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ESS RFQ EXPERIMENTAL MODAL ANALYSIS

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Abstract

The European Spallation Source-ESS, which is currently under construction and commissioning at Lund, Sweden is a neutron source that consists of a 2 GeV linear accelerator (LINAC) accelerating a proton beam to a solid Tungsten (W) target. The proton beam is produced by the Ion Source (ISRC) and transported through the Low Energy Beam Transport (LEBT) to the Radio Frequency Quadrupole (RFQ) that will then focus, bunch and accelerate it to 3.6 MeV. The RFQ beam commissioning started in October 2021, following the RF conditioning phase in summer 2021. This current work presents an experimental modal analysis performed on the RFQ including the comparative analysis with the modal finite element simulation using the ANSYS ® software suite. Measurements were performed using accelerometer sensors connected to a data acquisition system excited with an impact hammer. Geophones were used in parallel to the modal measurements in order to monitor the seismic background of the accelerator tunnel. Acquired data were post-processed and analyzed with dedicated software, juxtaposed with simulated results in order to determine the resonance frequencies, structural deformation patterns (mode shapes) and error margin between experimental and simulated results.

INTRODUCTION

The ESS RFQ designed and built by CEA-IRFU in France, was delivered to the ESS site in 2019. Following a period of system installation and testing, RF power conditioning commenced in summer 2021 and first proton beam was injected in the RFQ in October of the same year. The RFQ cavity is installed between the Low Energy Beam Transport (LEBT) and Medium Energy Beam Transport (MEBT) sections. It has a total length of 4.55 m divided in 5 segments operating at the resonant frequency of 352.21 MHz. Respectively, the RF power is delivered to the RFQ using two coaxial antenna couplers placed symmetrically 45 deg from the vertical axis equipped with ceramic windows that couple in total 1.1 MW of RF power during operation . Frequency detuning due to manufacturing errors and cavity thermal expansion caused by RF power losses is mitigated using 60 slug tuners and water cooling circuits [1]. Experimental modal analysis is the method to evaluate the dynamic response of the RFQ under external excitations in the final installation configuration in view of identifying the modal profile and vibrational response of this operationally critical component [2-6].

TEST SETUP & METHODOLOGY

In order to measure cavity response caused by external excitation, five (5) accelerometers were installed on the same side of each segment of the RFQ. The sensing devices used, were high sensitivity triaxial accelerometers from PCB Piezoelectronics® (Model 356B18) that were fixed with threaded studs on the cavity ensuring adequate response in higher frequencies.

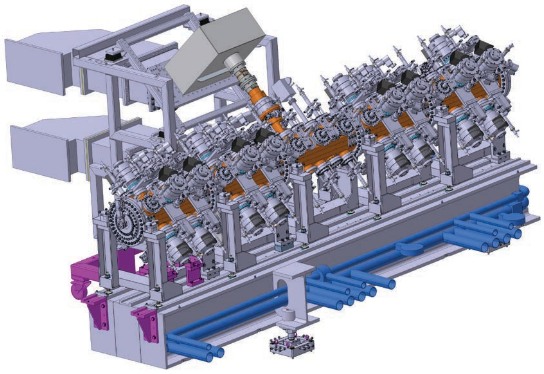

Figure 1: ESS Radio Frequency Quadrupole.

Moreover, two geophones were used for background vibration measurements placed on the accelerator tunnel floor and RFQ girder. The 6TD broadband type from Güralp ® with integrated digitizer and output sensitivity 2400 V/ms^{-1} and measurement range from 0.03 Hz to 100 Hz was used. An impact hammer with a medium hardness tip was chosen to excite the cavity in five (5) equally spaced points at the center of each segment with ten (10) strikes per point for acquired data averaging. The accelerometers were connected to the 16-analog channel sensor data acquisition system SIRIUS® from Dewesoft®. Each analog channel can achieve a dynamic range of 160 dB in time and frequency domain with a sampling rate of 200 kHz enabling high quality, low-error measurements.

Data analysis and post-processing was performed with MEscopeVES® software from Vibrant Technologies® in order to extract the resonant frequencies from frequency response functions, damping factors and mode shapes. The results and vibrational patterns were plotted and compared with the results from the finite elements analysis using ANSYS®. Figure 2 presents an example of an accelerometer sensor installation on the RFQ main body and on the right part the data acquisition system with the five (5) sensors connected and the impact hammer.

