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MEASUREMENT OF THE VIBRATION RESPONSE OF THE EXFEL RF COUPLER AND COMPARISON WITH SIMULATED DATA (FINITE ELEMENT ANALYSES)

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Abstract

The coupler is one of the main and most sensitive components of the European X-ray Free Electron Laser (EXFEL) superconducting cryomodule.

More than 800 couplers were transported for about 900 km assembled in a cryomodule during the assembly phase of the EXFEL without any visible damage. In another project, a very similar coupler design showed a week point in one of the bellows when transported over a similar distance with a comparable transport set up.

Therefore we decided to further study the coupler behaviour: we investigated the frequency response of the coupler on a vibration table in a controlled environment for different road and loading conditions and compared the data with simulated ones. This paper present the work performed so far and our conclusions.

INTRODUCTION

The EXFEL project has adopted with minor modifications the TTF-3 coupler design (see Figure 1) to power the 1.3 GHz TESLA-style cavities in its linac [1]. These couplers were developed within the TESLA collaboration in the last 30 years to be used for pulsed operation with several hundred kilowatts of input power at a ~ 1% duty factor.

The 800 EXFEL couplers (Figure 1), being the cryomodules assembled at the CEA (Saclay) facility, were transported completely mounted in the cryomodule from the French site to the final test and installation site at DESY Hamburg, a distance of about 900 km.

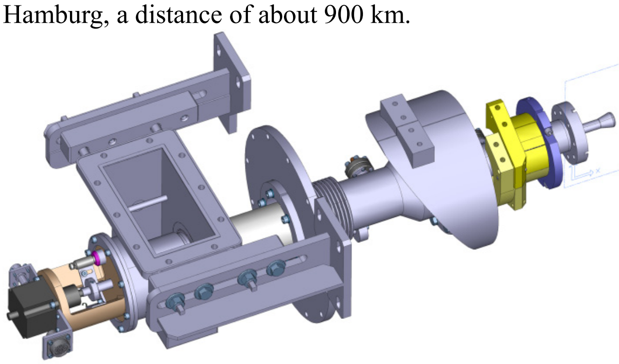

Figure 1: An EXFEL coupler.

None of the couplers were damaged during transport, nor showed transport related problems during test or installation in the linac. The 800 couplers are now in operation since more than 2 years and are working as expected.

However, in another project, TTF-3-like couplers, installed in a very similar condition, were damaged during transport after just a few hundreds of kilometres: one of the inner bellows (at the cold side) became leaky, causing the cavity vacuum to be contaminated. The faulty bellows was in deep investigated, material and production defects were quickly excluded; the design was then investigated: a finite element modal analysis of the whole coupler showed the first eingemode at ~15 Hz. The same frequency was then measured at the transport frame during a test transport of a cryomodule, monitored with vibration loggers. The suspicious is that the vibration of the frame during the long transport resonated with the 15 Hz eingenmode of the coupler and brought it to failure.

Therefore, we decided to further investigate the EXFEL couplers for possible weaknesses in the bellows area.

First of all we performed a modal and a harmonic response analysis of the EXFEL coupler design, to evaluate the eigenmodes of the assembly and its frequency response to external forces for the specific EXFEL system and possible differences with the design of the failed coupler.

Then we extensively tested a coupler at the BFSV Verpackungsinstitut Hamburg GmbH [2]: an accredited test institute that tests packaging according to national and international standards.

FINITE ELEMENT ANALYSIS

The analyses were performed on the “movable” part of the coupler. Figure 2 shows a section of a coupler with on one side the connection to the accelerating cavity (circled in yellow) and on the other the connection to the outer vessel of the cryomodule (circled in red). Thanks to the 2 bellows in-between the 2 connections, the middle part is free to move in the vertical and lateral direction, being the axial direction fixed by the inner antenna.

