MODEL-BASED SIMULATION FRAMEWORK FOR MULTI-AXIS RANDOM VIBRATION TESTING

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ABSTRACT

Dynamic environmental test campaigns play a crucial role in verifying that the components under test can withstand the vibrational environment expected during their operation. Multiple-Input Multiple-Output (MIMO) control strategies have seen increasing attention due to their enhanced capability to accurately replicate the in-service environment, leading to more representative stress states on the component. Numerical models capturing the complex dynamic behaviour of the test hardware and article can be used to guide the preparation of MIMO tests by predicting the test results and by optimizing the set-up configuration and test settings. This pre-test analysis also helps to protect the integrity of the structure under test. This paper focuses on the methodologies used for the development of a virtual simulation environment of a vibration test rig, which consists of a multi-axis shaker platform and four electromagnetic exciters in a decoupled build. First, a lumped-parameter model of the electromagnetic shakers is derived and is experimentally validated. Secondly, the coupling of the exciter models with a reduced-order model (ROM) of the multi-axis shaker platform is investigated. Finally, the model correlation is evaluated.

Keywords: *MIMO control, multi-axis vibration testing, environmental testing, digital twin.*

1. INTRODUCTION

Multi-axis excitation setups have gained traction for vibration testing of components for high-end applications, where realistic near-operational loads must be replicated while keeping the test specimen safe from failure. A virtual testing environment built from a combination of test and simulation data would allow to not only optimize but also de-risk the test campaign *a priori*. Such a Digital Twin (DT) approach would allow for virtual pre-testing, but also for Hybrid Testing, with the simulation environment running in real-time with the test, giving access to unmeasurable quantities through estimation schemes [1].

This paper reports the efforts allocated into the development of a framework for deploying a virtual simulation environment for a multi-axis vibration test rig and its preliminary results.

2. MULTI-AXIS VIBRATION TESTING SETUP

The 4-axis vibration testing system shown in Fig. 1(a) is the center object for the development of the proposed virtual testing framework. This platform was built by S.E.R.E.M.E. (Bondoufle, France).

This system combines 4 electrodynamic actuators in a decoupled build, where 3 of the shakers excite the table in-plane motion, and a 4th generates vibrations in the vertical direction.

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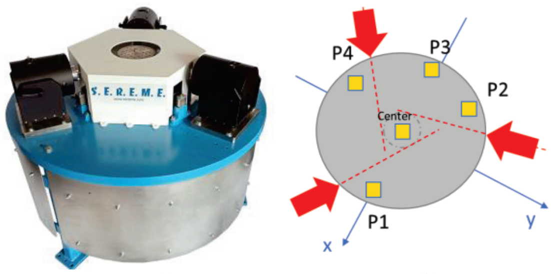

(a) (b)

Figure 1. Multi-axis vibration testing system (a); instrumentation and shaker connections to table (b).

A combination of uniaxial and triaxial accelerometers were placed on the shaker table, which are represented by the yellow squares in Fig. 1(b). A Simcenter SCADAS Mobile and Simcenter Testlab software were used for data acquisition and data processing, in order to compute the frequency response functions (FRF) describing the dynamics of the system. Additionally, Fig. 1(b) shows that the horizontal shakers are not aligned with the center of the table, allowing for its rotation around the vertical axis, which further helps in decoupling the actuators, and results in a fourth degree-of-freedom (DOF).

The setup described in the previous section combines 3 Modal Shop 2075E shakers in the horizontal plane and a Dynalabs DYN-PM-440 in the vertical direction.

These electrodynamic actuators are composed by a wire coil suspended in a magnetic field and connected to the shaker table, such that it outputs a force proportional to the current passing through the coil.

3. DIGITAL TWIN FOR VIRTUAL PRE-TESTING

3.1 Electrodynamic shaker modelling

For the purpose of building a Digital Twin (DT) of the full test rig that encapsulates all of the complex coupled dynamics between the test hardware components, a correlated model of these shakers should be included within the framework. Several modelling approaches have been presented in the existing literature, in this work the lumped parameter electro-mechanical model presented in [2] is used, where a 3 degrees-of-freedom mechanical system is coupled to the electric circuit describing the complex impedance of the coil [2, 3].

The consideration of 3 separate moving masses results in 3 modes of vibration characterizing the dynamics of the shaker.

A dedicated test campaign for characterizing the dynamic behaviour of each shaker in different loading configurations was conducted. This paper follows the method described in [3], which proved suitable for estimating both mechanical and electrical parameters of the system. Tab. 1 presents the 2 loading configurations used for testing the DynaLabs DYN-PM-440 shaker, and the respective modal parameters estimated using the PolyMAX method [4].

