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Application of dynamic substructuring and in situ blocked force method for structure borne noise prediction in industrial machinery

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ABSTRACT

Prediction of structure borne noise from industrial machinery allows not only to adopt mitigation measures to avoid excessive vibration at the design stage but also for problem solving after the final implementation. These measures also avoid potential damage to machinery tooling and the amount of defective products, whilst reducing the disturbance to operators within the working area and people in nearby facilities. Different strategies for achieving accurate predictions range from numerical and analytical methods, such as FEA and SEA, to methods which use measured data. Dynamic sub-structuring, an example of the latter, has been used for this research to characterise vibration contributions of three key assembly elements: source, isolator and receiver. The in-situ blocked force method was used to extract intrinsic properties of an operational vibration source as well as the mobility of the receiver and the dynamic stiffness of the isolators. Dynamic sub-structuring was then used together with the blocked forces data in order to predict structure-borne noise at the source interface with the isolators and at remote locations in the receiver. Predictions of source behaviour as part of an assembly were then compared with actual measurements made on the installation to serve as a validation of the method.

Keywords: Structure-Borne, Vibration, Prediction

1. INTRODUCTION

Industrial machinery presents a twofold problem in terms of vibration isolation design: a too stiff connection would propagate important vibrations to the surrounding floor and structures affecting nearby machinery and workers, whilst a too soft isolation would allow movement within the machine and therefore affect its precision and product quality as a result of misalignments, and damage to inner machine tooling as a consequence of excessive vibrations.

In order to account for these factors and provide valid solutions at either the design stage or for investigating vibration mitigation measures, methods capable of accurately predicting structure-borne noise become an essential tool for engineers. Some of the most widely used solutions include numerical and analytical methods such as FEA models, which provide good flexibility for adapting to different problems despite the high computational requirements. However, their disagreement with field data (1) has led to a wider spread of experimental based approaches such transfer path analysis or dynamic sub-structuring; the application of latter being one of the main focuses of this work.

The dynamic sub-structuring method was firstly defined for frequency domain applications by Jetmundsen et al (2), but its formulation was later expanded and applied to different problems (3). Despite being initially designed to simplify finite element problems in order to compensate their high computational requirements, this method also allows the use of other approaches such as measurement based for substructure characterization and has proven successful for predicting structure-borne vibration in different structures (4,5). The present work is a continuation of the latter research, which combines dynamic substructuring with the blocked forces method for source characterization.

In order to implement this methodology, the assembly is subdivided into the components: vibration source, isolator and receiver. These three elements are then characterised by performing accelerance or

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impedance measurements on the individual sub-structures and the source is additionally characterised by the blocked force measured in-situ (6).

Besides the good agreement shown between predictions and on-board validations of coupled assemblies with lighter structures, the accuracy of these methods in heavier structures (closer to realistic industrial machinery isolation) is yet to be assessed and will be the focus of this work.

2. THEORY

Prior to the description of the theory behind the methods used in this work, the use of a consistent nomenclature becomes essential to avoid confusion should be described: the assembly is subdivided into three general elements namely source (S), isolator (I) and receiver (R). The source is the noise generating structure which is to be coupled to a final structure known as receiver. These two elements are coupled via another structure defined as the isolator, which typically provides a resilient connection that reduces structure-borne vibration transmission to the receiver.

Figure 1 describes these assembly elements, together with four interfaces that comprise the different excitation/response positions used for experimental measurements: Internal mechanisms of the source which are not part of the interface with isolator (a), the source-isolator interface (b), the isolator-receiver interface (c), and remote points on the receiver away from the isolator interface (d).

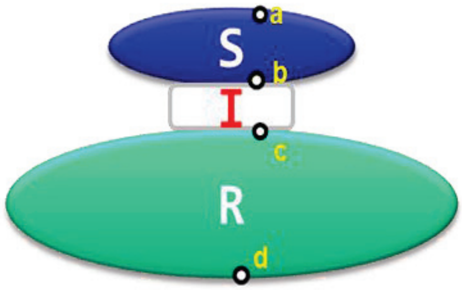

Figure 1: Source-Isolator-Receiver assembly diagram showing the different elements (S, I, R) and interfaces (a-d)

The following subscripts S, I, R are used to refer to the independent Source, Receiver and Isolator respectively; and subscript C for the Coupled assembly. Two more subscripts are also used to denote the sets of degrees of freedom (defined as interfaces in Figure 1) where response and excitation measurements are made respectively. As an example, ACcb refers to the accelerance of the coupled assembly where the response is observed below the isolator (c) when exciting at (b).

