MODAL ANALYSIS OF THE XFEL 1.3 GHz CAVITY AND CRYOMODULE MAIN COMPONENTS AND COMPARISON WITH MEASURED DATA

S. Barbanotti [†], A. Bellandi, J. Branlard, K. Jensch
DESY, 22607 Hamburg, Germany

Abstract

Future upgrades of the European X-ray Free Electron Laser (EXFEL) [1] may require driving the linac at higher duty factor, possibly extending to Continuous Wave (CW) mode. A R&D program has started at DESY, to prepare for a CW upgrade. Cryomodules are being tested in CW mode in our CryoModule Test Bench (CMTB) to study the performance and main issues for such an operation mode; sensitivity to vibration causing microphonics is one of the main concerns for the CW operation mode.

Therefore a detailed analysis is being performed to evaluate the frequency spectrum of the EXFEL cryomodule main components: the cavity itself, the cavity string, the cold mass and the vacuum vessel. Finite Element Modal Analyses have been performed and the results compared with data measured at the CMTB. This paper summarizes the main results and conclusions of such a study.

INTRODUCTION

The EXFEL linac operates nominally at 17.5 GeV in a burst mode with up to 2700 bunches within a 0.65 ms long bunch train and 10 Hz repetition rate. A possible upgrade of the EXFEL linac to CW or LP (long pulse) modes holds a great potential for a further improvement of X-ray FEL user operation.

One of the main modifications needed for a CW upgrade of the linac is the exchange of the first 17 accelerator modules with new ones designed for operation in CW mode at a relatively high gradient (up to 16 MV/m).

Figure 1: EXFEL cryomodules at DESY Hamburg.

The new CW design of the cryomodules will have to allow for bigger heat extraction from the helium bath surrounding the accelerating cavities (i.e. a larger 2-phase pipe), adequate cooling capability during cool down of the cryomodule and good isolation against vibration-induced microphonics.

The sensitivity of the components to external excitement strongly depends on the eigenmodes of the structure, therefore we decided, as first step in the R&D work on CW cryomodules, to perform a detailed study of the EXFEL cryomodules.

Vibrations in a cryomodule can have many different sources and are strongly dependent on the environment where the components are installed.

The next paragraphs describe the modal analysis performed on a standard EXFEL cryomodule design (Figure 1) to identify the main eigenmodes of the different components and the comparison of the calculated values against the ones measured on a real cavity or cryomodule.

Figure 2: EXFEL cavity.

ANALYSED COMPONENTS

An EXFEL cryomodule is a complex assembly of many components; a finite element modal analysis of the whole cryomodule would require a very powerful computing machine and would not deliver clear results. Therefore we decided to study its main components individually: the accelerating cavity, the cold mass with string and the vacuum vessel.

Cavity

The EXFEL cavity is a 9-cell Niobium Tesla-type cavity with two HOM (High Order Mode), one pick up and one coupler port. The cavity is integrated in a titanium tank and a cryomodule contains eight cavities connected via stainless steel bellows [2].

Figure 3: EXFEL cold mass with string at CEA Saclay

For the modal analysis we considered the "naked" cavity (no tank) without ports (only the opening remained, Figure 2).

Cold Mass with Cavity String

The GRP is also the main support for all the pipes running inside the cryomodule and the two thermal shields (Figure 3).

[†] serena.barbanotti@desy.de

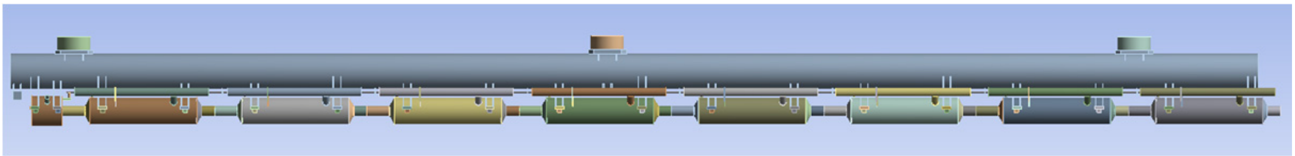

Figure 4: The GRP with string.

The GRP is supported at three positions by the vacuum vessel. The middle support is fixed, while the two lateral ones are free to slide longitudinally, to avoid damages due to thermal contraction.

In the modal analysis we considered only the GRP itself together with the cavity string (Figure 4).

Vacuum Vessel

The vacuum vessel is the outer shell of the cryomodule. It thermally isolates the inner cold mass from the outside and provides the structural support for the whole assembly.

