Experimental validation of the Finite Element-Multibody model of a cryomodule during road transportation

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Abstract. The present activity aims to test the Transportation Tooling (TT) designed for the Cryomodule SSR1 at Fermilab facilities. The tests consisted of road transportation trials of a cryomodule sub-assembly, suspended on a truck using the designed TT. The truck drove along a path inside Fermilab facilities. The trial was performed at an approximate speed of about 25 km/h, which is close to the transportation conditions of the complete Cryomodule. Several accelerometers were mounted on the Transportation Tooling frame and the cryomodule sub-assembly. This allowed comparing the vibration behavior of the inner frame of the TT with the solicitation coming from the truck loading bed, to assess the filtering capabilities of the tooling. Also, the acceleration of the main components could be monitored during the whole transportation, to obtain a validation of the developed numerical model.

1. Introduction

The PIP-II (Proton Improvement Plan-II) project is a proton driver superconducting linac designed and assembled at Fermilab. The core components of the assembly are Superconducting Radio Frequency (SRF) cavities [1] which operates in a vacuum cryogenic environment [2] exploiting superconducting materials [3] to accelerate a particles beam. Different kinds of cavities are used in the PIP-II project: 650 MHz multicell cavities (LB650, HB650) [4], 325 MHz single spoke resonators (SSR1, SSR2) [5] and half wave resonator (HWR) [6, 7]. Since these components are thin-walled and air-tight, a critical step in the cryomodule life-cycle is represented by transportation through different assembly facilities. Thus, adequate supports and shock absorber systems must be designed to reduce the damage risk during transportation [8, 9]. In the framework of this project, the prototype of the cryomodule (CM) SSR1 has been assembled and it has been moved by truck among different facilities at Fermilab. In order to reduce vibration and stress of the internal parts of the CM, a Transportation Tool (TT) was designed in the framework of a collaboration between the University of Pisa and Fermilab and it was installed on the truck to bear the CM during the transportation [10]. The TT consists of two frames, connected through elastic helical isolators (HI), which were chosen during the design phase to act as a mechanical low-pass filter, preventing the high frequency (above 15 Hz) oscillations coming from the road asperities to excite the resonance frequencies of the CM internal components. The HI characteristics were chosen after performing an in-depth analysis of the CM+TT using a multi-level Finite Element-Multibody approach already developed by the authors also for different applications [11]. The TT frames and the external
vessel of the CM were modeled in the FE environment and exported in MB through a modal reduction technique. To limit the computational effort, the internal components of the CM (e.g. cavities, two-phase pipe, bellows, etc.) were modeled in the MB environment through properly selected parts or elements (e.g. rigid parts, beams, lumped stiffness, etc.).

This paper describes the experimental test which allows obtaining a first validation of the numerical model, which consisted of the actual truck transportation of the sub-assembly at a late assembly stage. During the transportations, 20 triaxial accelerometers were placed on the TT frames and several internal components of the cryomodule (e.g. cavities, solenoids, two-phase pipe, etc.). The acquired signals were then used to validate the mixed FE-MB model. In particular, the acceleration of the external frame of the TT, rigidly connected to the truck loading bed, was imposed as inputs to the model. Consequently, the experimental and numerical acceleration of the internal frame of the CM were compared to experimental results, to validate the model and to assess the actual filtering capabilities of the TT.

2. Road trials description
On the 20th of November 2019 a transportation trial for the Cryomodule (CM) SSR1 sub-assembly was performed onsite at Fermilab. The designed Transportation Tooling (TT), presented by the authors in [10], was assembled and equipped with the chosen helical isolators (M32-850-08-[H]-B, IDC Shock & Vibration Isolation Products) between the inner and outer frame, as shown in Figure 1.

![TT overview: (a) design and (b) assembly before painting.](image)

The trial was highly significant because the transported component was at an almost-final assembly stage. The mass of the sub-assembly was 7257 kg. The mounting flanges of the external vessel were used to connect the CM to the TT, as it will be done for full-assembly transportation. The inner frame itself was weighed, showing a mass of 1215 kg. Finally, some stripes were used to rigidly connect the outer frame to the truck bed. Figure 2 shows the CM mounted on the TT and ready for transportation.
Figure 2. CM and TT mounted on the loading bed and ready for transportation.

