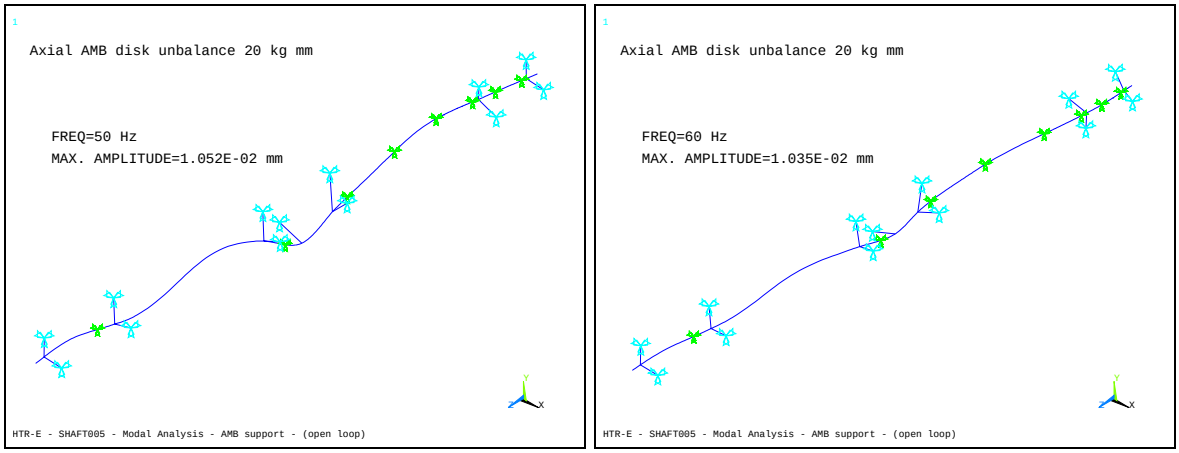


figure 43 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

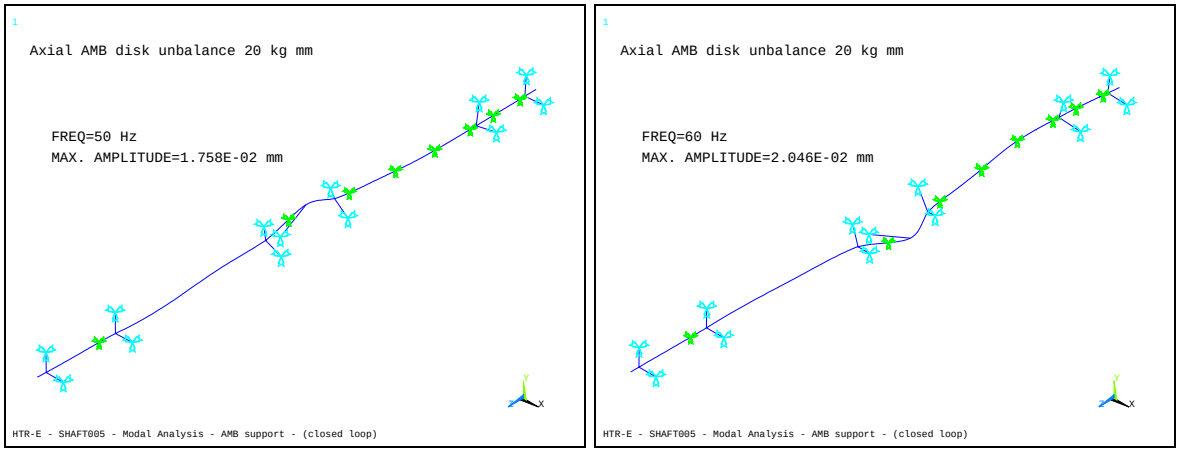


figure 44 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

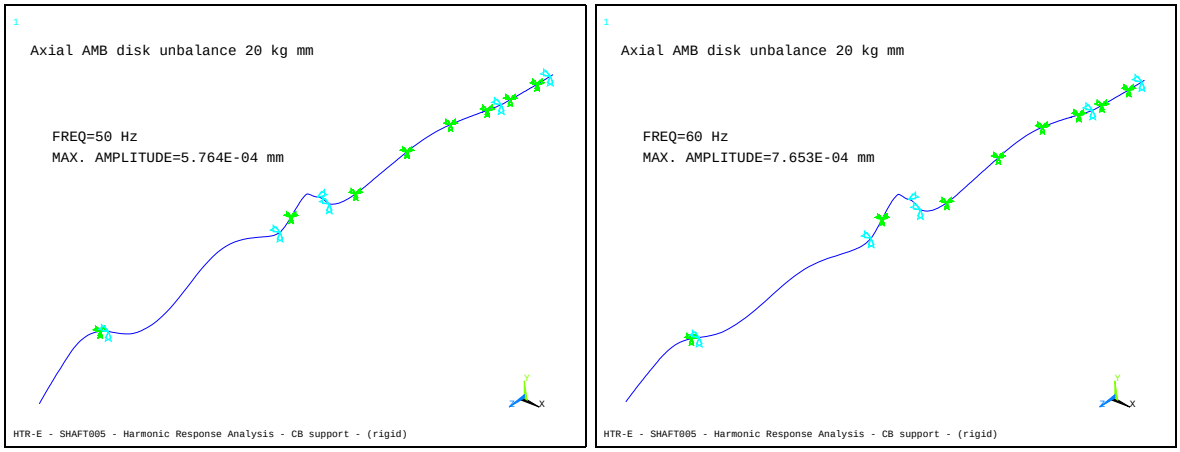


