Prediction of structure borne noise and vibration for resiliently coupled equipment using blocked forces and substructuring

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Abstract

The transmission of vibration from a machine to its foundation can be predicted if all the elements of the installation are appropriately characterised. In order to do so the machine must be characterised in terms of its intrinsic operational vibration behaviour; e.g. blocked forces according to ISO 20270:2019. This data can be combined with a model of the installation formed from the passive properties of its individual elements (vibration source, isolation system and receiver) by sub-structuring. The approach is powerful since it allows elements of the system to be changed, e.g. the stiffness of isolators, to form virtual prototypes to predict noise and vibration at any position of the assembly. In this paper a case study is presented for a typical industrial installation comprising a vibrating machine attached to an inertia block supported by resilient mounts on a factory floor. The model is validated by comparing predictions of floor vibration to those subsequently measured on a physical realisation of the assembly.

1 Introduction

Industrial machinery has the potential to generate structure-borne sound and vibration that propagates to the surrounding floor and structures affecting nearby sensitive machinery and workers, have an influence in its precision and damage its inner tooling, potentially having significant effects on its performance. In order to predict structure-borne sound and vibration from a machine to its nearby environment, there is a need to characterise each element individually to anticipate how the assembled structure would behave. This would allow not only mitigation measures after construction but also optimisation actions at the design phase of a project.

In some cases, vibration sources can be characterised using modelling software. However, as a result of high computational requirements and disagreements with field-data [1], measurements are necessary in most cases. Since the structure-borne sound power of a source is also highly dependent on the receiver, it is widely accepted that a characterisation independent on the mounting interface is required and the parameters commonly used are free velocity [2] and blocked force [3]. These methods can be combined with the dynamic sub-structuring approach, as defined for example by Jetmundsen et al [4] or Rixen, de Klerk et al [5], which have the capability to associate measured or simulated frequency response functions of individual elements which would be part of the same assembly to predict its overall behaviour once coupled.

This paper presents a case study concerning the application of the in-situ blocked forces together with the sub-structuring method to an air compressor and inertia block installed on resilient mounts. The first objective is to calculate the blocked forces at the feet of the air compressor and at the corners of the inertia block it is attached to, and verify that they are independent of the receiver they are coupled to, as they should be by definition (see section 2). The second aim of the paper is to compare predicted vibration levels obtained from blocked forces to those directly measured at remote points on the receiver when the source was operating. Finally, a sub-structuring approach subdividing the assembly into four components namely vibration source, inertia block, isolator and receiver, is applied to predict vibration experienced at two locations of the receiver and is compared with actual operational measurements.

2 Theory

The assembly presented in the paper is composed of four elements namely vibration source (S), inertia block (IB), isolator (I) and receiver (R). A two-stage air compressor was used as a vibration source rigidly coupled to a concrete inertia block implemented within the system to replicate isolated foundations set-ups, providing mass damping and increasing system stability as a result of increased stiffness and lower centre of gravity. These elements are supported on isolators, which provide a soft connection reducing structure-borne vibration transmitted to the receiver.

Figure 1 describes the elements of the assembly with their interfaces, indicating the different excitation and response positions used for experimental measurements. (a) is the location of the internal forces within the source, (b) represents the source-inertia block interface, (c) is the inertia block-isolator interface, (d) is the isolator-receiver interface and (e) is the location of a point on the receiver away from the interface.