Table 1. Modal parameters estimated using PolyMAX for Dynalabs shaker under 2 loading configurations.

Configuration	Mass(g)	Suspension Mode		Coil Mode	
		f_n(Hz)	ζ_n(%)	f_n(Hz)	ζ_n(%)
Empty	16	30.34	25.24	3422.34	2.05
Loaded	135	25.78	25.49	2833.41	2.32

Experimental data was then used to define the parameters of the analytical model of the exciters.

The lumped-parameter model was implemented in the systems simulation software Simcenter Amesim and it is shown in Fig. 2.

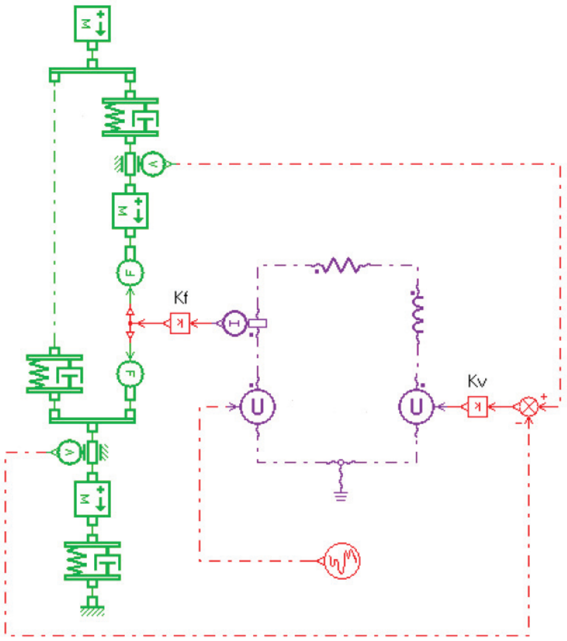

Figure 2. Simcenter Amesim implementation of lumped-parameter model for electrodynamic exciter.

To validate the proposed model of the actuators, the simulated FRFs and the experimentally measured ones were compared for each of the shaker models. The results showed that a good correlation between model and test data was achieved, as it is illustrated in Fig. 3 for the vertical exciter.

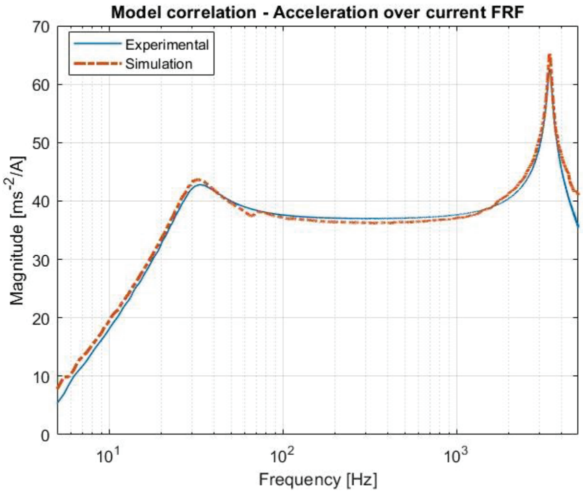

Figure 3. Vertical shaker model correlation with experimental data.

3.2 Multi-axis shaker platform model

The next step in the development of the proposed virtual test scenario is to have a model of the multi-axis platform that connects all the exciters to the eventual test specimen. For this purpose, a Finite Element (FE) model was made available by the manufacturer. This FE model combined mesh elements with superelements obtained via the Craig-Bampton reduction technique [5].

A framework to further reduce the initial model and convert it into an efficient state-space format was investigated and implemented.

Initially, the structural global mass and stiffness matrices of the FE model were exported using Simcenter Nastran. Modal analysis followed, transposing the problem into modal coordinates. Knowing the locations of the shaker connections, modal participation factors were computed for the intended loading scenario, allowing to further reduce the model from an initial larger set of modes to only a few modes, preserving the key dynamics of the system in a frequency bandwidth up to 3 kHz. Additionally, proportional damping was added to the model. Finally, a state-space representation was built using the resulting reduced structural matrices [6,7].

3.3 Coupled model

With all components modelled, it was then possible to couple them together, forming the intended Digital Twin of the full test rig.

Fig. 4 illustrates the implementation of the open-loop DT using Simcenter Amesim. The signal generator connects to the amplifiers driving each of the shakers mounted on the multi-axis platform. The shaker models then output a force signal into the respective input degree-of-freedom of the state-space model of the multi-axis platform, simulating the excitation of the vibration table. Kinematic quantities (displacements, velocities, accelerations) at 37 locations of the shaker table can then be selected as outputs of the SS model, for visualization of results and further processing.