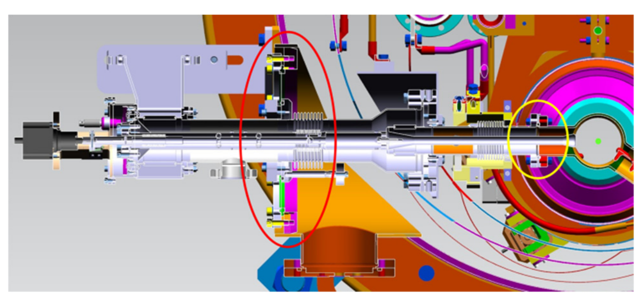

Figure 2: Section of an EXFEL coupler assembled in the cryomodule; in red and yellow the connections to the module (fixed points).

For the simulations, we considered only the part free to move (between the yellow and red circles) since the two “extremes” are fixed to the cryomodule once the coupler is

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fully assembled. The 3D CAD model was simplified removing all unnecessary components, openings, and design details not relevant for the analyses (see Figure 3).

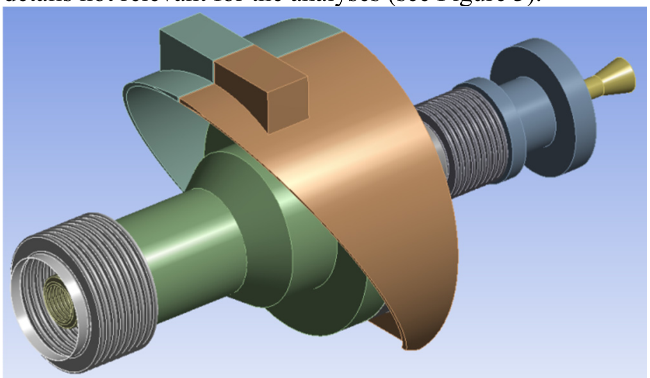

Figure 3: The finite element model.

The simulations were performed with Ansys Workbench. Figure 4 shows as example the mesh of one of the bellows. The overall mesh has 1.060.000 elements and 170.000 nodes.

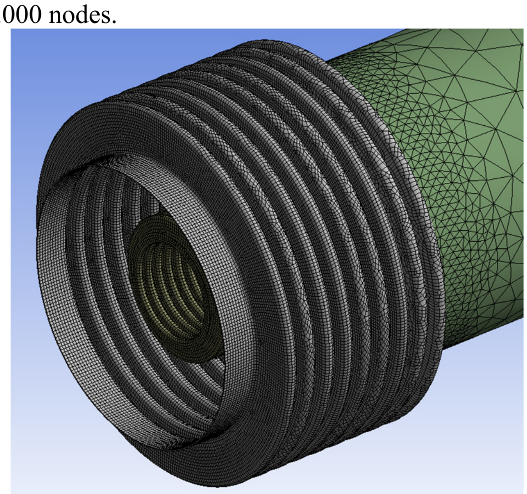

Figure 4: A detail of the mesh.

The model for the modal analysis was fixed at the bellows extremities in all directions (fixed support) while the inner support of the antenna at the warm side was fixed only in the axial direction (to simulate the bayonet connection).

The same mesh and design was also used to perform a pre-stressed modal analysis to take into account the self-weight of the assembly, but the results showed minimal differences (less than 0.1 Hz).

The harmonic response analysis was performed as "mode superposition" analsysis, i.e. using the results of the modal anlysis as input. A lateral force of 10 N at the 80 K interface was the only load applied.

Results

The first eingenmodes of the modal analysis are summarized in Table 1. The first lateral and vertical mode are at ~18 Hz. This mode, relevant for our analysis, is shown in Figure 5.

Figure 6 shows the frequency response of the 80 K interface in the range 0 – 200 Hz. The three frequencies highlighted in the modal analysis are evident, with the higher amplitude for the first mode (~20 Hz).