DATA ANALYSIS

A simplified meshed RFQ geometry with assigned measurement and impact points was created in the in-built SIRIUS® software with input from the detailed 3D CAD model. During measurements, data blocks that correspond to the response of accelerometers to impact hammer exci-

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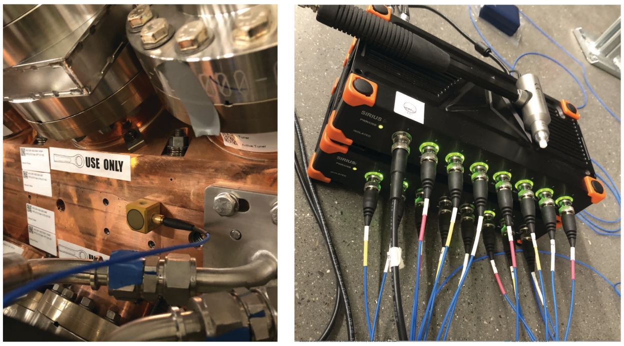

Figure 2: Left:An accelerometer installed on the RFQ body, Right: Data acquisition system and impact hammer for experimental modal analysis.

tation were acquired with the data acquisition system and locally stored to a computer. During post-processing, each transfer function (magnitude, phase and direction) is associated with each point and the response of all nodes of the mesh is calculated via interpolation. Figure 3 presents the simplified meshed RFQ model used in data acquisition system software with the accelerometer installation locations snapped to the geometry. The acquired transfer functions from each point are superimposed and the number of measured peaks are estimated using the Modal Peaks method from the options provided by MEscopeVES®.

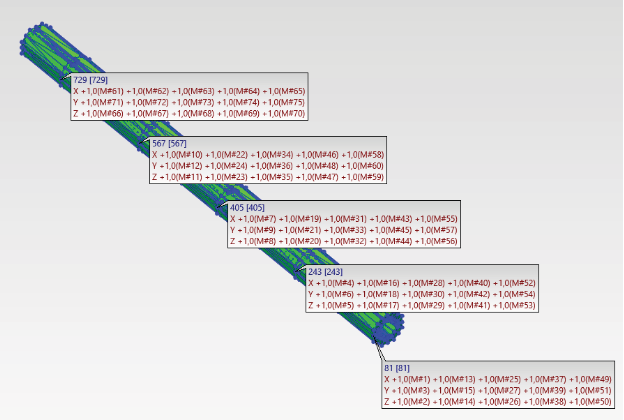

Figure 3: Meshed RFQ model with measurement points.

Modal peaks method calculates the peaks by summing together squared values of the imaginary parts of the acquired data, a method preferred when the transfer function relates acceleration and force. Subsequently, the subset of peaks that consist resonant frequencies are determined using the coQuad and fitting methods applied on the complex functions of frequency response. Resonant frequencies and damping factors are calculated using the least squared error curve fit of these functions and the evaluation of the roots of the extracted characteristic polynomial. Complex Mode Indicator Functions (CMIFs) a multi-degree of freedom method is preferred due to the closely coupled observed modal peaks present in the set of overlaid frequency response functions.

An exponential window for noise removal was applied on the acquired spectra, introducing an artificial damping [7].

Figure 4 presents the superimposed frequency response functions in coQuad representation in the frequency range of up to 1.4 kHz and the estimated resonant peaks using the aforementioned methods. The estimated frequencies from measurements along with damping factors and residue magnitudes are presented in Table 2. *Damping factors* are expressed as (%) percent of critical damping whereas *Residue* represents the magnitude of a resonance peak appearing in a frequency response function.

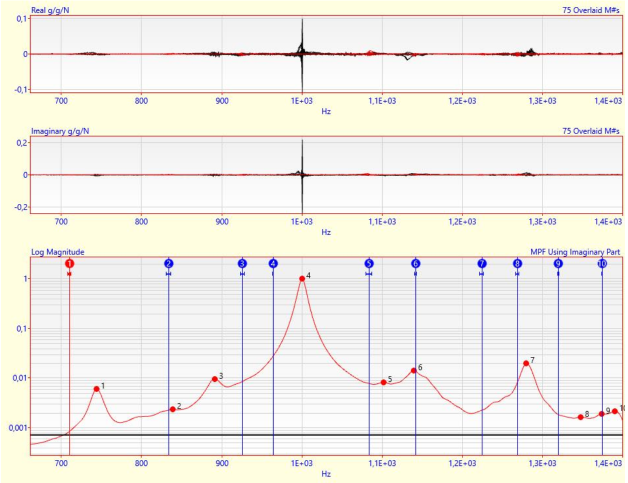

Figure 4: Estimation of calculated resonant frequencies.

Table 1: Measured Modal Frequencies and Calculated Damping Factors and Residue Magnitudes

Mode	Frequency [Hz]	Damping [%]	Residue Mag.
1	710	0.315	0.0051
2	834	0.346	0.0173
3	926	0.243	0.0675
4	964	0.028	0.0069
5	1080	0.317	0.1200
6	1140	0.105	0.0095
7	1220	0.174	0.0133
8	1270	0.141	0.0095
9	1320	0.062	0.0129
10	1370	0.008	0.0004

Figure 5 presents the data collected for background vibrations over an hour of measurements with the geophone sensors on tunnel floor and RFQ girder. The results show the Power Spectral Density (PSD) depicting the resonance peaks of the background vibration spectrum and how the power of the signal is distributed over the frequency domain. Background measurements will be used for data normalisation and will be subtracted from the measured resonant frequencies.