figure 45 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

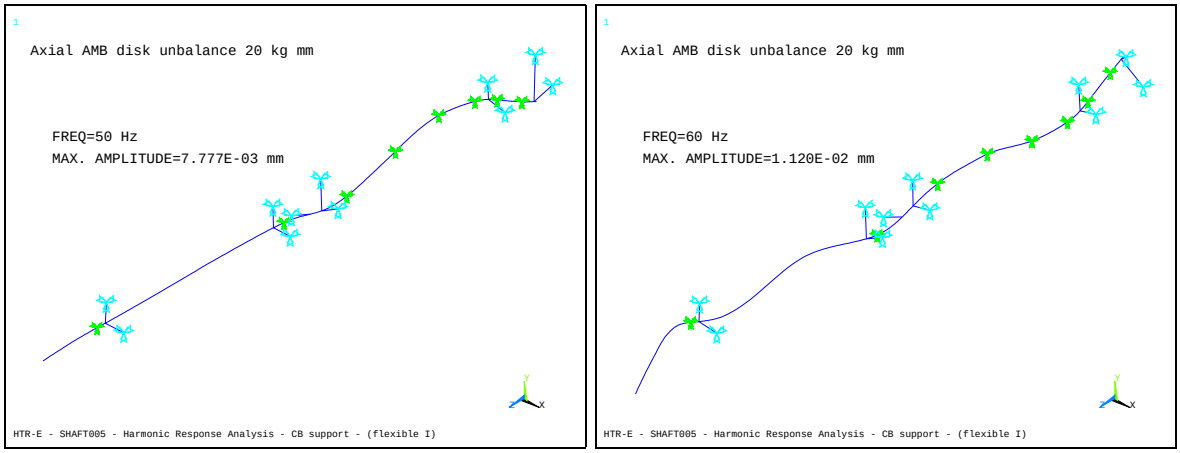


figure 46 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

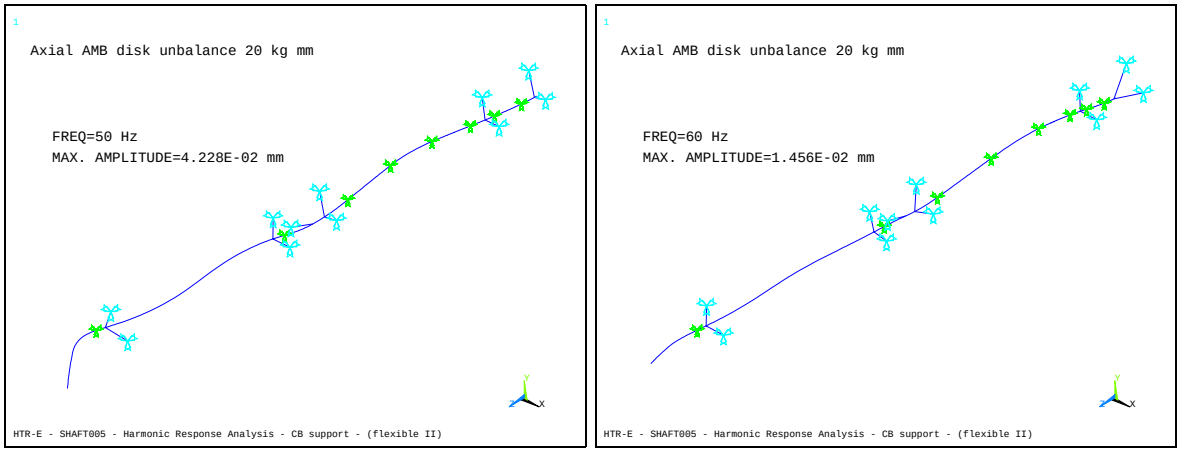


figure 47 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the disk of the axial AMB