2.1. Road path
The transportation aimed to bring the CM from Lab2 to ICB (two plants at Fermilab), where the assembly will be completed and the main check will be performed. An overview of the accelerations measured along the full path is provided in Figure 3, where the comparison between the signals acquired along the vertical direction by two sample accelerometers, placed on the outer and inner frame respectively, at corresponding locations are shown. As can be noted, the vibration amplitude over time is almost constant, since the truck speed was kept constant for the whole transportation, and road conditions were similar along the whole path. Anyway, some spikes can be noted in the signal (e.g. close to minute 5) which will be analyzed in the next sections.

Figure 3. Full path of the trial: comparison between outer and inner frame accelerations.

2.2. Accelerometer placement
Several accelerometers were placed on the TT to assess its filtering capabilities. Four main locations were selected (as shown in Figure 4, which is the top view of the TT), to fully describe the 3D motion of the TT. The sensors were placed at each location, one on the outer frame and one on the inner frame, for a total of eight triaxial accelerometers. Since the accelerometers were mounted at almost corresponding locations on the outer and the inner frame, the data comparison will allow to assess the filtering capabilities of the suspension system. Only a subset of sensors was monitored during transportation: outer frame 1, 2 and 3 (OUT1, OUT2 and OUT3) and inner frame 1 and 3 (IN1 and IN3).
In addition to the sensors mounted on the TT, several accelerometers were mounted on the main components of the CM. Figure 5a shows the internal components of the CM, including cavity 1, cavity 2 and cavity 8 which were monitored (C1, C2 and C8 respectively).

Figure 5b shows the position of other sensors in the internal part of the CM. In particular, sensors were placed on the two-phase pipe, at a coordinate corresponding to the solenoids number 2 and number 4 (2-PP2 and 2-PP4, respectively), and the strong back response was measured in correspondence of cavities 1 and 8 (SB1 and SB8). The other monitored components were: solenoid 3 (S3), coupler 2 and 5 (Cp2 and Cp5), and thermal shield, in correspondence of cavity 5 (TS4). Finally, the gate valves were monitored, in both upstream and downstream locations (GV_US and GV_DS).
3. Measured data analysis

The described test produced data related to 54 channels (18 triaxial accelerometers) recorded at 800 Hz for a duration of about 120 minutes. This huge amount of data was segmented to extract relevant information in terms of filtering assessment. Two main segments were considered: truck traveling at 25 km/h in steady-state conditions and truck traveling at 25 km/h subject to impulsive bumping. Due to the major severity of the impulsive bumping, the following analysis refers to this operating condition.

3.1. Truck traveling at 25 km/h, impulsive bump

This segment corresponds to a period in which the truck was traveling at about 25 km/h and an impulsive loading was noted in the vertical acceleration profile. An overview of the 60 seconds time history, which includes the signal spike related to the bumping, acquired by the reference accelerometers along the vertical direction is provided in Figure 6. Figure 6(a) highlights that the acceleration peak of the outer frame (black curve, 10.6 m/s$^2$) is much higher with respect to the steady-state behavior (1.5 m/s$^2$). Also, as highlighted in Figure 6 (b), the acceleration peak of the inner frame (red curve, 1.9 m/s$^2$) is higher with respect to the steady-state behavior (0.2 m/s$^2$, i.e. about 0.02 g). Anyway, the comparison between black and red curves shows that the accelerations of the inner frame are smaller than the accelerations of the outer frame by a factor of about 5, thus proving a good performance of the mechanical filter.

![Figure 6. Time history: 25 km/h with an impulsive bump.](image)

4. Filtering performance assessment
The suspension system aims to act as a mechanical filter to reduce the dynamic loading produced by the road acting on the CM. In order to assess the actual system performance, the described time histories were analyzed in the frequency domain.

The FFT of the time history acquired by the reference accelerometers along the vertical direction during the segment including the impulsive bump, and shown in Figure 6, is reported in Figure 7. Figure 7(a) shows the full spectrum while Figure 7(b) shows the low-frequency range (from 0 to 35 Hz which is the range of interest for transportation issues).

![Figure 7 FFT of the vertical acceleration](image)

Figure 7. FFT of the vertical acceleration: (a) full spectrum and (b) low-frequency spectrum.