2.1 Blocked Force Method for active source characterisation

Unlike for airborne sound, for which acoustic sound power is the standard and provides a straightforward procedure for source prediction in different situations; for the case of structure-borne vibration there is no such method due to the fact that vibration behavior is highly dependent on the type of connection with a receiver structure. As a result, the use of vibration power is not useful for characterizing vibration sources that are likely to be installed in different ways (i.e. on different receiver structures). Ideal source characterization quantities are instead those that are transferrable from one assembly to another, for example the blocked force or free velocity.

Blocked forces of structure borne sound sources can be obtained *in situ* as demonstrated in (6,7). The in-situ blocked force method extracts properties of a vibrating source which can be transferred to its different assemblies using an inverse method. The blocked force can be defined in terms of acceleration as:

$$\bar{f}_{Sb} = A_{S,bb}^{-1}\tilde{a}_{Sb} \tag{1}$$

where f_{Sb} is the blocked force of the source at interface b, A_S is the source FRF and a_{sb} is the acceleration of the free source. Over score and tilde denote blocked and free conditions respectively.

An alternative of the blocked force equation 1 can also be derived for coupled assemblies, i.e. measurements *in situ*, therefore not requiring free-free conditions:

$$\bar{f}_{Sb} = A_{C,bb}^{-1}a_{Cb} \tag{2}$$

where f_{Sb} is the blocked force of the source at interface b, $A_{C,bb}$ is the coupled FRF at the source part and a_{Cb} is the operational acceleration of the coupled source at b.

The obtained blocked force is an intrinsic characteristic of the vibration source, therefore it can be used to predict the structure borne vibration when being part of other assemblies.

2.2 Dynamic sub-structuring

As mentioned in the previous section and detailed in (7), the dynamic substructuring method (DS) describes the behaviour of a coupled assembly using description of the individual contributions of the subsystems it is composed of. Therefore, this method offers several advantages compared with global ones that solve the entire system at once (3).

Inputs of DS in its frequency domain implementation consist of accelerance or equivalent measures (such as mobility or dynamic stiffness) of the elements at their interfaces with other assembly elements (e.g. Source at interface b with the Isolator). This technique also allows freedom for the characterisation of the different assembly elements, enabling the combination of numerical and analytical approaches (e.g. FEA or SEA); or experimental methods that incorporate directly measured data, which is the option presented in this work.

Despite all these advantages, the use of dynamic sub-structuring has implicit limitations that condition the reliability of the resulting predictions. To a large extent the uncertainties come from the fact that the application of matrix inversion is highly sensitive to errors, being able to affect the entire matrix when only one element is wrong before inversion (2). Another important factor affecting the accuracy of predictions of sub-structuring is the number of degrees of freedom (DOF) accounted for. Due to the inherent complexity of interface dynamics, a lack of information regarding translational and rotational DOF can strongly influence the error between prediction and validation measurements.

The definition of the transfer function of the coupled system from FRFs of independent characterisations of the assembly elements can be formulated as described in Eq. 3:

$$H_C = Y_{Rd}\,[Y_S + Y_{RI}]^{-1} Y_S \tag{3}$$

where Y_S and Y_{Rd} are the FRFs of the source and receiver d interface respectively, and Y_{RI} is the combination of receiver and isolator FRF and is defined as:

$$Y_{RI} = [Z_S + Z_I]^{-1} \tag{4}$$

3. EXPERIMENTAL SETUP

The three elements that form the studied assembly were independently characterised under either free-free or blocked conditions in order to allow the implementation of the methodology combining the use of blocked forces for active source characterisation together with dynamic sub-structuring of the entire assembly. As a result, accelerance FRFs were derived from hammer excitations and acceleration responses of the individual substructures in-situ.