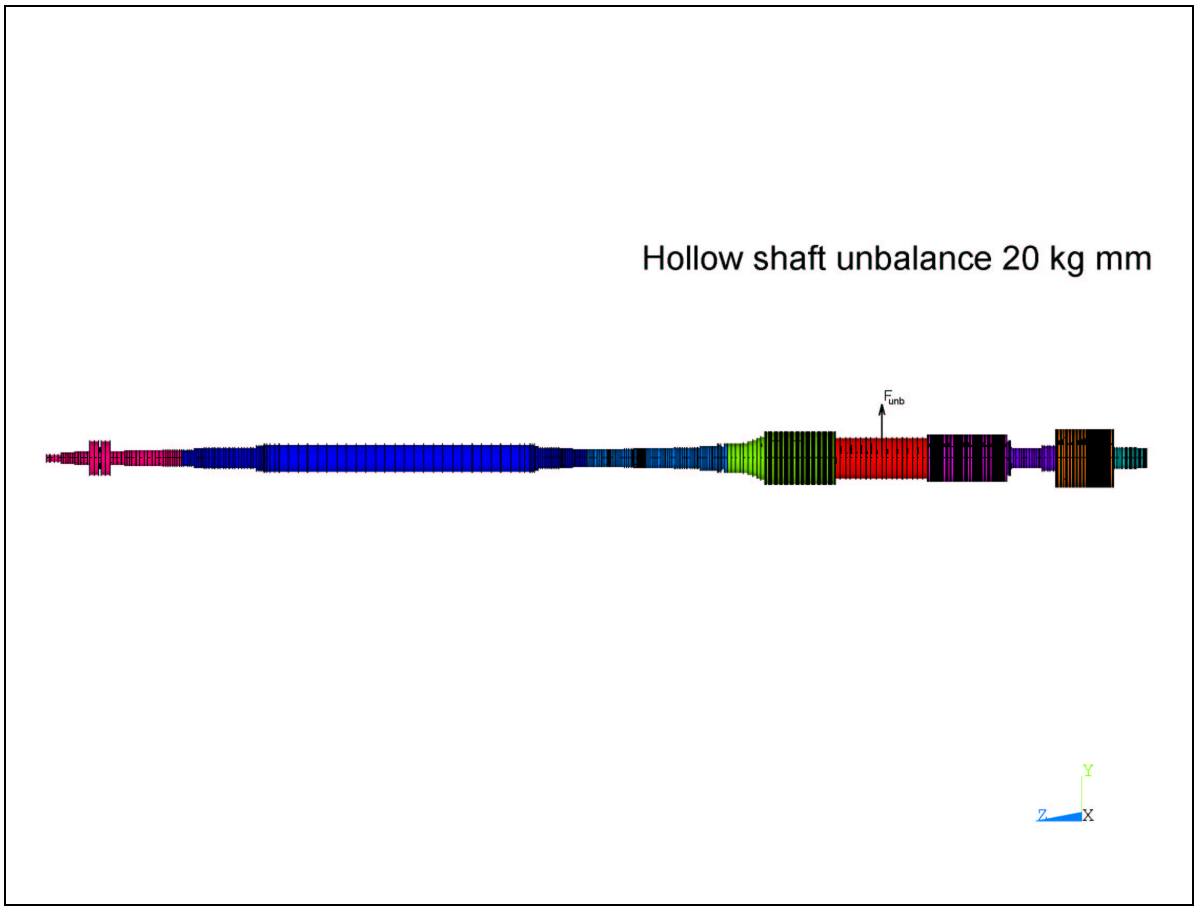


figure 48 Harmonic Response Analysis
Unbalance of 20 kg mm in the hollow shaft

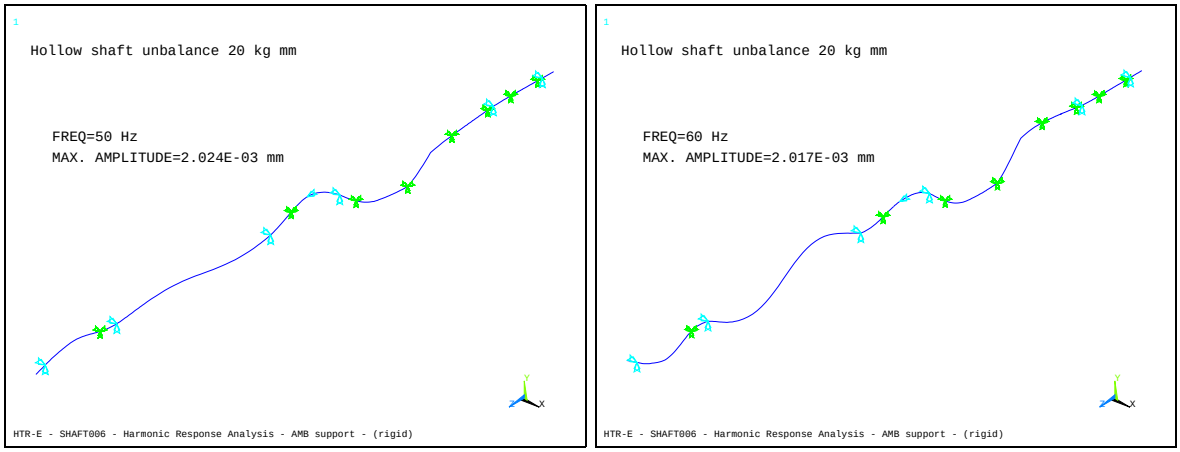


figure 49 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

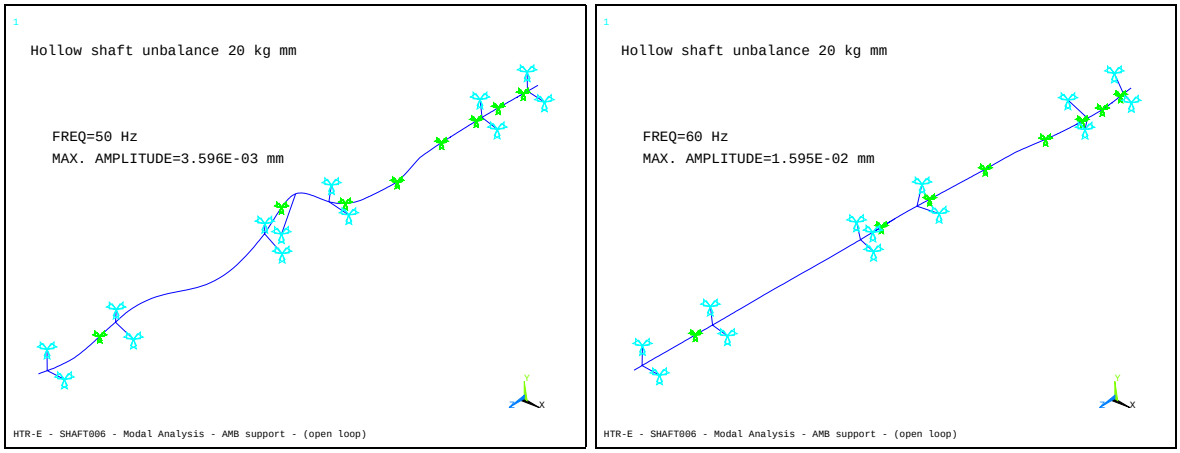


figure 50 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

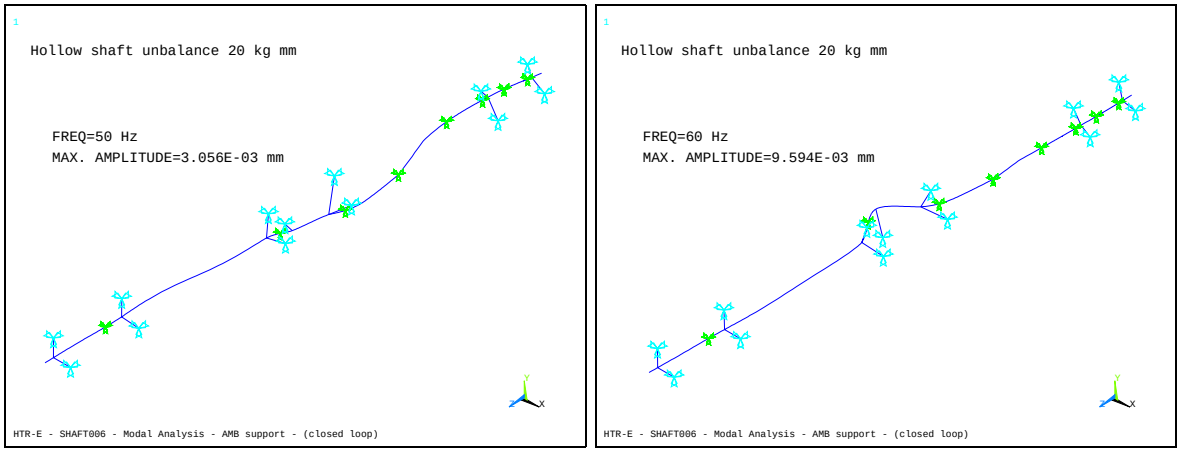