Table 1: Results (in Hz)

Frequency (Hz)	**direction**
17.9	Vertical and lateral
56-57	Vertical and lateral
103-106	Vertical and lateral

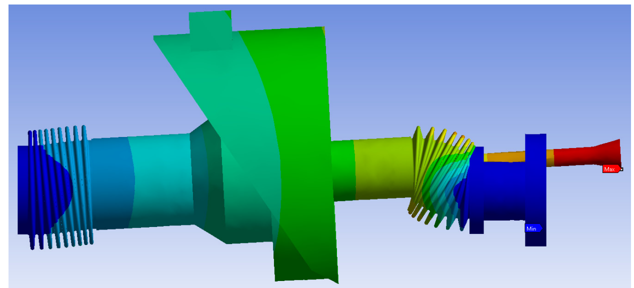

Figure 5: The profile of the 1st Eigenmode.

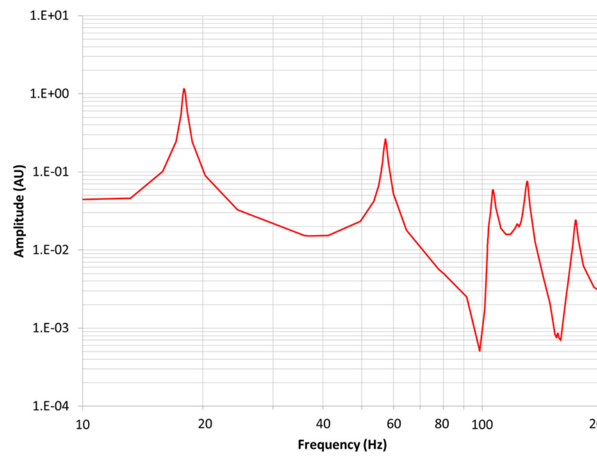

Figure 6: The harmonic response at the 80 K interface.

VIBRATION TEST

In June 2019 we performed a vibration study on the EXFEL coupler. We assembled the coupler on a test support (Figure 7) and instrumented it with various sensors to measure the acceleration during a shaking test performed at the BFSV Verpackungsinstitut Hamburg GmbH.

Figure 7: The coupler on the test support.

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Sensors

Three types of sensors were used for the test:

- SlamStick Shock & Vibration Accelerometer Loggers from Mide' [3]: tri-axial accelerometers piezoelectric, configurable sampling rate up to 20 kHz
- B&K Piezoeletric sensors (DESY-MEA)
- 3 Piezoelectric sensors provided by the testing institute (BFSV)

The slam stick and the piezoelectric sensors were positioned on the fixed coupler support and on the movable 80 K interface (Figure 8), while, thanks to their reduced dimensions, 2 additional B&K sensors were positioned very close to the cold bellows. The piezoelectric sensors were positioned on the fixed support and on the small coupler flange next to the cold bellows.

Figure 8: The coupler with the sensors.

Test Setup

The shaking test was performed with a Vibration tester Unholtz-Dickie Corporation – SA60-T1000/AR. The vibration test rig was set up with a horizontal test axis. The coupler was position like in Figure 9, with the antenna axis perpendicular to the shaking axis (to simulate vibration in the longitudinal direction once the coupler is installed on the cryomodule transport frame).

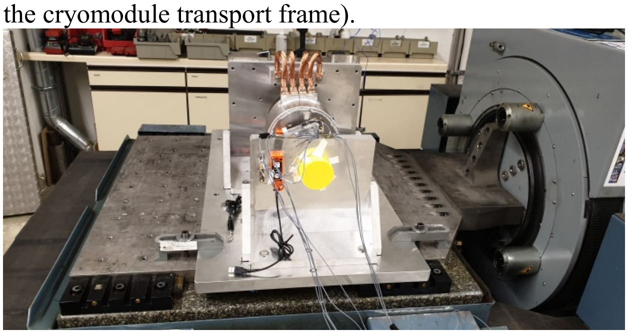

Figure 9: The coupler on the shaking table.

"Sweep tests" were performed with the following char-acteristics: frequency range from 4 to 200 Hz and back from 200 to 4 Hz, acceleration constant at 1 g.

The 1g value was considered a conservative value for a standard EXFEL transport: during the ~800 transports of EXFEL cryomodules from CEA Saclay to DESY Hamburg [4] the maximum longitudinal acceleration values were well below 1g.