In the EXFEL linac the vessel is hanging from the ceiling; it is fixed at one point and free to slide longitudinally at the second support.

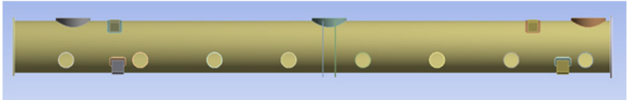

Figure 5: The Vacuum Vessel.

FINITE ELEMENT ANALYSIS

All the finite element analyses were performed with Ansys Workbench; the Modal and Harmonic Response modules were used in their standard configuration. The modal analyses were set up to deliver the first few modes of each assembly. Further details on the harmonic response analysis are summarised in the next paragraphs.

Geometry

The 3D geometric models were imported from the CAD software NX and simplified (example in Figure 5) following some simple rules:

- All fasteners or similar assembly components were removed.
- Holes were closed whenever not necessary for the simulation (holes for screws, pockets …).
- Geometry was simplified if not interfering with the simulation results (for example, flanges were model as simple cylinders, chamfers were removed, …)
- The use of constraints was reduced as much as possible, grouping together components in the geometry model.
- The cavity and vacuum vessel models have only bonded connections. The GRP with cavity string has bonded connection except for the connection between the cavity supports and the GRP (more details in the boundary condition paragraph).

Mesh

The total number of elements and nodes was the limiting factor in the simulation. Therefore, a "sweep" mesh was used wherever possible. Thin elements were used as well, if appropriate. For large and regular components, a mesh sizing of ~30 mm was used. For smaller or more sensitive components, elements of a few millimetres were used as illustrated in Figure 6 and Figure 7 respectively.

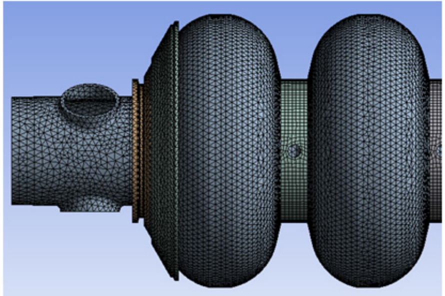

Figure 6: Cavity mesh example.

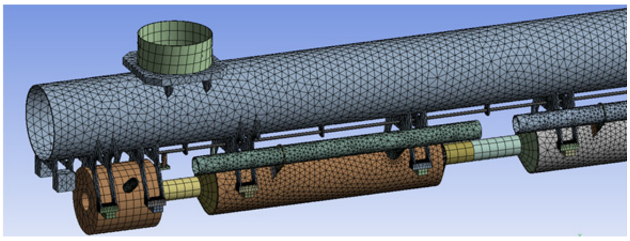

Figure 7: String mesh example.

Table 1 summarises the number of elements and nodes for the different components.

Table 1: Elements and Nodes

Component	Elements	Nodes
Cavity	300.000	640.000
Cold Mass and String	360.000	750.000
Vacuum Vessel	84.000	160.000

Loads and Boundary Conditions

Vacuum Vessel The first component we investigated was the vacuum vessel. The vessel is made of carbon steel, flanges of stainless steel.

The vessel was studied both in the hanging position, as installed in the EXFEL linac, and laying on the floor, as in the test stands. The two configurations showed minimal frequency differences (a few Hz) and very similar mode shapes. Table 2 shows the results for the hanging model.

A preliminary analysis of the vessel included a pre-stressed condition imported from a static structural analysis, to take into account the vessel's own weight and the weight of the cold mass distributed on the three upper openings. The difference in the results between the simulation with and without the pre-stressed condition was so small (in the range of 0.1 Hz) that we decided to neglect it for further analyses.

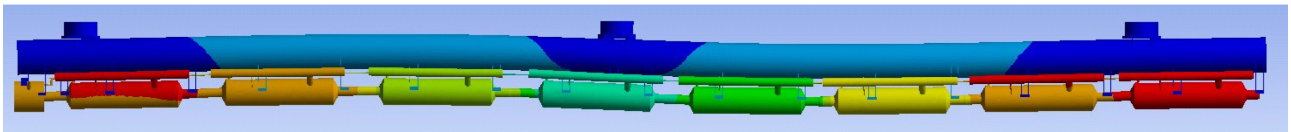

Figure 8: The first mode of the cold mass with string.

Cavity The cavity was modelled without tank or ports. The end rings are the fixed points (red arrows in Figure 9).