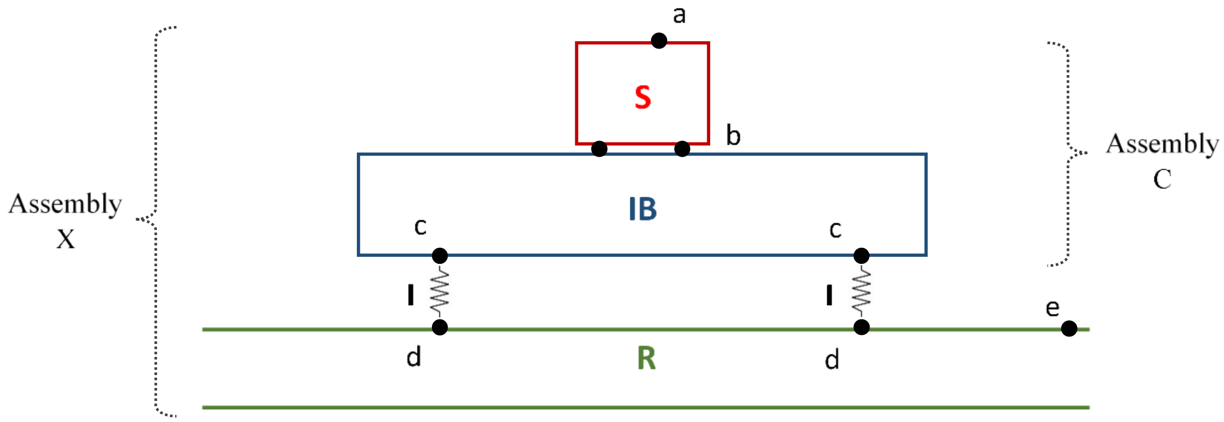

Figure 1: Assembly diagram showing the four elements (S, IB, I, R) with their interfaces (a, b, c, d, e)

The subscripts S, IB, I, R are used to refer to the independent Source, Inertia Block, Isolator, Receiver respective elements, when C and X are used to describe the aforementioned assemblies. Two more subscripts detail the interfaces where response and excitation measurements are captured respectively. For instance, $Y_{X,eb}$ refers to the mobility matrix of the assembly X where the response is observed at (e) when exciting (b).

2.1 In-situ blocked force method

Approaches such as the inverse methods measuring operational forces at the source-receiver interface in-situ have proven successful, particularly in transfer path analysis [6]. However, the forces obtained are not intrinsic properties of the source since they are largely influenced by its mounting condition as well as the receiver itself. Ideal source characterisation quantities are instead those that are transferable from one assembly to another, for example the blocked force or free velocity.

In order to characterise the source S, the free velocity $v_{S,b}$ can be measured at the contact points (b) while the source is hanging and running at constant operation conditions. The blocked forces can be determined in-situ according to:

$$f_{S,b} = Y_{S,bb}^{-1} \, v_{S,b} \tag{1}$$

where $f_{S,b}$ is the blocked forces at interface (b), $Y_{S,bb}$ is the free source mobility, and $v_{S,b}$ is the operational free velocity.

In most cases, operating the source in free conditions is not feasible and the blocked forces can also be obtained when the vibration source is installed within any assembly, independently from its boundary conditions:

$$f_{S,b} = Y_{X,bb}^{-1} \, v_{X,b} \tag{2}$$

where $f_{S,b}$ is the blocked forces at interface (b), $Y_{X,bb}$ is the mobility at the source-inertia block interface of the assembly X and $v_{X,b}$ is the operational velocity of the coupled source at (b).
As just presented, the blocked forces for source characterisation reveal the intrinsic properties of the latter allowing one to make a prediction of structure borne noise produced by the source when installed in different environments. This has already been demonstrated previously for simple [7] and more complex assemblies [8][9] and will be further illustrated in this paper.

2.2 Dynamic sub-structuring

As described in [10], dynamic sub-structuring (DS) methods determine the behaviour of an assembly using individual characterisations of the different elements composing it. As formulated in Eq. 3, DS requires mobility (or equivalent such as compliance or accelerance) inputs of the elements at their interface locations. Thus, several advantages can be identified compared to global approaches predicting overall behaviours of assemblies. DS allows a wide range of characterisation methods of the assembly elements, enabling the combination of numerical approaches such as finite element method (FEM) and experimental in-situ measurements which is the option presented in this paper. Hence, one of the main benefits of this method is the possibility to adapt dynamic stiffness on substructure level i.e. inertia block or isolators in our example (vibration source and receiver are usually invariable in industrial applications) to optimise system behaviours and reach designed solutions to specific applications.

Despite this, the use of the DS method presents limitations affecting the accuracy of the predictions obtained [11]. Matrix inversion is highly sensitive to errors [4] and only few erroneous elements have the potential to affect entire matrices to be inversed, propagating uncertainties across the entire calculations.