figure 51 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

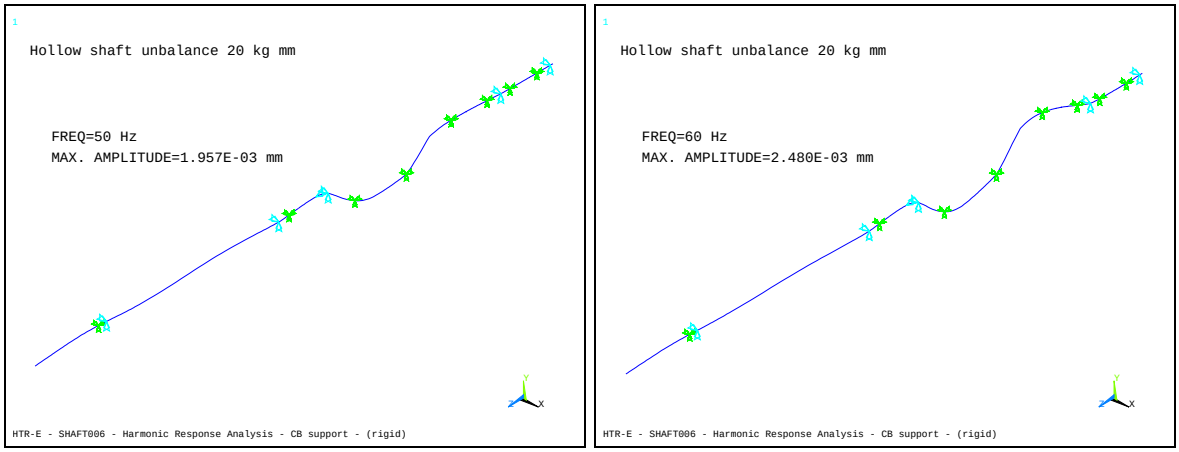


figure 52 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

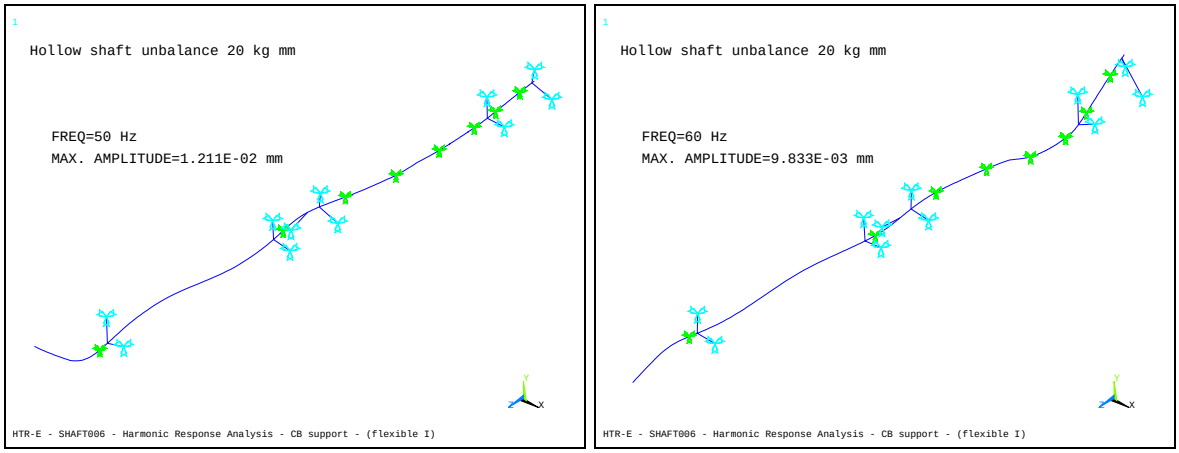


figure 53 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

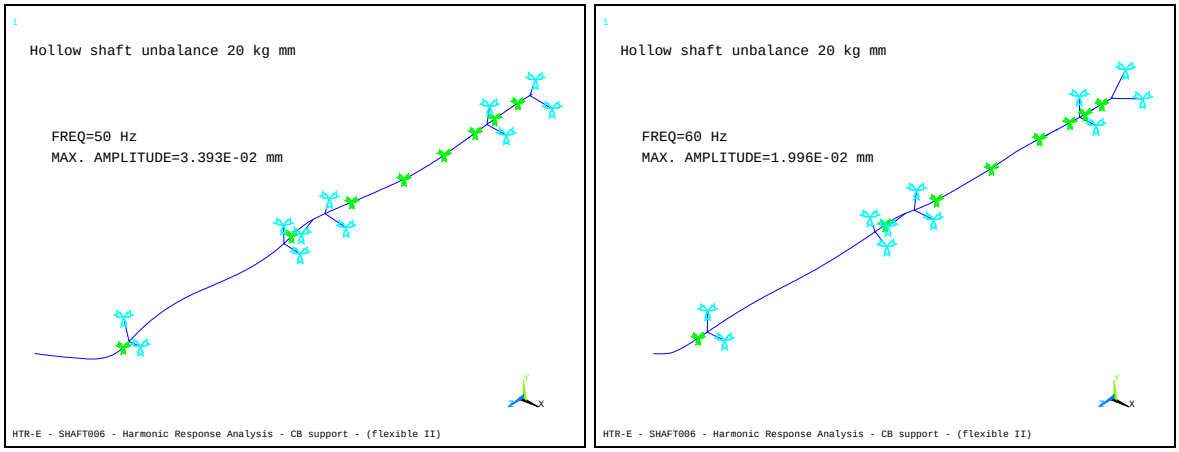


figure 54 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with unbalance of 20 kg mm in the hollow shaft