The test was repeated in 3 different conditions:

- With the 5K thermal interface fully installed like in an EXFEL cryomodule (test 1)
- Without the linking part on the 5K thermal interface (test 2, Figure 10 highlighted in red)
- Without the whole 5K thermal interface, including the holder (test 3, Figure 10 highlighted in green).

Results

As expected, the three different types of sensors showed very similar data, with acceleration value in same range. The data presented in this paragraph are the one taken from the testing institute, plotting directly the acceleration measured versus the input frequency of the shaking rig.

Figure 11 shows the acceleration measured at the coupler port during the first test. Three peaks can be easily recognised, one around 19-20 Hz, one at 60 Hz and a third one just above 100 Hz. These peaks are very close to the results of the modal analysis presented above and the trend of the acceleration vs frequency has a very good agreement with the harmonic response results also presented above.

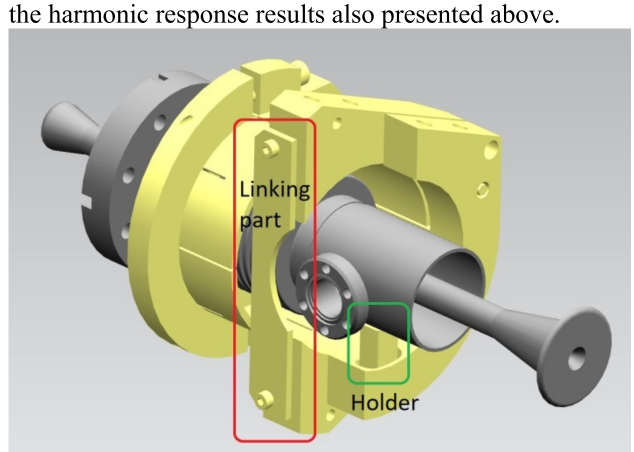

Figure 10: The 5K thermal interface (yellow) with the linking part and the holder.

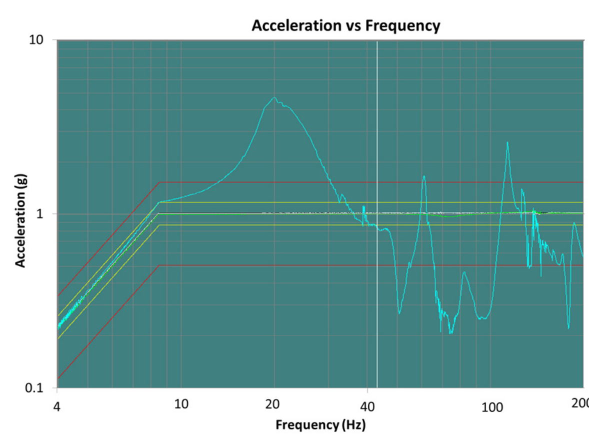

Figure 11: Acceleration vs frequency at the coupler port during the first sweep test (test 1).

During the test we could clearly see the resonance frequency just observing the coupler during the sweep. As

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soon as the frequency got close to the first expected resonance, the whole "free part" (the one between the two bellows) would start oscillating with higher amplitude than the rest of the assembly. The peak of the coupler antenna (protruding from the cavity-side support) would move left and right of a few millimetres. The same effect would repeat, with smaller amplitude, when reaching the other resonance frequencies.

At the same time, we could hear something "ringing" when the frequency was close to the first resonance; we suspected the source of the noise to be the cold bellows hitting the linking part, but we were not able to clearly identify it.

Therefore we decided to remove the linking part and have a look at it. Once removed, it showed a clear damage at the closest point to the bellows and the bellows itself had something like a dent at the corresponding point (see Figure 12).

Therefore we repeated a second sweep test removing the linking part. The test procedure was kept the same and the results were very similar. The same resonance frequencies and amplitude levels were observed.