The mobility at the (e) location of the coupled assembly X can be obtained from the independent characterisations of the sub-elements composing the assembly, and is formulated as:

$$Y_{X,eb} = Y_{R,ed} \left[Y_I + Y_{R,dd}\right]^{-1} Y_I \left[- Y_I \left(Y_I + Y_{R,dd}\right)^{-1} Y_I + Y_I + Y_{C,cc}\right]^{-1} Y_{C,cb} \tag{3}$$

where Y_R and Y_I are the mobility matrices of the receiver and isolator respectively, and $Y_{C,cc}$ and $Y_{C,cb}$ are the combinations of the source and inertia block obtained by sub-structuring, using:

$$Y_{C,cc} = \left[Z_{IB} + Z_{S,bb}\right]^{-1} \tag{4}$$

$$Y_{C,cb} = Y_{IB,cb} \left(Y_{S,bb} + Y_{IB,bb}\right)^{-1} Y_{S,bb} \tag{5}$$

3 Experimental set-up

3.1 Sub-assembly characterisations

The four components of the assembly were individually characterised with mobility FRFs obtained from artificial excitations and velocity responses at the interface locations of each elements. These were combined with measures of the velocity at the same locations while the air compressor was operating at constant conditions.

The instrumentation used for these experiments consisted of 4533-B001 (B&K) single axis accelerometers as response sensors, and an 8207 instrumentation hammer (B&K) for performing the different structure excitations. The force and velocity measures together with their FRFs were synchronously collected using a SIRIUS acquisition card (DEWESOFT) at a sampling rate of 16450 Hz with a frequency resolution of 1 Hz/data point.

3.1.1 Source

The vibration source is a 3 horsepower (HP) Clarke XEV16 air compressor weighing 69 kg. It is composed of a V twin pump and an air tank volume of 100 Litres.

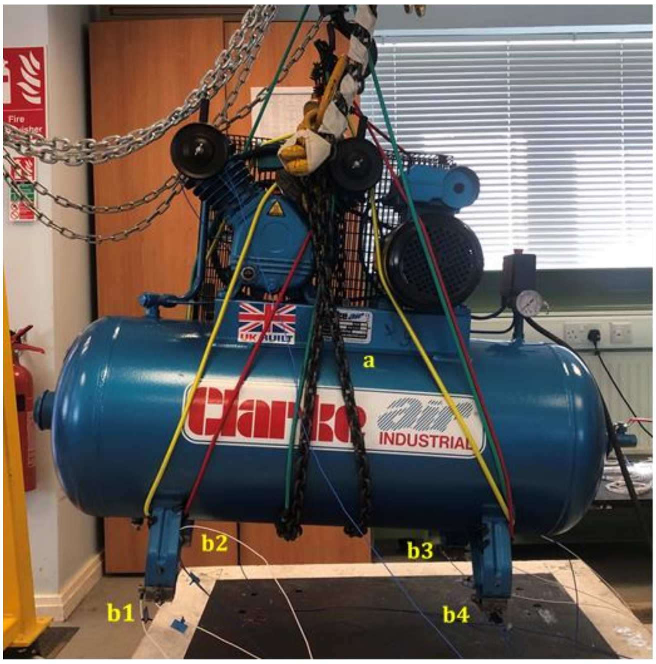

Figure 2: Vibration source hanging, with (a) and (b) interface positions

The machine was raised and kept hanging with steel chains and bungee cords to get as close as possible to free-free conditions. Twelve transducers were used for the independent source characterisation providing acceleration in X, Y and Z directions at each foot of the air compressor. The source was excited with a hammer and responses were measured at the machine feet to obtain the mobility required for sub-structuring analysis (see Eq. 3).

3.1.2 Inertia Block

The inertia block weighs 825 kg and is composed of a 1 x 1 x 0.3 m concrete structure with a 0.8 x 0.8 x 0.04 m steel plate built within it. The latter offers a homogeneous and flat surface with precise threaded holes, allowing for an ideal coupling between the arrangement and the interfaces (b).