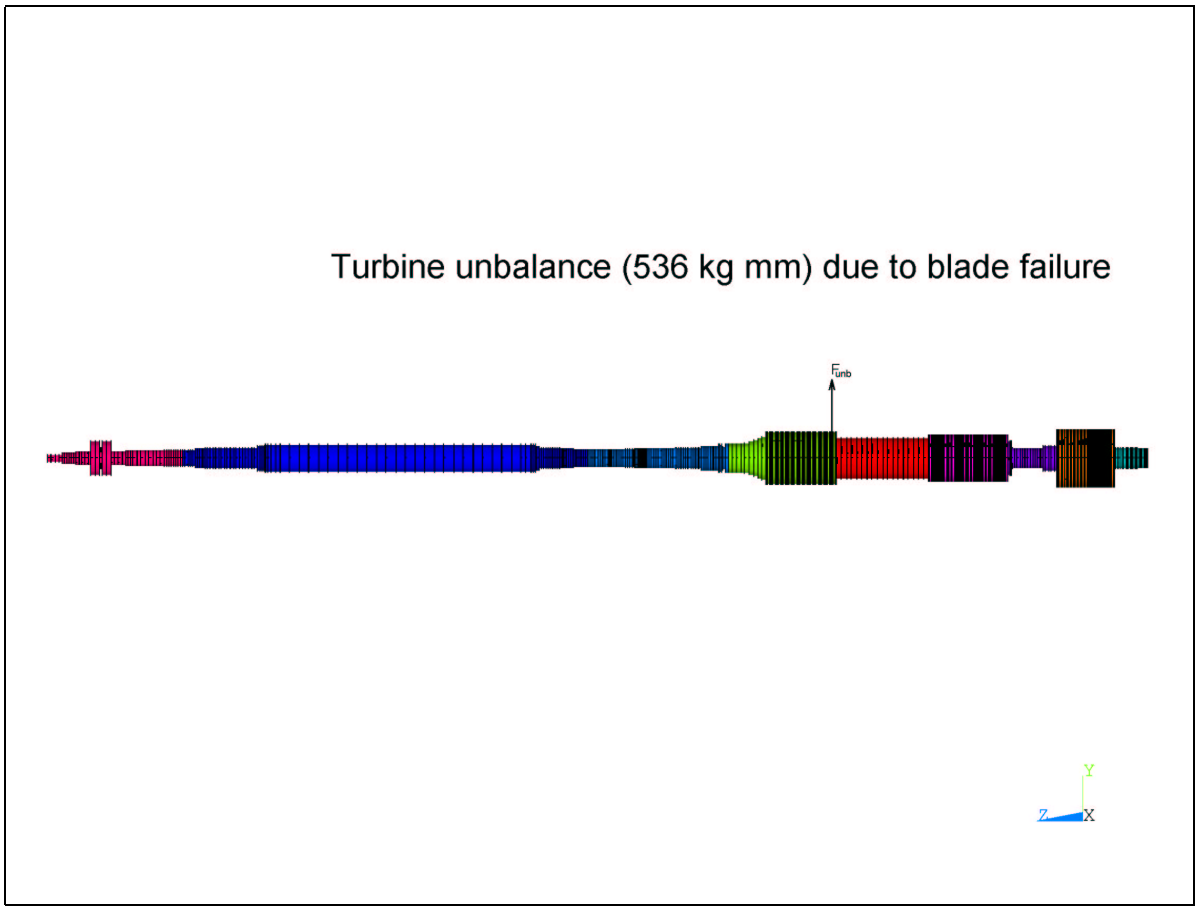


figure 55 Harmonic Response Analysis
Unbalance of 536 kg mm in the turbine

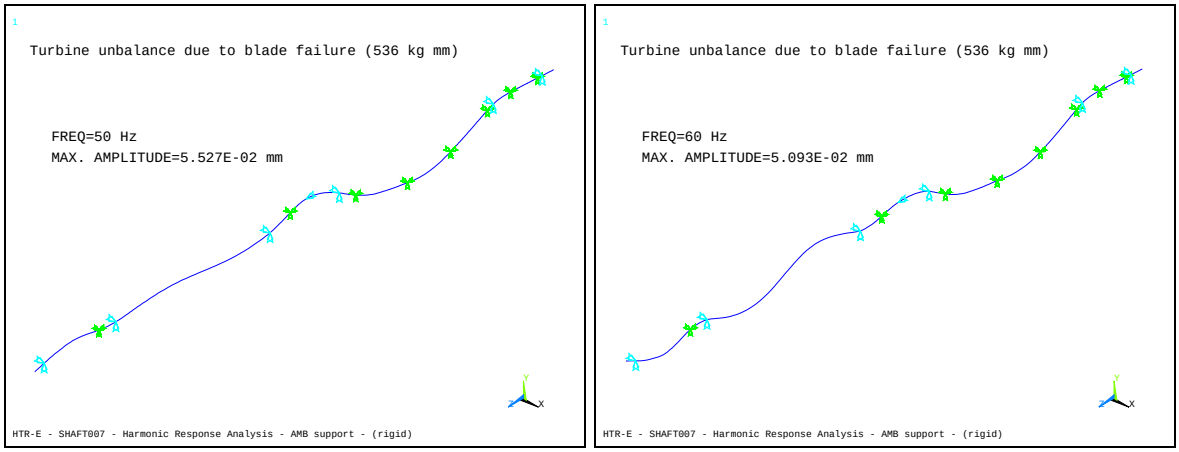


figure 56 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

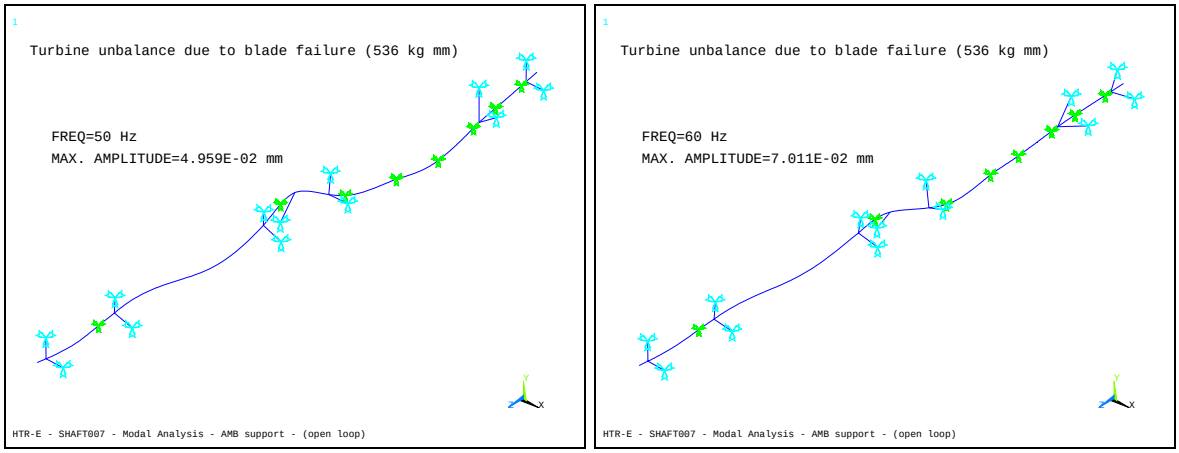


figure 57 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

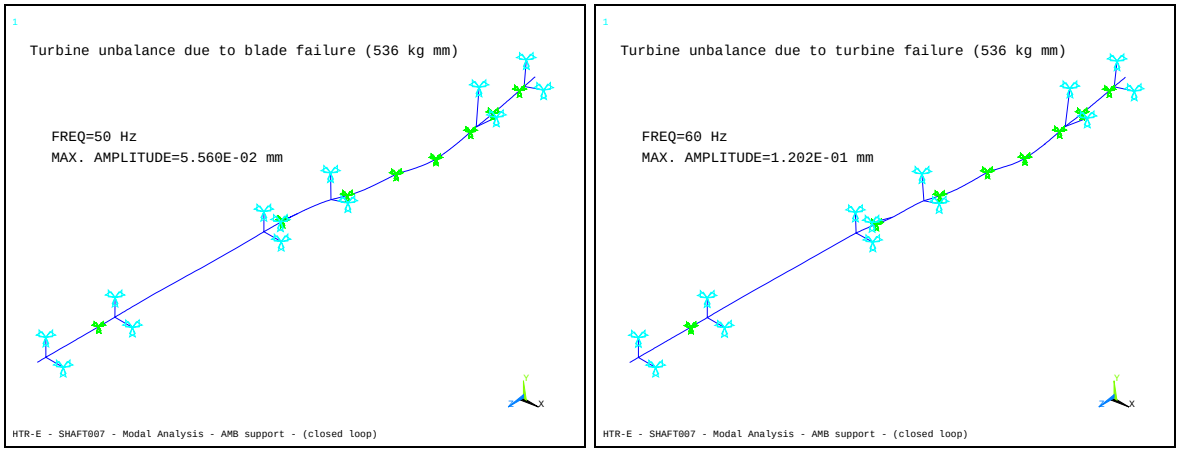