The instrumentation used for these experiments consisted of 4533-B001 (B&K) single axis accelerometers and a SV84 (Svantek) triaxial accelerometer as response sensors, and an 8207 instrumentation hammer (B&K) for performing the different structure excitations. The force and acceleration measures together with their FRFs were synchronously collected using a SIRIUS acquisition card (DEWESOFT) at a sampling rate of 20000Hz with a frequency resolution of 0.6 Hz/data point.

3.1 Source and Receiver characterisation

The source selected for this experiment consisted of a slider-crank horizontal piston driven by an AC motor which was bolted to a 910x760x325mm steel block (Figure 2). The rotational speed of the AC motor was adjustable, in terms of input voltage by the use of a digital controller, as well as the weight of the driven piston, by the use of different amounts of metal plates on its end (Figure 2-right).

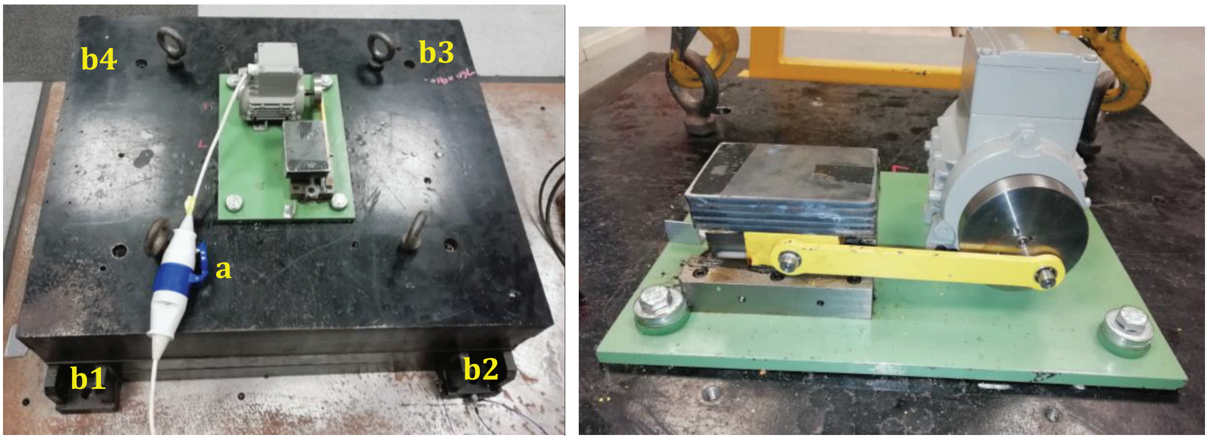

Figure 2: Vibration source from the top (left) and detailed view of the slider-crank AC motor (right)

An overall of twelve sensors were used for the source independent characterisation providing means of acceleration in X, Y and Z directions, for each of the four corners of the block under free-free conditions which were implemented by supporting the structure under four soft rubber pads.

Artificial excitations were applied at the connecting points between the source and the rubber pads, together with operational measurements under 5 different velocities (ranging from 5.2 to 8.2Hz equivalent to 311 and 494rpm) and two piston loads (1380 and 1720g).

Regarding the receiver structure, a 25mm thick metal plate supported on a 25mm non-shrinkable grout (Figure 3 left) was chosen. Hammer excitations were applied in X, Y and Z direction at the four connecting points with the source structure and means of acceleration were recorded at the same connecting points together with a triaxial transducer which was positioned in a remote location from the interface.