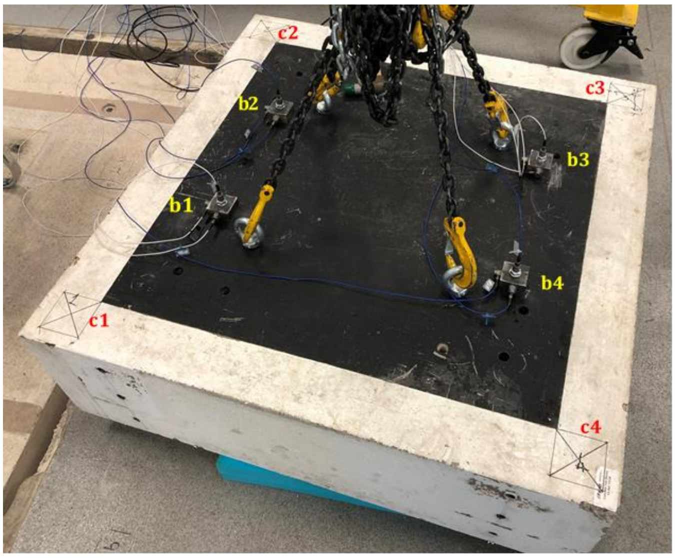

Figure 3: Inertia Block hanging, with (b) and (c) interface positions

Similarly to the source, the inertia block was suspended with steel chains to replicate free-free conditions. Twelve transducers were used for the inertia block characterisation providing acceleration in X, Y and Z directions at each location of (b) when exciting (b) and (c). Four accelerometers were also placed at the corners of the block at (c) to measure the vertical mobilities of the structure used in the sub-structuring calculations.

3.1.3 Isolator

Two types of isolators manufactured by Farrat Isolevel were used in this experiment. Four 75 x 75 x 75mm natural rubber pads NR6250II [12] and four 50 x 50 x 25mm granulated cork composite pads VM7025PP [13] typically used as industrial machinery isolators were selected as interfaces between the inertia block and the receiver. They were vertically characterised with a dynamic hydraulic testing press (MTS, USA). This machine uses the ISO 6721 Part 12 test standards for conducting DMA (determination of dynamic mechanical properties) of materials in compression, at frequencies up to 200 Hz. The test procedure characterises the viscoelastic properties by determining the storage (E'), loss (E'') and complex (E*) moduli as well as the tan delta (tan δ) as a function of frequency. In our example, the only needed parameter is the complex dynamic stiffness (K*) which is required to obtain the isolator mobility used in Eq. 3.

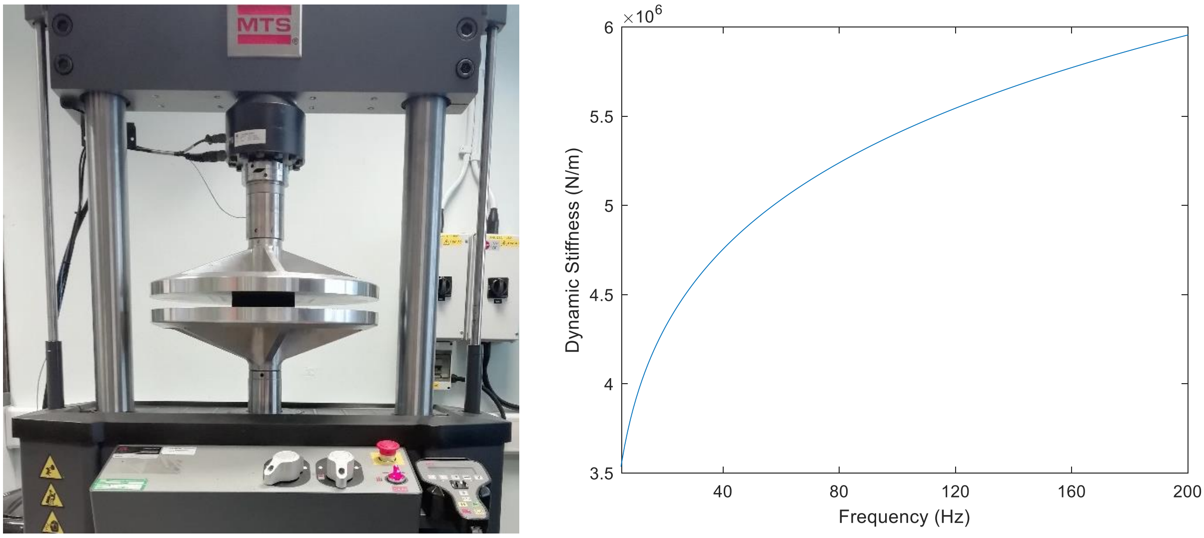

Figure 4: Dynamic compression for isolator characterisation (left) and dynamic stiffness of VM70 obtained in the vertical direction (Z) (right)

3.1.4 Receiver

The receiver is a 1.5 x 1.5 x 0.25 m concrete foundation supported by stiff pads (Farrat structural thermal breaks, elastic modulus of 4100 MPa). Thus, it is supposed to present similar mean mobility to a continuous heavy weight factory floor.