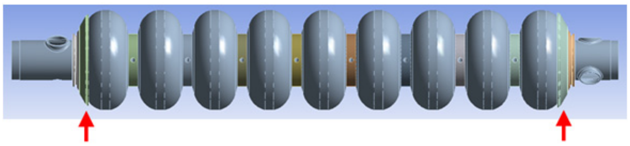

Figure 9: Cavity fixed points.

The cavity is made of Niobium, while the end rings are NbTi (to allow welding to the titanium tank).

The model included a pre-stressed condition imported from a static structural analysis, to take into account the cavity own weight.

Cold Mass with Cavity String

The model of the cold mass with cavity string is slightly more complicated since it has to:

- take into account the longitudinal freedom of movement of the two upper lateral supports;
- allow the cavity supports to slide longitudinally along the GRP pipe, but to follow the movement of the GRP in the horizontal and vertical direction;
- weakly connect the ends of the cavities (to simulate the inter-cavity bellows).

The first requirement was easily satisfied using a “displacement” boundary condition, fixing the displacement to zero in the lateral and vertical direction only.

The second one was fulfilled by coupling the degrees of freedom between cavities and GRP supports, forcing the lateral and vertical points on the supports to move together.

The bellows were simulated as tubes of a very soft material, to simplify the mesh but keep the flexible connection between two consecutive cavities.

Additionally, to reduce the number of elements and nodes, the cavities and the superconducting magnet were simulated as tubes of a material with a very high density, to preserve the component total weight (important in the modal analysis) but simplify the geometry.

Results of the Modal Analyses

Table 2 summarizes the first eigenmodes of the cavity and vacuum vessel; one of the cavity modes is also shown in Figure 10.

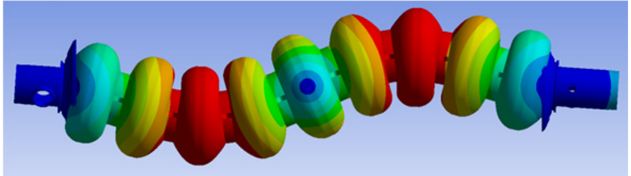

Figure 10: Example of a cavity mode (152Hz).

Table 2: Cavity and Vessel first Eigenmodes (in Hz)

Cavity	Vacuum vessel
59 – 60*	15 (lateral)
150 – 152*	38 (vertical)
202	42 (vertical)
266 – 270*	48 (lateral)
391 – 398*	54 (lateral)
402	56 (vertical)

*(same mode in lateral and vertical direction)

The results for the cold mass with string are listed in Table 3. The first mode is shown in Figure 8: one can observe that the GRP (the big pipe at the top) shows almost no displacement, while the string of eight cavities and the magnet independently moves in the longitudinal direction. This is exactly the movement we wanted to allow using the coupled degree of freedoms.

Table 3: Cold Mass with String first Eigenmodes (in Hz)

Cold mass with string	Direction
22	longitudinal (string only)
25	lateral
27	lateral
27	longitudinal (string only)
32	vertical
40	lateral (quad only)
41	vertical
54	longitudinal (string only)
58	longitudinal (string only)
62	lateral

Harmonic Response Analyses

A harmonic response analysis was performed on the cavity and the vacuum vessel. For the cavity, a vertical and longitudinal force of 10 N was alternatively used as input load; the input load was simulated as a sinusoidal load with a frequency varying from 0 to 800 Hz. For the vessel the input load was as well a force of 10 N applied on the middle opening, either vertically or laterally, but the frequency sweep was limited to 400 Hz.

A damping factor of 1% was used in all simulations to reduce the amplification of oscillations matching a natural frequency of the system.

The cavity frequency response to the longitudinal and vertical load is shown in Figure 11. The red solid line is the lateral response at the central stiffening ring, while the light blue dashed is the longitudinal response at the NbTi ring (the red arrow in Figure 9).

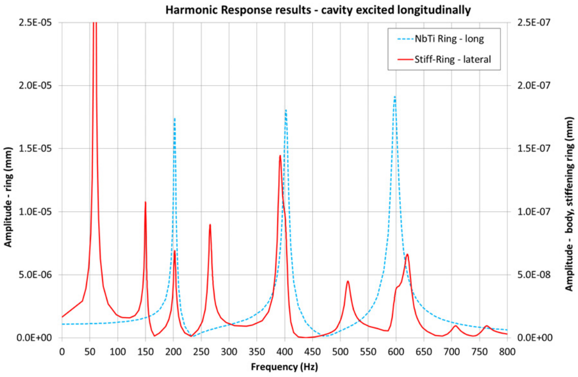

Figure 11: Cavity response to a longitudinal load.