figure 58 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

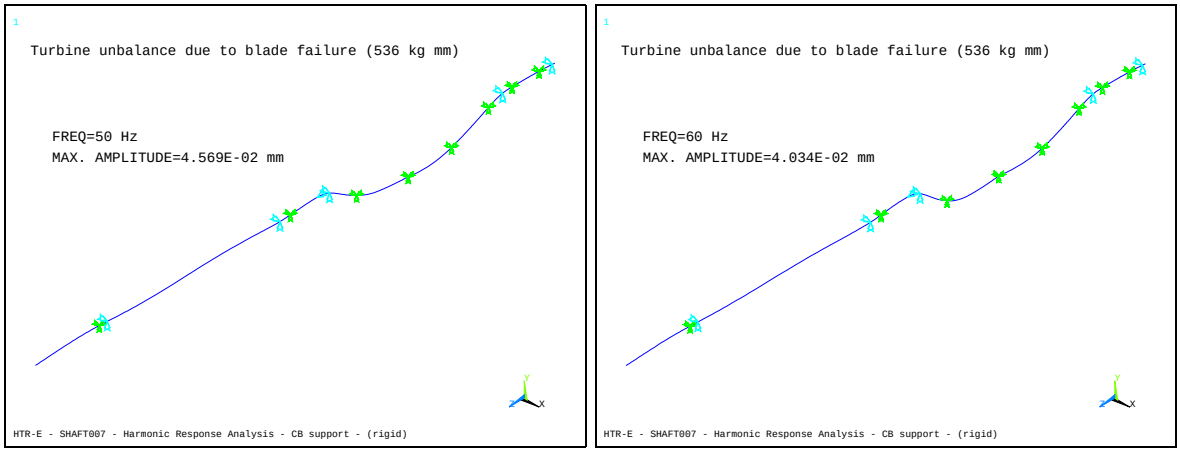


figure 59 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

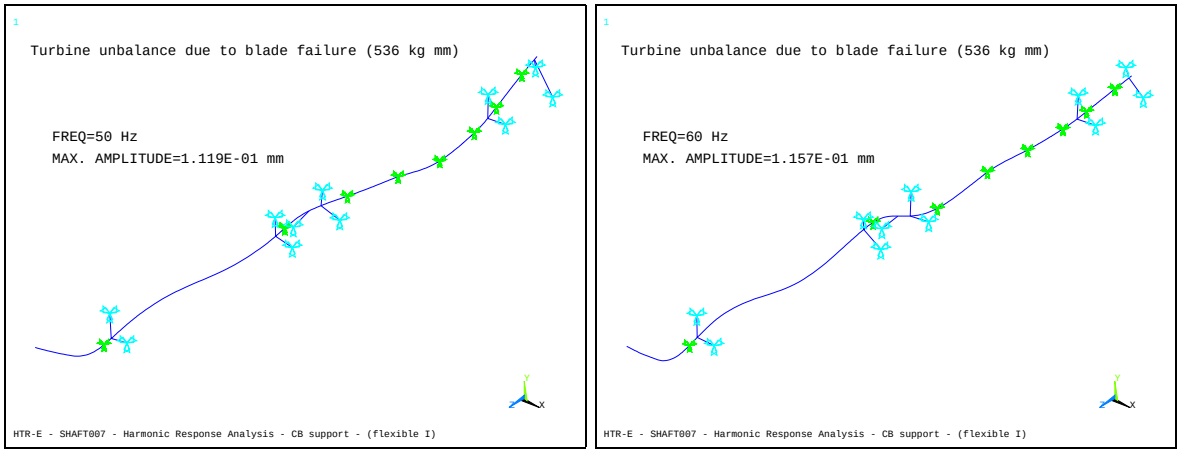


figure 60 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

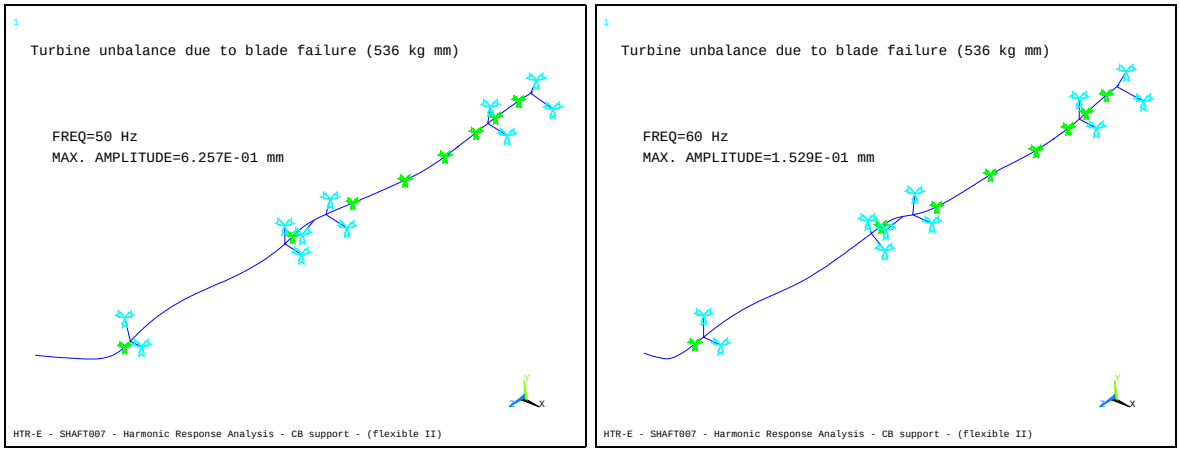


figure 61 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 536 kg mm in the turbine