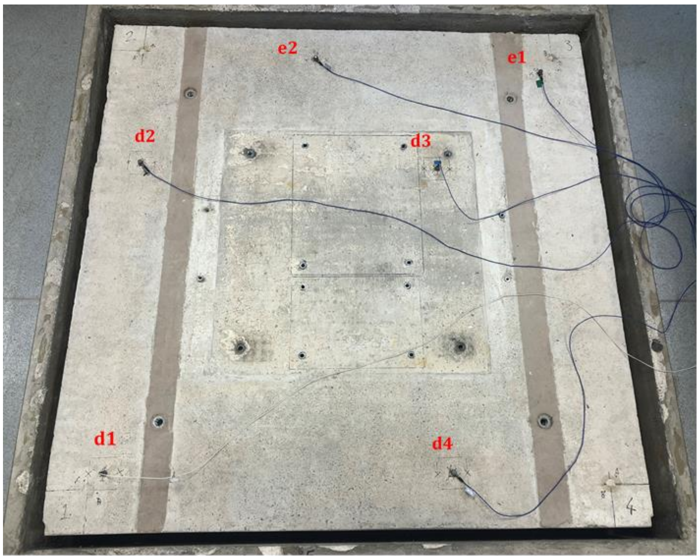

Figure 5: Receiver structure with (d) and (e) interface positions

The slab was excited using an instrumented hammer in the vertical direction (Z) at the four connection points with the isolators (d) and at two remote locations (e) on the receiver and velocity was recorded at those points to obtain the mobility matrices required in Eq. 3.

3.2 Coupled assembly experiment

Figure 6 presents the coupled experiment, corresponding to assembly X in Figure 1. It is composed of the air compressor rigidly coupled to its inertia block separated from the receiver by isolators. The inertia block was positioned off-centre on the receiver to avoid any potential symmetry simplifying the case study to evaluate the robustness of the method to be later used on continuous factory floors.

Figure 6: Coupled assembly with interface positions

The assembly was excited with the instrumented hammer to obtain the mobility matrices at (b) and (c) interfaces, used in the blocked force calculations presented in section 4.1. Operational measurements were also performed, at a constant motor cadence of 1320 revolutions per minute (22 Hz) with an open valve displacing a volume of air of 14 cubic feet per minute (cfm), to collect structure velocities at different interface positions (in particular at (b), (c) and (e) to obtain the results presented in the following section).

4 Results

In the following sub-sections, the blocked forces calculated at the interface (c) from one configuration (assembly X with NR62 isolators) is used to predict the velocity of a point on the receiver from a second configuration (assembly X with VM70 isolators). This predicted velocity is compared with direct operational measurement to demonstrate that the blocked force is not dependent on its mounting conditions. Secondly, the sub-structuring and blocked force methods are combined to predict the velocity experienced at the same point of the receiver and once again compared with direct operational measures.

4.1 Blocked forces predictions

Operational blocked forces of the assembly X using natural rubber NR62 isolators have been computed at the corners of the inertia block (c) using the two following formulations. Eq. 6 uses a direct measurement of the velocity at (c), when Eq. 7 derives this velocity from the mobility matrix between (b) and (c) and the blocked forces at (b).