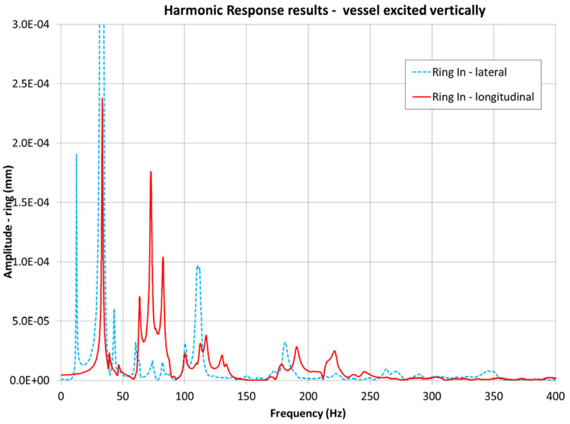

Figure 12: Vessel frequency response to a vertical load.

Figure 12 shows the same results for the vacuum vessel. Here the load is applied at the central post and the frequency response displayed at the big flange at the cavity one side of the vessel.

COMPARISON WITH MEASUREMENTS

Some studies have been performed to measure the vibrations on a cryomodule and cavities during linac operation or on a test stand and therefore some of the calculated data can be compared with measured ones.

First Measurements on a Single Cavity

One of the first studies on the resonance frequencies of a single cavity were performed by T. Schilcher in his PhD Thesis [3]. A cavity fixed at its extremities was excited with sound waves from a loudspeaker while a piezoelectric crystal measured the response of the cavity. The first measured resonance frequencies were found at 96, 175, 239 and 281 Hz (the strongest being the 175 Hz). We can find some similitudes with the data we simulated, but the comparison stops there due to the evolution of the cavity design since these firsts measurements.

Measurements on a Vacuum Vessel with String

In spring 2019 we performed a series of “hammering tests” on an EXFEL cryomodule. Using a hammer weighting 1 kg we hit the vessel at different places and recorded the induced acceleration at different positions with three tri-axial piezoelectric accelerometers (Slam-Stick Shock & Vibration Accelerometer Loggers from Mide’ [4], Figure 13).

Figure 13: “Hammering test” tools.

The test was performed both on a fully assembled cryomodule and on an empty vessel with cold mass. The sensors were positioned on the vacuum vessel either at the post openings or at the big flanges at the ends. Figure 14 shows the typical hit response in the time domain, measured on the vessel. The ringing is rapidly absorbed with a time constant of 250 msec.

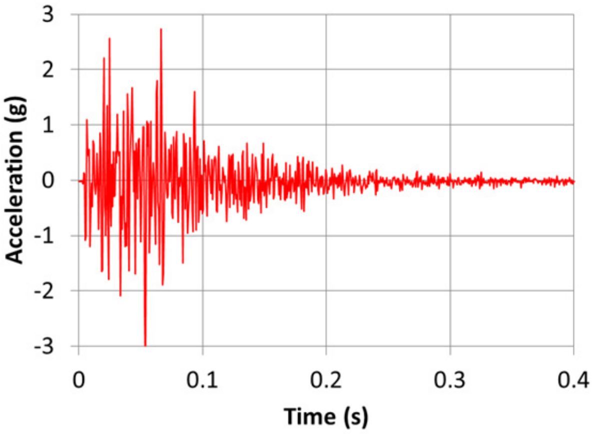

Figure 14: Typical acceleration values.

The first series of tests was devoted to assessing which direction of the hits (vertical, longitudinal and transverse) coupled the most to the sensor’s three directions (x,y,z). Every effort was taken to provide hits of consistent strength and momentum, regardless of the direction. The test was repeated several times in an attempt to average out inaccuracies inherent to this approach. Lateral and vertical responses usually showed similar profile. This first test also confirmed that a hit in the vicinity of the sensor can saturate the readings (total sensor range +/- 16 g). Further studies will require special care of this aspect.

For the second series of tests, we applied repeated vertical hits (20) in the middle of the vessel and measured the corresponding responses at both ends of the cryomodule. The signal FFTs were averaged to provide a better signal to noise ratio and isolate dominant frequencies. The results in vertical and longitudinal directions are shown in Figure 15.