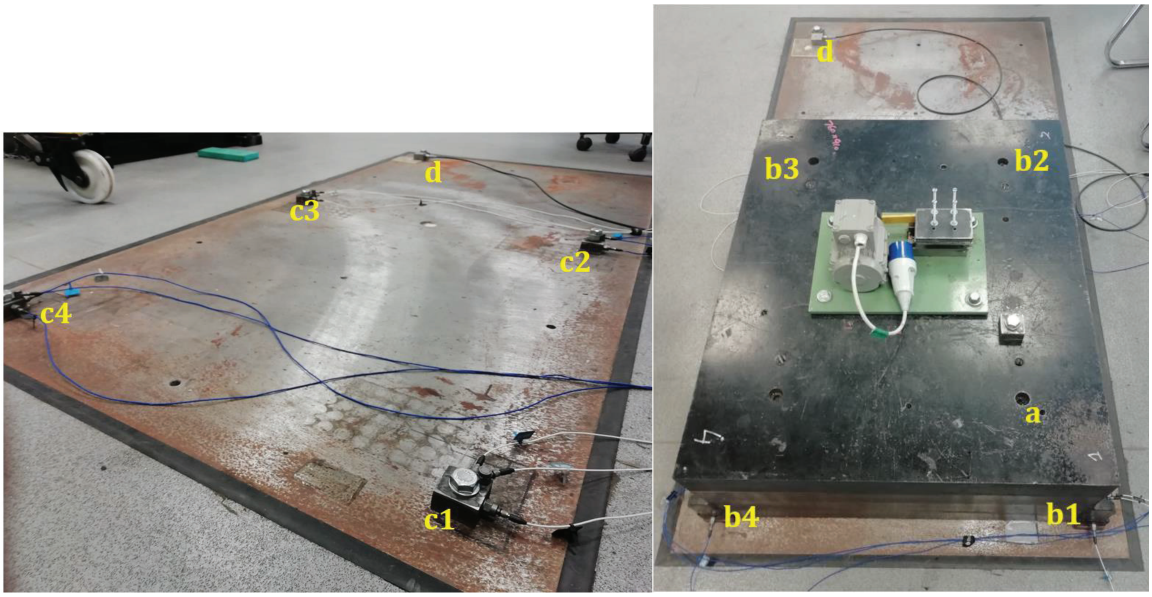

Figure 3: Receiver structure from the top (left) distinguishing c and d interfaces; right: Coupled assembly view from the top distinguishing the interfaces a, b and d

As a result, an overall of 15 accelerometers and hammer excitations were performed for characterising this assembly element under blocked conditions.

3.2 Isolator characterisation

A nitrile rubber and granulated cork composite Farrat material(8) named Vidam and typically used as industrial heavy machinery damper was chosen as coupling between source and receiver. Four 120x60x25mm rectangular pads of this material were characterised under two complementary methods: dynamic compression and in-situ method (Figure 4 left and right respectively).

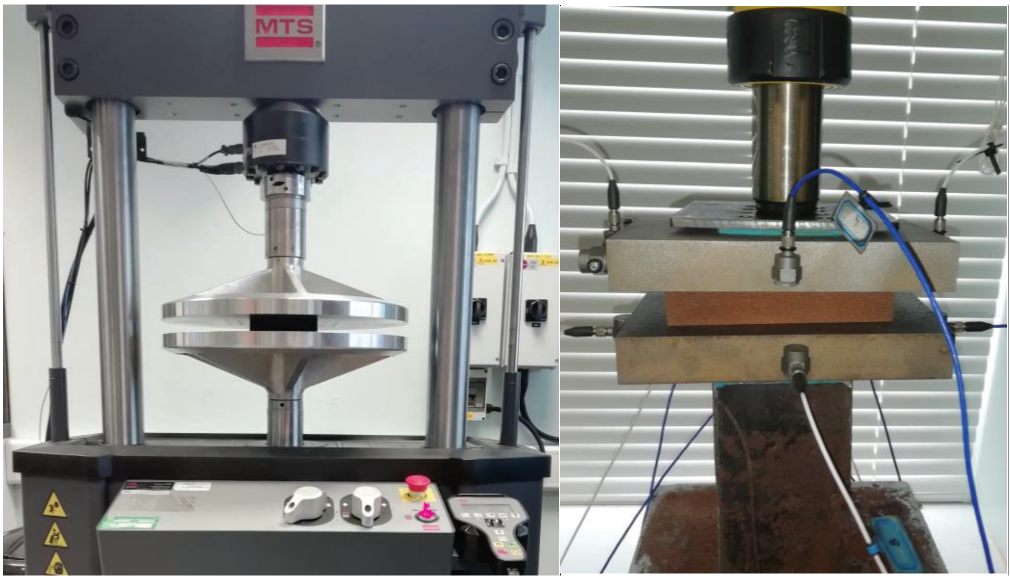

Figure 4: Dynamic compression (left) and in situ (right) isolator characterisation experimental setups