$$f_{S,c} = Y_{X,cc}^{-1}\, v_{X,c} \tag{6}$$

$$f_{S,c} = Y_{X,cc}^{-1}\; Y_{X,cb}\, f_{S,b} \tag{7}$$

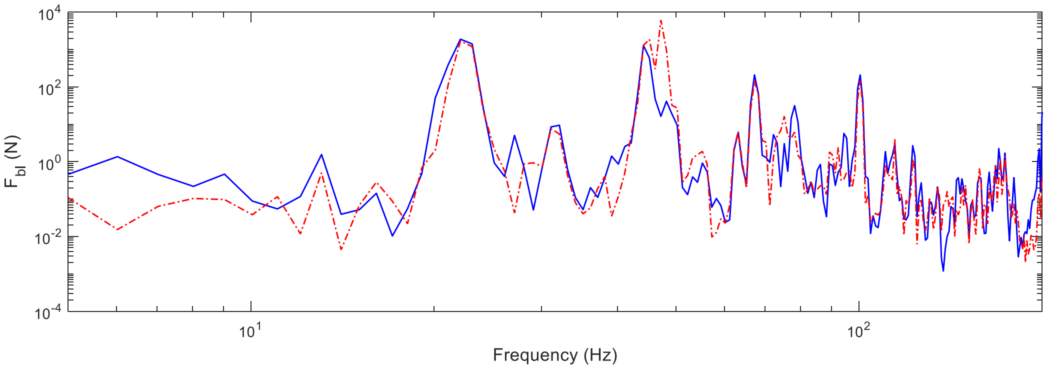

Figure 7: Logarithmic representation of the vertical blocked forces at the (c) interface using Eq. 6 (blue) and Eq. 7 (red-dashed) in narrow band frequency between 5 and 200 Hz

This figure presents a good agreement at the operational velocity of the source (22 Hz) and its harmonics (multiples of the fundamental frequency). Some disparities are observed below 20 Hz and between the peaks, due to the fact that they are located at frequencies not excited by the vibration source. However, in theory, the blocked force method is not restricted to any particular frequency range, see for example [14]. This comparison therefore validates the blocked forces obtained at the (b) interface for this range of frequency.

Since the blocked forces at (b) present a satisfactory result, it is interesting to consider the air compressor and the inertia block placed below as an individual vibration source and verify the reliability of the blocked forces at (c). In order to do so, a predicted velocity at the (e) position, located on the receiver away from the isolator interface, can be obtained using the blocked forces at (c) coming from the assembly X on NR62 isolator pads and from the mobility matrix between (e) and (c) coming from the assembly X on VM70 isolator pads:

$$v_{X,e} = \; Y_{X,ec} \, f_{S,c} \tag{8}$$

The predicted velocity provided a good fit with the in-situ direct operational measurement of the assembly X on VM70 isolators, with good agreement in the narrow band representation at the peaks defining the source operational speed and the successive harmonics, and also in the third octave representation. This enables the use of the blocked force method as a reliable independent active source characterisation, which is therefore descriptive of this source performance in any other assembly.

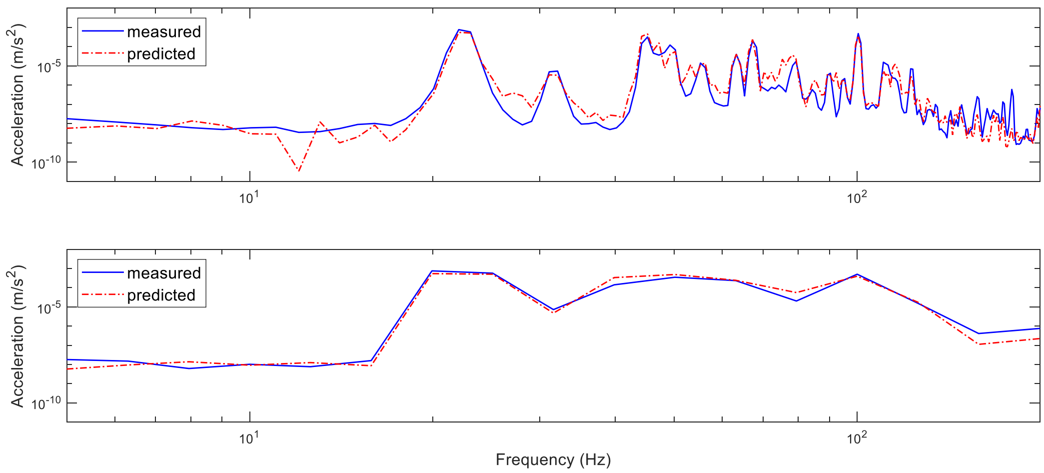

Figure 8: Logarithmic representation of the vertical acceleration measured (blue) and predicted at (e) using Eq. 8 (red-dashed) in narrow band frequency (top) and in third octave band (bottom) between 5 and 200 Hz