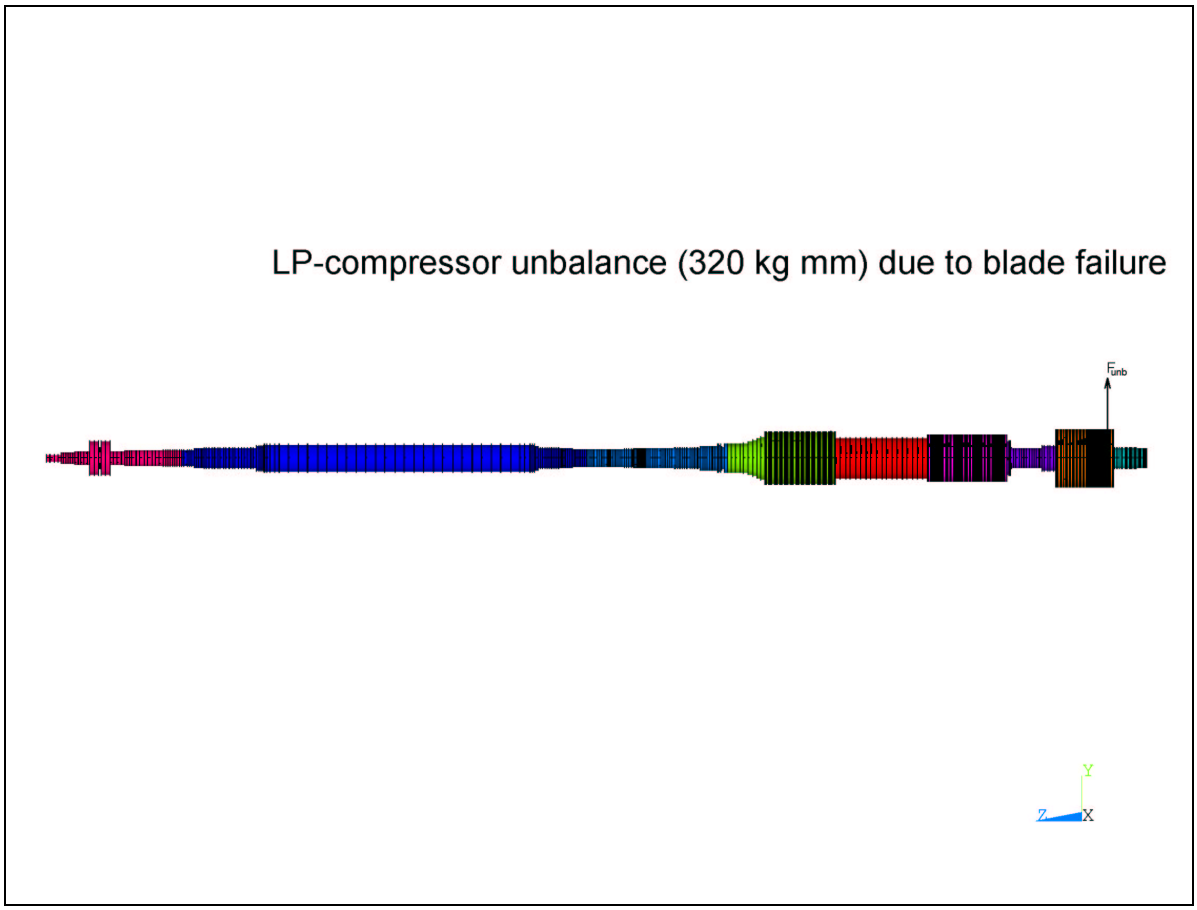
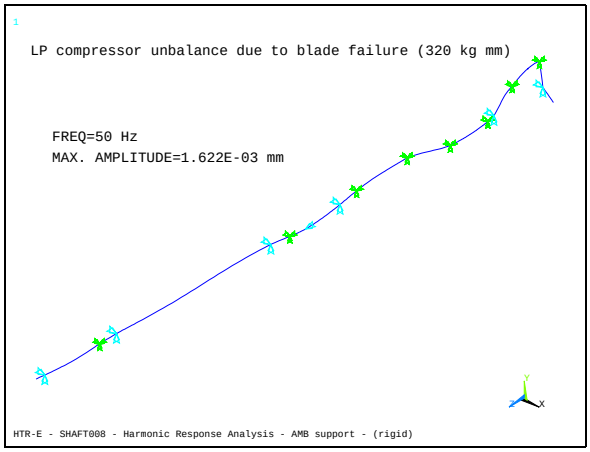


figure 62 Harmonic Response Analysis
Unbalance of 320 kg mm in the LP-compressor



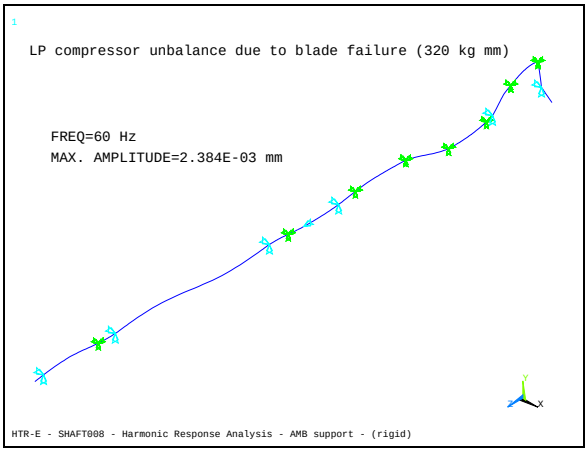
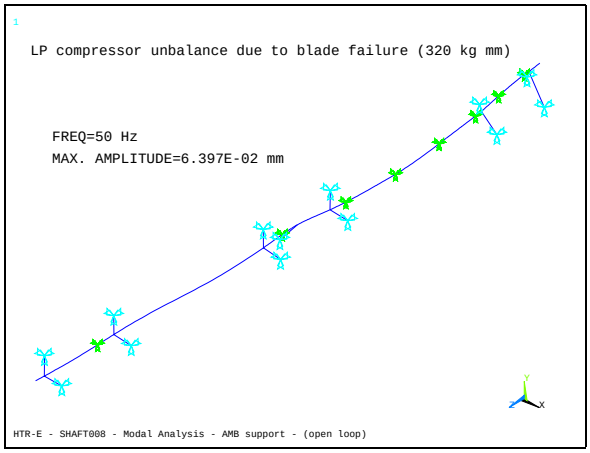


figure 63 Harmonic Response Analysis - AMB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor



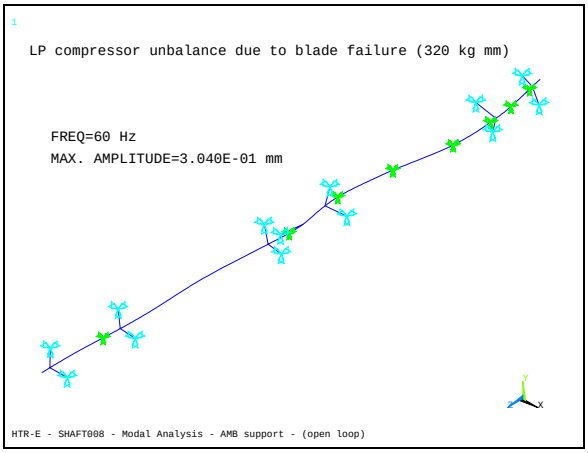
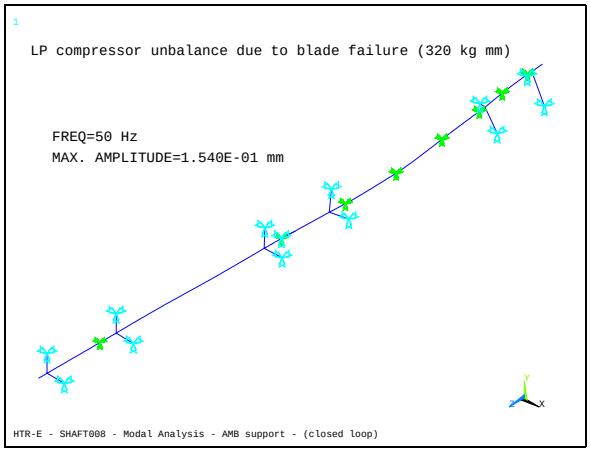


figure 64 Harmonic Response Analysis - AMB support (open loop)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor



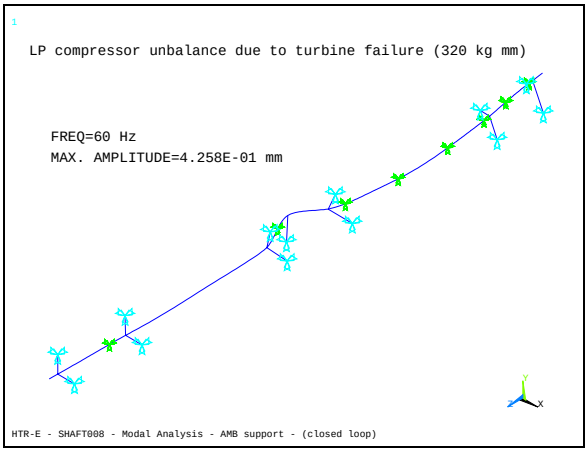


figure 65 Harmonic Response Analysis - AMB support (closed loop)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor

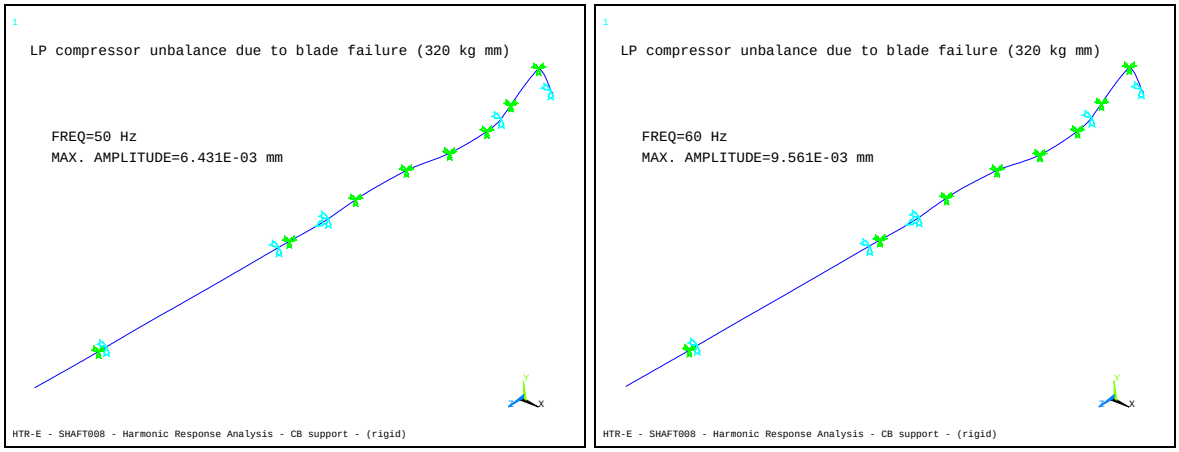


figure 66 Harmonic Response Analysis - CB support (rigid)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor

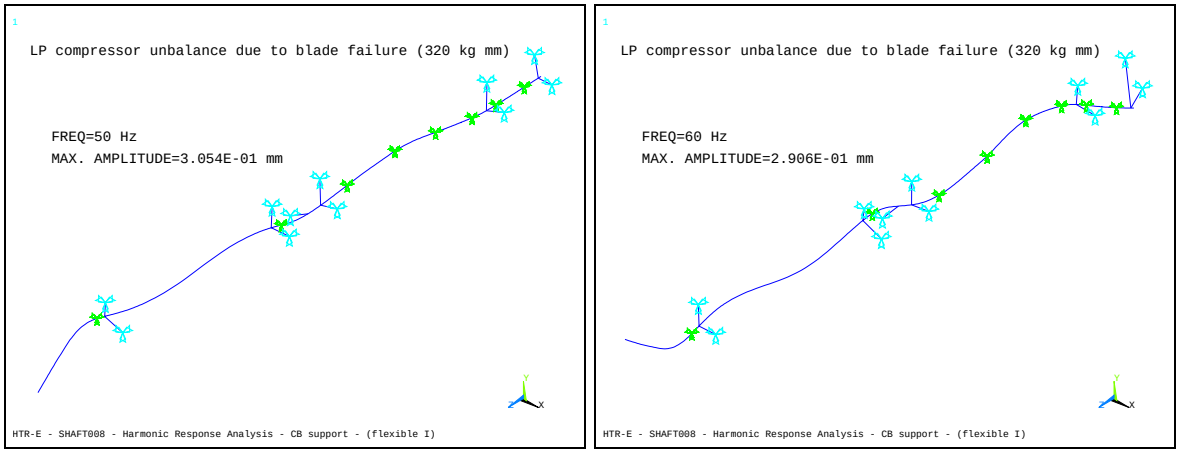


figure 67 Harmonic Response Analysis - CB support (flexible I)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor

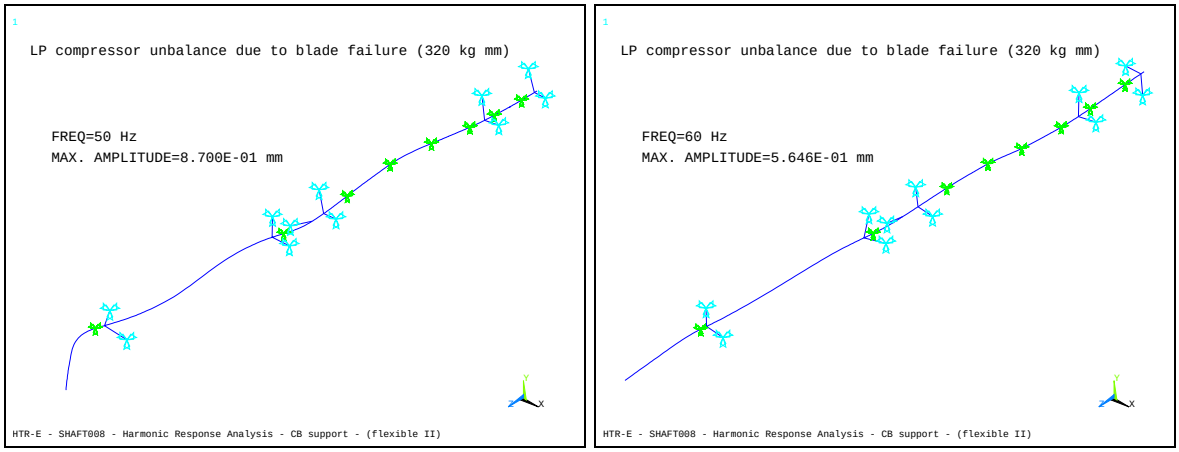


figure 68 Harmonic Response Analysis - CB support (flexible II)
Response at 3000 and 3600 rpm with an unbalance of 320 kg mm in the LP-compressor