Dynamic compression characterisation was performed at frequencies between 1 and 100 Hz using a dynamic hydraulic testing press (MTS, USA) with an applied static preload of 4.5kN equivalent to a quarter of the overall weight of the source structure. Preconditioning was applied to the sample prior to the experiment in order to obtain more accurate and repeatable results in terms of complex dynamic.

In addition to this experiment and in order to also provide the performance of the isolators in terms of X and Y directions, the rectangular pad was also characterised using an *in situ* mass-isolator-mass procedure as described in (9) when applying a preload of 4.5kN using a pneumatic pump. It consisted of the acquisition of point and transfer mobilities above and below the material when connected to two known masses (Figure 4-right). 12 single axis accelerometers were used for this experiment (4 in Z and 2 in X and Y above and below the isolator) together with the application of forces above and below the rectangular pad of Vidam. Apparent mass was extracted from the accelerance FRFs acquired with the *in situ* method and then compared with the same obtained using the dynamic hydraulic testing press in Figure 5.

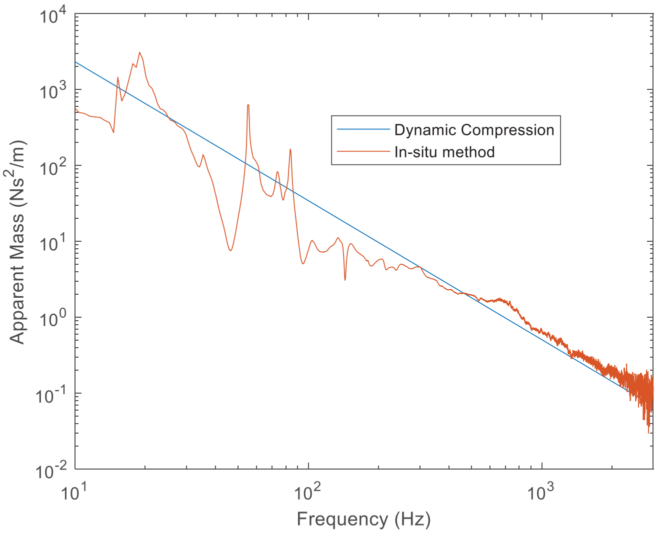

Figure 5: Apparent mass of Vidam obtained in vertical direction (Z) using the dynamic compression (blue) and the in situ (red) isolator characterisation experimental setups

Results show good agreement in frequency and justify the use of the in-situ method as a reliable approach to obtain the behaviour of isolators in the two axial directions.

3.3 Coupled Assembly Experiment

In order to provide validation data to compare with the predictions using the independent assembly element characterisations, the whole assembly was implemented by supporting the source structure to the receiver metal plate via four Vidam isolators as shown in Figure 3-right.

An overall of 15 acceleration channels (12 uniaxial sensors and 1 triaxial) recorded artificial excitations performed with an instrumentation hammer in the three directions at interfaces a, b and d. As a result, the accelerances obtained from the resulting FRFs were compared with the BF and DS predictions described in the following section.

4. RESULTS

4.1 Machine Vibration prediction

The blocked forces method was firstly used to predict the acceleration at the interface between the source and the isolator when coupled together by using the Eq.5:

$$a_{C,b} = A_{C,bb}\bar{f}_{Sb} \tag{5}$$

where $a_{C,bb}$ is the acceleration of the coupled assembly between the four source feet and the remote triaxial response at the receiver (interfaces b and d respectively). The average of the four feet predicted accelerances was compared with the average of the ones obtained in situ and can be visually observed in Figure 6 in X and Z directions (selected as the most representative of the system) in terms of narrow frequency and third octave bands.