4.2 Sub-structuring prediction

The mobility matrix $Y_{X,eb}$ can be derived from the mobilities of each element of the assembly as described in Eq. 3. The latter can then be inserted in Eq. 9 with the afore-validated blocked forces at (b) interface to predict the operational velocity experienced at a remote location (e) of the receiver, when the inertia block is supported on VM70 pads:

$$v_{X,e} = Y_{X,eb}\, f_{S,b} \tag{9}$$

This calculated velocity is compared in Figure 9 with the direct operational velocity recorded at the (e) position as part of the assembly X. The most important frequencies regarding perception are those where the peaks are located in the spectrum. Considering that, and as highlighted by the third octave representation, the predicted vertical vibration is found to be in decent agreement with the measured one between 20 to 130 Hz.

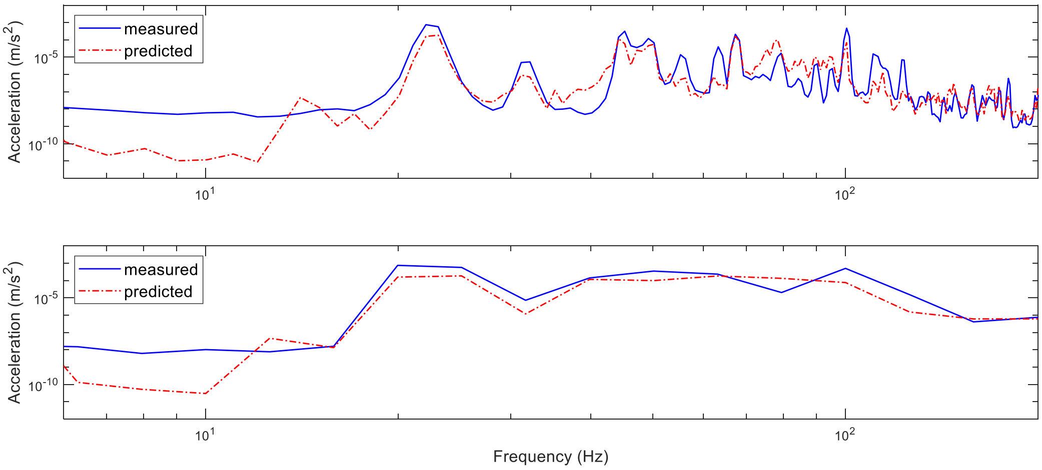

Figure 9: Logarithmic representation of the vertical acceleration measured (blue) and predicted at (e) using Eq. 9 (red-dashed) in narrow band frequency (top) and in third octave band (bottom) between 5 and 200 Hz

Figure 9 demonstrates that the blocked forces measured in-situ in a realistic installation can be combined with mobility FRFs of individual elements by sub-structuring to make structure-borne sound and vibration prediction of the combined assembly.

5 Conclusion

This paper has investigated the in-situ blocked force together with a sub-structuring approach in the context of industrial machinery vibration source. In order to replicate usual isolated foundation designs, an inertia block has been inserted within the usual Source-Isolator-Receiver system. The two different vibration source configurations (air compressor and air compressor/inertia block) were characterised at each connection point between the source and the rest of the assembly.

Two validation results are presented in this paper to demonstrate that the blocked force in-situ method is a reliable approach to characterise a vibration source independently from its mounting condition. It was shown that the blocked forces could be used to predict the vibration velocity of a point located on the receiver when the machine was installed in a different condition than the one in which it was characterised. Thus, these forces could be applied to reconstruct the response of that same source as part of any other assemblies.

Finally, a sub-structuring approach combined with the blocked force method was successfully applied on the four-element structure to predict the vibration level experienced on the receiver. However, this method remains sensitive to potential errors that could emerge from the complexity of characterising every sub-element under free conditions combined with the difficulty of accessing some of the interfaces and take into account the correct number of degrees of freedom.

Although the results presented in the paper are promising, future work should be undertaken to apply this methodology on heavier machinery in places offering more realistic conditions such as industrial factories. Alternatively, the implementation of analytical and numerical data for the characterisation of assembly elements such as the isolator and the inertia block would be crucial for vibration isolation companies to be able to optimise their design based on their client needs.

Acknowledgements

This work was supported by an Innovate UK Knowledge Transfer Partnership between Farrat Isolevel and University of Salford.

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