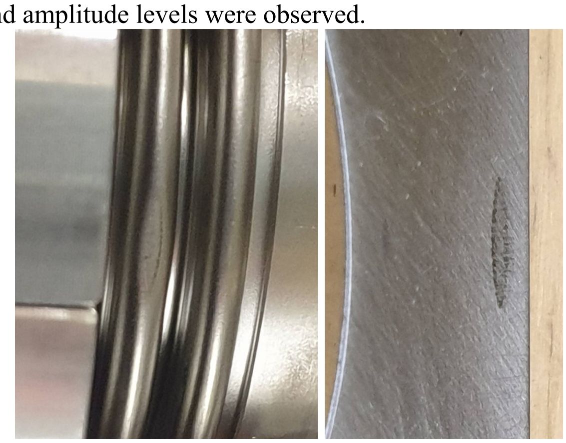

Figure 12: Left, the dent on the bellows – right, the damage on the linking part.

For the third test we decided to completely remove the 5K interface, to simulate the transport condition of a TTF type3 coupler (installed in some EXFEL prototype and preseries cryomodules) and evaluate the effect of the holder (the small part at the bottom of the 5K interface that avoid free vertical movement of the middle part, see Figure 10).

The results on the way "up" the sweep (i.e. increasing the frequency from 2 to 200 Hz) are very similar to the previous ones. But, on the way "back", when we approached the 20 Hz frequency, the coupler started ringing differently and we noticed that the antenna was moving down. We realised soon after that the bellows was failing and it completely broke before the sweep was back to the starting frequency.

Figure 13 and Figure 14 show the bellows after the failure and the acceleration vs frequency profile during the failure. The peak highlighted in red happened exactly at the breaking moment.

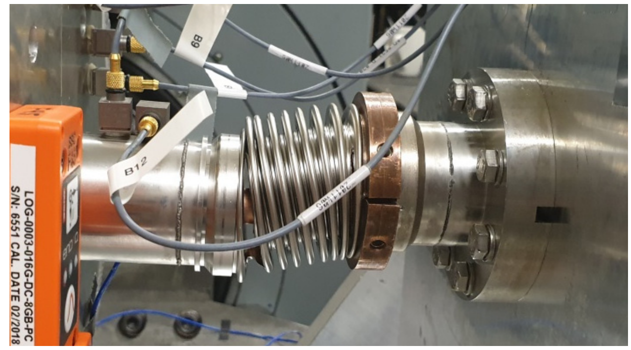

Figure 13: The bellows after the failure at test 3.

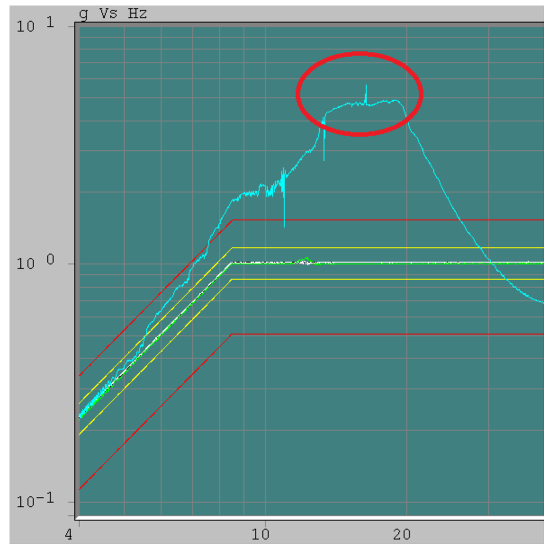

Figure 14: The acceleration vs frequency profile during the bellows failure.

CONCLUSION AND OUTLOOK

The EXFEL coupler resonance frequencies were computationally investigated and a vibration test was performed to evaluate the a real component.

As a first positive result, the measured data showed very good agreement with the simulated ones, validating the simulation method and approach.

More important, the vibration test confirmed the cold bellows as the critical point of the assembly in case of transport without any form of support or damping frame.

The following points should be addressed before further transports of an assembled coupler:

- Possible design modifications at the coupler 5K interface linking part to avoid damages at the bellows and at the holder to keep the support effect but reduce the possible hammering effect (choose a softer material?)
- Further vibration studies on a EXFEL coupler under real transport conditions
- Study of the existing transport frame, to better understand the damping effect around the critical frequencies.

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