Results show that predictions of the vibration coming into the source very accurately match the in situ measured data in both terms of narrow band and third octaves. Results at frequencies below 8Hz were omitted due to a lack of coherence in the experimental FRFs.

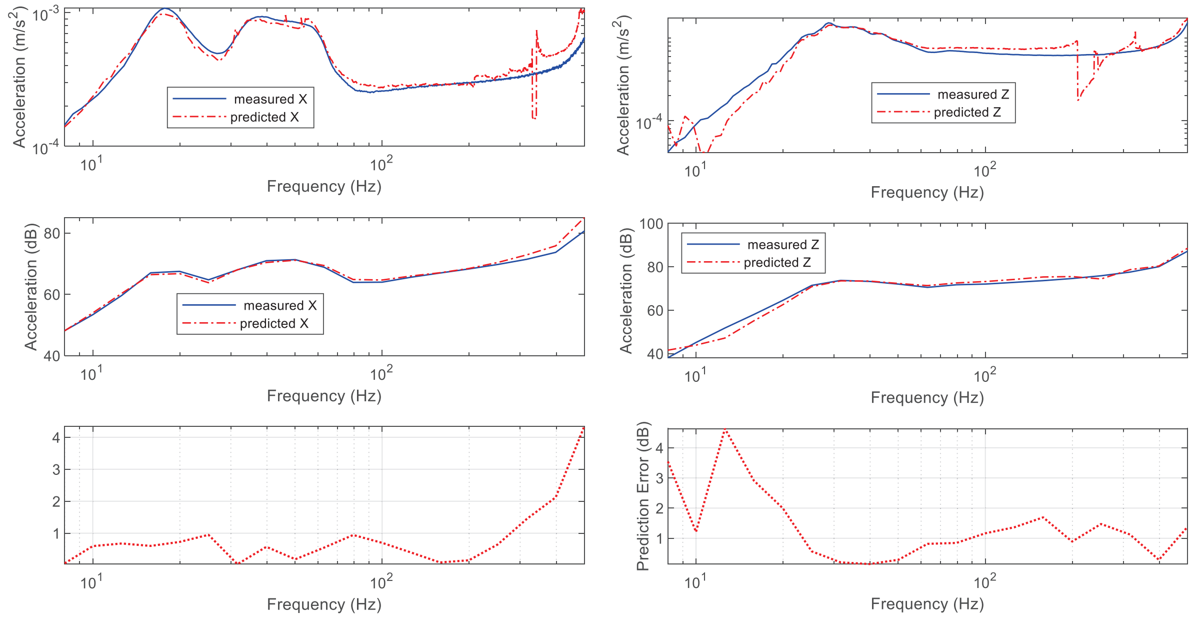

Figure 6: X (left) and Z (right) acceleration obtained in the coupled measurement (blue) vs prediction using BF (red-dashed) in narrow band frequency (top) in m/s2 and per third octave band (middle) in decibels (ref. 1µm/s2). Bottom: error between prediction and in situ obtained coupled acceleration (dB) in third octaves.

4.2 Remote acceleration prediction

Once validated the use of BF for predicting the amount of vibration on the feet of the source structure a different formulation is applied to the resulting FRFs to obtain an estimation of the vibration at the triaxial accelerometer located in the receiver outside the interface with the isolator pads:

$$a_{C,d} = A_{C,db}\bar{f}_{Sb} \tag{6}$$

where $a_{C,db}$ is the acceleration of the coupled assembly at the remote triaxial on the receiver (positions d) when applying an artificial excitation at a.

The acceleration recorded in the triaxial accelerometer was compared with the one predicted using Eq. 6 and can be seen in Figure 7 in X and Z directions in terms of narrow frequency and third octave bands.

The predicted accelerance provided a good fit to the in situ validation data exhibiting errors below 4dB for almost all the frequencies studied. Error peaks found at low frequencies are related to hardware limitations which led to a lack of coherence in the obtained FRFs. These results validate the use of the blocked forces method as a reliable independent active source characterisation which is also descriptive of its performance in new assemblies.