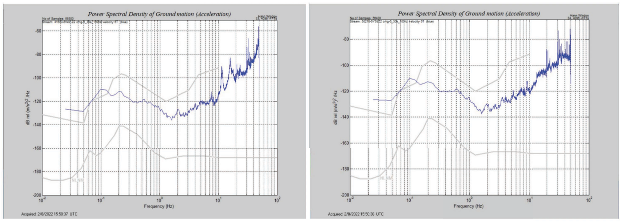

Figure 5: Power Spectral Density of ground motion for geophones on the accelerator tunnel (left) and RFQ girder (right).

ANSYS MODAL ANALYSIS

A Modal analysis providing the natural frequencies (eigen frequences) at which the RFQ will resonate have been performed using ANSYS® software. A simplified RFQ model was imported and boundary conditions were selected to represent the degrees of freedom (DoF) of installed cavity configuration taking into consideration the LEBT-MEBT interfaces, supports and coupler connections. Fixed boundary conditions were used for these interfaces and the model was simulated in order to obtain the first ten (10) resonant eigen-frequencies and mode shapes of the structure.

Figure 6 presents the measured experimental mode shapes (left) compared with the theoretically calculated from ANSYS® for four (4) resonant frequencies. Preliminary results indicate the level of agreement as presented in Table 2 that summarises the results and the associated errors.

Table 2: Comparison of Measured (Experimental) and Simulated (Theoretical) Resonant Frequencies

Mode	Experimental	Theoretical	Difference [%]
1	710	711.5	0.2
2	834	873.0	4.5
3	1140	1091.6	4.4
4	1370	1380.0	0.7

Results agreement can be further improved by increasing the number of measurement points by deploying additional sensors on multiple RFQ locations in the next measurement campaign. In combination with additional excitation points, radially and longitudinally distributed on the cavity, interpolation errors of the data acquisition system for mode shapes evaluation will be further reduced. Moreover, in order to improve the evaluation of the fitted resonant frequencies and mode shapes from MEscopeVES® software, a finer finite elements mesh can be introduced in the model.

Observed errors and resonant frequency shifting are induced due to simplifications on the installed configuration during data analysis and model preparation for simulation. For example, the introduction of fixed boundary conditions in modal simulations introduces the assumption of infinite stiffness on model boundaries that differs from the finite stiffness of the exact same points in the installed configuration. Additionally, the model does not take into consideration the multiple installed water hoses and cables that could further influence the resonant frequencies of the structure. An explanation of the disagreement between experimental and theoretical results on some mode shapes can be explained by the fact that ANSYS® evaluates all the theoretical resonant modes, including the ones with high damping ratios that can be masked and challenging to acquire during experimental modal analysis.

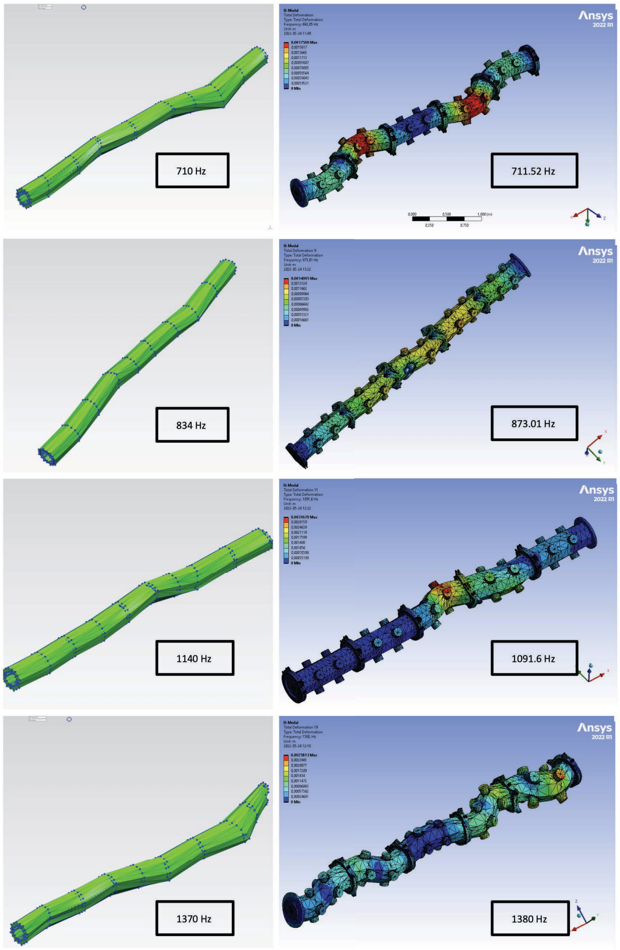

Figure 6: Mode shapes (deflection patterns) from experimental (left) and theoretical modal analysis (right).

CONCLUSIONS

Experimental modal measurements using a flexible, portable measurement set-up were performed on the ESS RFQ and results were compared with ANSYS® modal simulations. The experimental modal frequencies calculated agree within a 5% margin of error to those derived from the simulations. Differences observed during data comparison and analysis, rely on the assumptions used during measurements and simulations; with respect to the number of measured and excitation points. To further reduce such errors, next steps could include the repetition of the measurements with sensors and multiple excitation points in different vectoral directions.

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