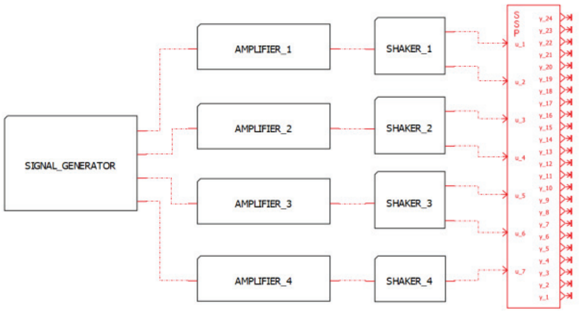

Figure 4. Implementation of test rig Digital Twin in Simcenter Amesim.

4. RESULTS

The proposed DT deployed in Simcenter Amesim was compared to experimental data to assess model correlation.

Fig. 5 plots some of the experimentally collected FRFs between the measurements of the center accelerometer and the drives to each of the actuators. The amplitude peaks correspond to the primary modes of vibration of the platform. The highest resonance on the vertical direction FRF corresponds to the coil mode of the shaker, whose frequency has shifted to a lower value with respect to what can be seen in Fig. 3. This is due to the added mass loading of the moving components, which the shaker is partially supporting in static conditions. This was not initially considered and required updating the model parameters for this exciter.

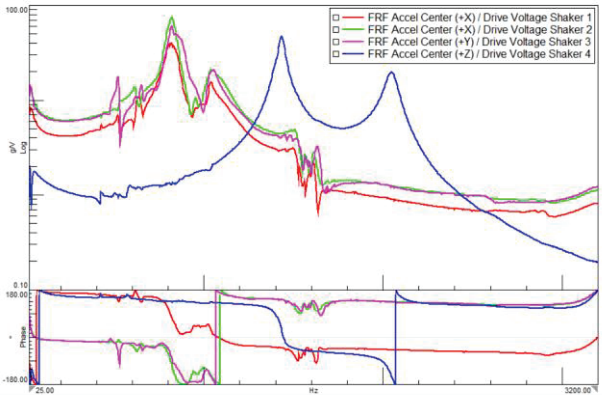

Figure 5. Experimentally measured acceleration-over-voltage FRFs of multi-axis vibration system.

For simplicity, correlation efforts are here described only for the behaviour in the vertical direction. Fig. 6 shows a comparison between the FRFs of the vertical acceleration measured at the center of the table over the drive voltage to the amplifier feeding the vertical exciter.

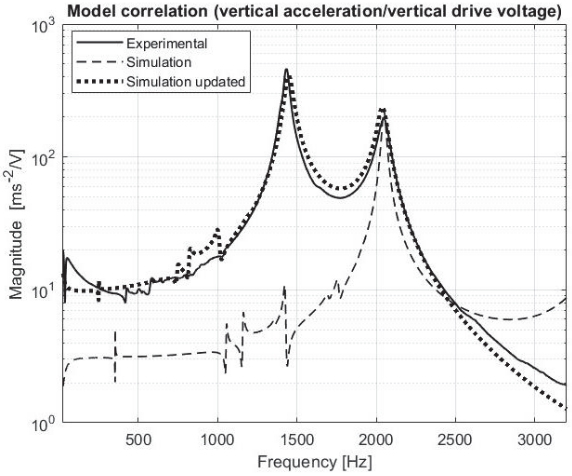

Figure 6. Model correlation analysis – comparison of vertical acceleration-over-voltage FRFs.

The model derived initially did not fit the physical data in a satisfactory manner. It can be inferred that this model appeared to be considerably stiffer than the physical setup, having its poles shifted to higher frequencies. To achieve a higher model accuracy, some iterations of this model were tested by directly tuning the stiffness matrix of the system and the expected table mass of the vertical shaker. This preliminary tuning exercise resulted in a good matching of the principal resonances between experimental and updated model, as can be seen in Fig. 6.

5. CONCLUSIONS AND FUTURE WORK

A model-based simulation framework for virtual vibration testing in a multi-axis test rig was developed, combining lumped-parameter models of the exciters and a reduced order state-space model of the multi-axis system. A preliminary DT was deployed in Simcenter Amesim and the model was correlated with experimental data.

Future directions include further expanding on the correlation activities and researching methods to update the initial condensed ROM. Additionally, the framework should be extended to the inclusion of a specimen-under-test, tackling the challenges associated with modelling the coupling between test hardware and device. The inclusion of a controller model in the DT will allow for a closed-loop simulation-based virtual vibration testing environment.

6. ACKNOWLEDGMENTS

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