The black curve in both figures represents the vertical acceleration measured by the reference accelerometer on the outer frame (i.e. the system input) while the red curve refers to the corresponding accelerometer on the inner frame (i.e. the system output). The plots highlight that an amplification of the acceleration of the inner frame is found at frequencies lower than 5 Hz as expected because in this range lie the natural frequencies of the CM and TT assembly, which emphasize the rigid-body-motion modes. It is worth noting that these modes are not considered dangerous for the CM, since they only involve a rigid motion of the system and they produce almost-zero stresses on the critical components. On the other hand, the output response is always lower than the input load in the frequency range above...
10 Hz. This is due to the helical isolators, which act as a low-pass-filter, preventing high-frequency harmonics to load the Cryomodule.

5. Numerical model comparison

5.1. Comparison for the inner frame

The results measured during the transportation were compared with the outcomes of the previously developed numerical models, described in [10]. The total mass of the modelled sub-assembly was 5969 kg, i.e. about the 82 % of the actual transported sub-assembly mass. Figure 8 shows the comparison between numerical and experimental data concerning the magnitude of the displacements of a reference monitored point (Point 3) of the inner frame. The red curve represents the inner frame experimental displacement, while the green curve represents the inner frame numerical displacement. The comparison between green and red curve highlights an overall good correlation between numerical and experimental results. Similar plots are obtained considering other monitored points on the inner frame.

![Figure 8. Comparison between experimental and numerical displacement magnitude: (a) Point 1 and (b) Point 3.](image)

Considering the frequency domain, two points on the inner frame were studied: Point 1 and Point 3, as shown in Figure 9. The black line represents the magnitude of the FFT of the outer frame experimental acceleration, the red line represents the magnitude of the FFT of the inner frame experimental acceleration while the green line represents the magnitude of the FFT of the inner frame numerical acceleration. Figure 9(a) refers to Point 1 (Front Right) and Figure 9(b) refers to Point 3 (Rear Left). As can be noted, the acceleration reduction due to isolators is obtained for both experimental and numerical data for frequency values higher than 15 Hz. The numerical model well reproduces the amplitude of the inner acceleration in almost all the considered frequency range (red and green curves are almost overlapped). Some spikes are visible in the experimental data, i.e. at about 9 Hz for the Front Right sensor and at 12-14 Hz for the Rear Left sensor. It is worth noting that the green curve well represents the frequency associated at almost all the peaks of the experimental data, even if it does not precisely foresee the amplitude of all the peaks (which also depends on internal components damping, friction and small clearances).
5.2. **Comparison for the inner components**

Since several accelerometers were available, the same comparison between experimental and numerical results was performed for the other sensors. In particular, the accelerometers mounted on the cavities, on the two-phase pipe and on the solenoid were considered.

Figure 10 shows the experimental and numerical amplitude of the FFT of the acceleration measured at the Cavity 8 and Solenoid 3. As can be seen in Figure 10(a) for Cavity 8, the low-frequency range provides a good matching between red and green curves. Also, a good correspondence between the frequencies corresponding to the main peaks can be noted. On the other hand, some discrepancies can be found concerning the peaks amplitude for frequencies between 5 Hz and 15 Hz, where the numerical model underestimates the amplitude of the acceleration. For higher frequency values the matching between numerical and experimental model is good and the acceleration values are low thanks to the filtering effect due to the helical isolators. However, even in the 5-15 Hz range, the frequency values associated with the peaks are correctly identified by the numerical simulation, confirming the capability of the model to reproduce the natural modes of internal components; the discrepancies are mainly due to the amplitude of the peaks which, as anticipated, also depends on internal components damping, friction and small clearances.

In this case of solenoid 3, Figure 10(b), the matching between experimental and numerical data is very good in the 10-18 Hz frequency range, both in terms of frequency and magnitude. Some peaks at 9 Hz and 18-21 Hz are underestimated in the model. It is worth noting that, in the multibody model, the solenoid belongs to the CM deformable structure (imported from FEA as a modal neutral file), while the previous measure (Cavity 8) is related to a part that is modeled as rigid. The connection of these parts to the deformable structure is modeled through lumped rigid constraints and their behavior is very difficult to be modeled in a simplified model.
Figure 10. Comparison between experimental and numerical acceleration magnitude: (a) Cavity 8 and (b) Solenoid 3

6. Conclusions
The described activity allowed to experimentally assess the filtering capabilities of the Transportation Tooling designed for the Cryomodule SSR1 and to compare the results with the ones obtained in a previously developed multibody model. The analysis was performed basing on the transportation of a sub-assembly of the actual CM on a representative path inside the Fermilab facilities. The acceleration data, acquired on the inner frame, the outer frame and several components inside the CM, were analyzed in the time domain and in the frequency domain to assess filtering capabilities. Also, a comparison between experimental and numerical results was performed for several signals acquired on the inner and outer frame and for several locations inside the CM.