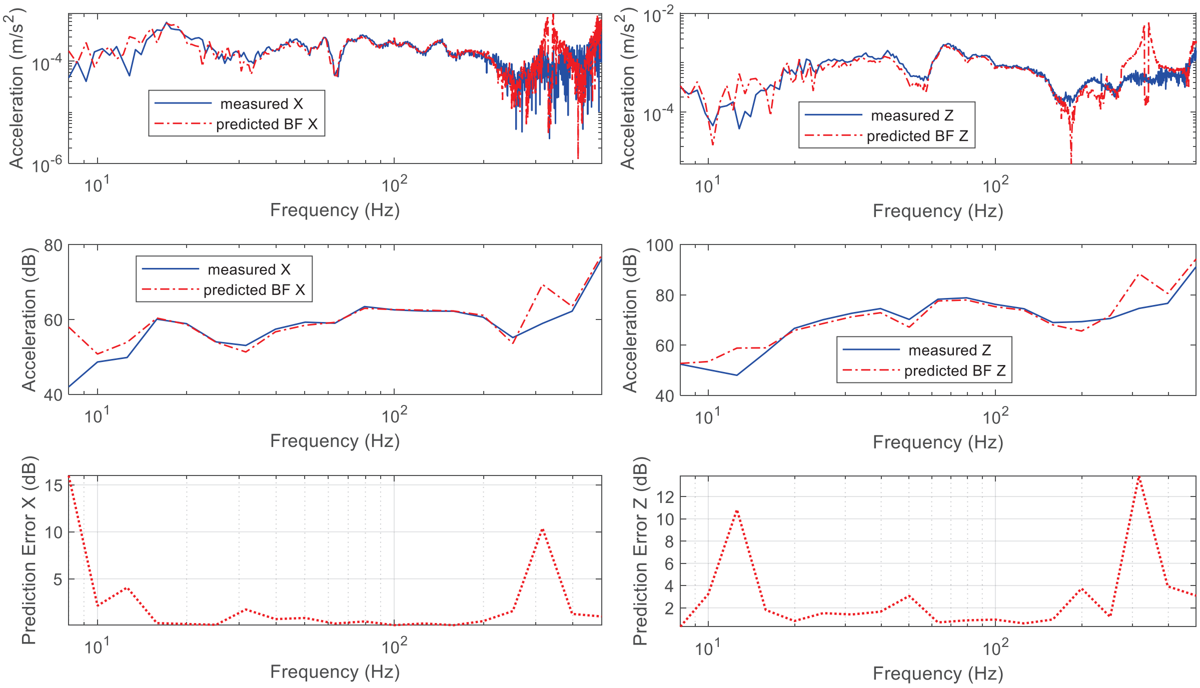

Figure 7: X (left) and Z (right) acceleration obtained in the coupled measurement (blue) vs prediction using BF (red-dashed) in narrow band frequency (top) in m/s2 and per third octave band (middle) in decibels (ref. 1µm/s2). Bottom: error between prediction and in situ obtained coupled acceleration (dB) in third octaves.

4.3 Dynamic Sub-structuring Prediction

Predictions using the combined BF and DS methods will be presented at the conference, and the application of alternative substructuring approaches will be explored as part of future work.

5. CONCLUSIONS

The work presented here demonstrates that the behaviour of a coupled assembly can be predicted using data from independent experiments performed on its elements. In order to achieve this, the source was characterised by its blocked force as it has been validated in the results of this paper. Further results showing the accuracy of this method together with dynamic sub-structuring for constructing the coupled assembly from accelerance matrices of isolators and receiver will be shown at the conference.

One of the key aspects of this methodology is that it would enable engineers not only to assess whether the use of an specific isolator would impact the vibration transmitted to the area were operators or precision machinery would be placed (receiver), but also the level of vibration experienced by the machine (machine tooling).

Future work includes the application of different sub-structuring approaches to the presented measurements and the validation of this methodology to heavier structures more representative of realistic situations such as industrial equipment supported on concrete inertia blocks. Alternatively, the use this methodology also allows the use of analytical and numerical data for the definition of independent measures of the assembly elements (such as analytical and numerical approaches) and therefore its implementation should be studied in more detail.

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