One should first state that we were not able to draw clear conclusions from these first tests regarding the frequencies that were excited with the hammering.

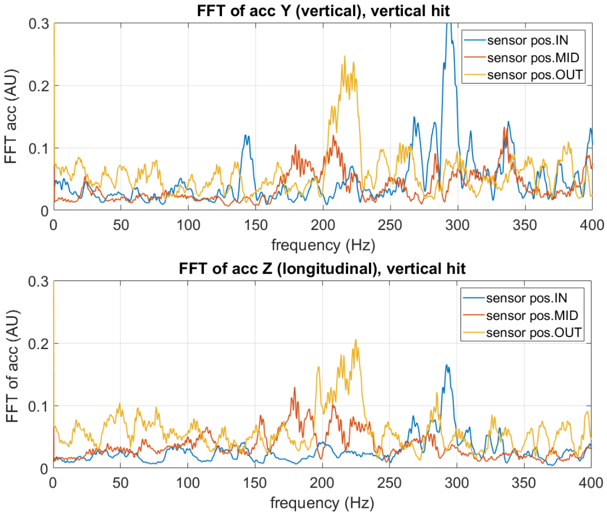

Figure 15: Averaged FFTs

The comparison with the harmonic response simulation results (Figure 12) shows some qualitative similitude in the 200 Hz area, but the peaks in the lower amplitude (40-140 Hz) range are much lower in the experimental data than in the simulation.

Our main conclusion after these tests is that the simulation provides some similitude with the experiment but one cannot conclude to a close match between the two. It could be due to the approximation done in the simulation or it could be due to limiting factors in the experimental set up (maybe not the best sensors for this kind of analysis, maybe the hammer hits are too small a stimulus to allow for a precise analysis of the resonant modes.)

Measurements in the XFEL Linac

A series of tests have been performed in May 2019 on the EXFEL cryomodules installed in the main linac at the RF station A16. For each of the 32 cavities in this RF station, one of the piezos installed in the frequency tuner was used to excite the cavity in the longitudinal direction while the other piezo was used to measure the effect of the excitation.

Piezos were excited with a sinusoidal voltage at different frequencies (200, 300, 400 and 500 Hz for some cavities), but the measured spectra are very consistent regardless of the frequency of the stimulus.

Figure 16 shows the results for all the cavities in the cryomodule A16.M4 (the fourth cryomodule in the RF station A16). The results for the other three cryomodules are very similar. A few frequencies can clearly be recognized on all cavities: 200, 260, 400 and 600 Hz. These frequencies are in very good agreement with the results of the modal simulation and of the harmonic response (Table 2 and Figure 11 respectively).

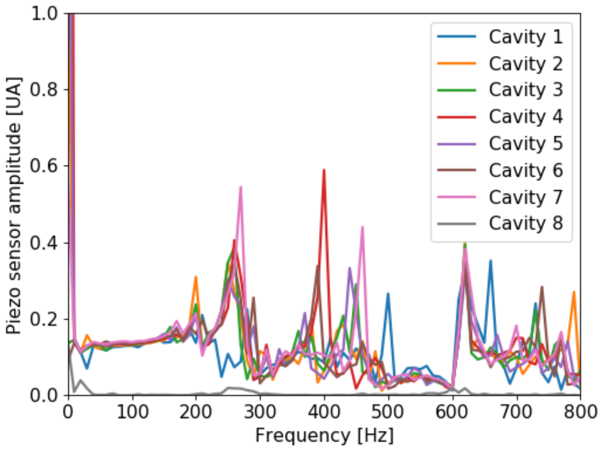

Figure 16: piezo response to a longitudinal load.

CONCLUSION AND OUTLOOK

In an effort to better understand the mechanical behaviour of the EXFEL cryomodule with respect to vibrations, a series of modal and harmonic response analyses have been performed on the cryomodule main components. When possible, simulation results are compared with experimental data.

A few conclusions can be drawn from this work:

- The vacuum vessel measurement didn't show any clear agreement with the simulated data. Some similitudes could be postulated, but no definite conclusions can be drawn. Further studies should be performed with a different set up or instrumentation, to better investigate the harmonic response of the vacuum vessel.
- The cavity analysis shows very good agreement with the measured data. The system is quite small and the boundary conditions well defined, making the simulation adherent to the reality;
- From the cavity measured data we can recognize which frequencies are "picked-up" from the cavity and are relevant for RF operation of the accelerator. Any further design work should keep these frequencies in scope.

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