The analyzed data allowed to assess the dynamic response of the system composed of the transportation tooling and the cryomodule sub-assembly. The data allowed to validate the satisfactory filtering performances of the suspension system, since the accelerations of the inner frame were found to be lower than the accelerations of the outer frame, for frequencies higher than 10 Hz (thus confirming the capability of the mechanical filter). Also, the visual inspection of the Transportation Tooling after the trials showed that no impact occurred between the inner and the outer frame. Leak checks were performed after transportation, highlighting that no damages occurred in the cryomodule.

The measured data also allowed to perform a comparison between experimental and numerical results. The comparison between displacements time histories denoted an overall good correlation between the model and the experimental setup. However, a deeper analysis of the accelerations profiles in the frequency domain showed some discrepancies in the frequency range 5-15 Hz. Indeed, while there is a fairly good agreement about the resonance frequency values, the amplitude of the acceleration computed in the model is underestimated in the above-mentioned frequency range. On the other hand, the amplitudes of numerical and experimental peaks are in good agreement in the low-frequency range and in the high-frequency range. The observed discrepancies were mainly ascribed to the model simplifying hypothesis, e.g.: poor connections description, use of beam elements (two-phase pipe), use of rigid bodies (cavities), lumped stiffnesses (bellows).

References
[1] Wu G, 2019, SRF cryomodules for pip–2 at Fermilab, 19th International Conference RF Superconductivity SRF 19, (Dresden) Germany.
[2] Roger V, Cheban S, Nicol T, Orlov Y, Passarelli D, Vecchiolla P, 2018, Design update of the SSR1 cryomodule for PIP-II project, Proceedings of the 9th International Particle Accelerator Conference IPAC 18, (Vancouver) Canada.

[3] Barzi E, Gallo G, Neri P, 2012, Fem analysis of nb-sn rutherford-type cables, IEEE Transactions on Applied Superconductivity 22 (3).

[4] Li J, Harms ER, Hocker A, Khabiboulline TN, Solyak N, Wong TTY, 2011, Development and integration testing of a power coupler for a 3.9-ghz superconducting multicell cavity resonator, IEEE Transactions on Applied Superconductivity 21 21–26.

[5] Passarelli D, Wands R, Merio M, Ristori L, Methodology for the structural design of single spoke accelerating cavities at fermilab, 2016, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 834 1–9.

[6] Conway Z, Barcikowski A, Cherry G, Fischer R, Guilfoyle B, Hopper C, Kedzie M, Kelly M, Kim S, MacDonald S, Ostroumov P, Reid T, Lebedev V, Lunin A, 2016, Progress towards a 2.0 k half-wave resonator cryomodule for fermilabs pip-ii project, in: Proceedings of the 28th Linear Accelerator Conference, LINAC 2016.

[7] Kim S, Conway Z, Kelly M, Ostroumov P, Gerbick S, Reid T, Kedzie M, MacDonald S, Caldwell D, 2015, Preservation of quality factor of half wave resonator during quenching in the presence of solenoid field, in: 6th International Particle Accelerator Conference, IPAC 2015.

[8] Whitlatch T, Curtis C, Daly E, Graves C, Henry J, Matsumoto K, Mutton P, Pitts J, Preble J, Sachleben W, Schneider W, Slachtouski S, Wiseman M, 2001, Shipping and alignment for the sns cryomodule, Proceedings of the 2001 Particle Accelerator Conference, Chicago.

[9] McGee M, Bocean B, Grimm C, Schappert W, Transatlantic transport of fermilab 3.9 ghz cryomodule for ttf/flash to desy, 2008, Proceedings of EPAC08, (Genoa) Italy.

[10] Neri P, Bucchi F, Passarelli D, 2020, A multilevel finite element-multibody approach to design the suspension system for the road transportation of SSR1 cryomodule, Transportation Engineering, 2, 100017.

[11] Bertini L, Bucchi F, Monelli BD, Neri P, 2018, Development of a simplified model for the vibration analysis of lawn mowers, Procedia Structural Integrity 8: 509-516.