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Structure borne noise characterization of an air generation and treatment unit (AGTU) for a train using the mobility method and sub-structuring

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ABSTRACT

Accurate predictions of train Interior structure borne noise are extremely challenging to achieve but are an essential requirement for rolling stock manufacturers seeking to provide the highest levels of passenger comfort. In order to predict interior noise from structure borne noise sources (prior to installation) it is first necessary to perform measurements that characterise the source using quantities that describe their vibration behavior intrinsically. This source characterisation data can then be combined with data from the train (receiver), or an FE model of the train, using the method known as sub-structuring. In this paper, a source characterisation case study is presented for a typical structure borne noise source known as an Air Generation and Treatment Unit (AGTU) that is to be installed on a train. It is described in the paper how the passive properties of the AGTU were characterised taking into account 6 degrees of freedom at each mount and predictions of the coupled behavior of the AGTU in a source-receiver assembly are presented. The work forms part of a larger collaborative research study involving a rolling stock manufacturer, their equipment suppliers and academia aimed at developing a joint methodology for the specification and prediction of structure borne noise.

Keywords: Structure Borne Noise, Vibration, Sub-Structuring, Blocked Force, TPA
I-INCE Classification of Subject Number: 43

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1. INTRODUCTION

The prediction of structure borne noise using experimental data is known to be challenging but with modern instrumentation and new methods emerging it is now feasible to make estimates fit for the purposes of equipment specification and virtual acoustic prototyping. In general, it has been found that the more sophisticated approaches, employing multi-channel data acquisition systems, show the most promise in terms of accuracy but they are time consuming and challenging to execute. On the other hand, simplified methods, are easier to implement but may lack the desired accuracy, especially at low frequencies. In practice, both approaches have their place depending on practicality, the accuracy required and the frequency range of interest much in the same way that FEA and SEA are complimentary to each other.

In this paper we present a purely experimental case study where a source of low frequency structure borne noise/vibration has been characterised in terms of its blocked force (operational characteristic) and mobility (passive property) for the purpose of predicting structure borne noise on a train. In a companion paper[1], also submitted to Internoise 2019, the characterisation of the operational behavior of the same source is addressed in detail and it is shown that the blocked forces of an air generation and treatment unit (AGTU) can be obtained in six degrees of freedom at each contact point by in-situ measurement.

In this paper we look at the equally challenging problem of sub-structure coupling which involves combining passive measurements of separate source and receiver substructures to predict the passive properties of an assembly. The combination of blocked force characterisation (operational source activity) and the source and receiver mobilities (the passive properties) then allow predictions of structure borne noise and vibration to be made. The background theory of sub-structure coupling and in-situ source characterisation is covered in the following section.

Although the work presented here is entirely measurement-based, the long term aim of the research is the combination of experimental and numerical models for the prediction of noise and vibration and for the specification of noise sources.

2. THEORY

The blocked force $\mathbf{f}_{\mathbf{S},\mathbf{bl}}$ of a structure borne sound source can be determined in-situ[2] using the equation,

$$\mathbf{f}_{\mathbf{S},\mathbf{bl}} = \mathbf{Y}_{\mathbf{C}}^{-\mathbf{1}}\mathbf{v}_{\mathbf{C}} \tag{1}$$

where $\mathbf{f}$, $\mathbf{Y}_{\mathbf{C}}$ and $\mathbf{v}$ are force, mobility and velocity respectively. Here, the uppercase subscript, **S**, denotes properties of source structure alone and **C** properties of the coupled source and receiver assembly. The lower-case subscript, **bl**, indicates a blocked condition.

The mobility of the source-receiver interface, $\mathbf{Y}_{\mathbf{C}}$, is a combination of the passive properties of the source and receiver substructures, i.e. the source and receiver mobilities $\mathbf{Y}_{\mathbf{S}}$ and $\mathbf{Y}_{\mathbf{R}}$ respectively. It can also be expressed as the inverse sum of the source and receiver impedances $\mathbf{Z}_{\mathbf{S}}$ and $\mathbf{Z}_{\mathbf{R}}$:

$$\boldsymbol{Y}_{\boldsymbol{C}} = \left[\boldsymbol{Y}_{\boldsymbol{S}}^{-\mathbf{1}} + \boldsymbol{Y}_{\boldsymbol{R}}^{-\mathbf{1}}\right]^{-\mathbf{1}} = \left[\boldsymbol{Z}_{\boldsymbol{S}} + \boldsymbol{Z}_{\boldsymbol{R}}\right]^{-\mathbf{1}} \tag{2}$$

Equation 2 in combination with Equation 1 can be used to predict vibration levels at the source-receiver interface of an assembly starting from data describing the separated substructures. What is generally of most interest however is the response of the assembly at a location which is remote from the source-receiver interface, e.g. a listener's position. For sound pressure this can be written as,

$$\mathbf{p'_C} = \mathbf{H'_C f_{S,bl}} \quad (3)$$

where $\mathbf{H_C}$ is a set of vibro-acoustic frequency response functions relating the degrees of freedom at the source-receiver interface to a reference point on or in a compartment of the assembly, **C**, and **p** is the sound pressure. Note that the dash symbol in $\mathbf{H'_C}$ and $\mathbf{p'_C}$ is used here to highlight that the assembly **C** need not be the one in which the source blocked forces were characterised.

When broken down into its constituent parts, i.e. source and receiver, Equation 3 can be rewritten as,

$$\mathbf{p'_C} = \mathbf{H_R}[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S f_{S,bl}} \quad (4)$$

where,

$$\mathbf{H'_C} = \mathbf{H_R}[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S} \quad (5)$$

is the equation for the frequency response functions that relate the interface degrees of freedom on the source receiver assembly to the point of interest. Also note that in equation 4, the term $[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S f_{S,bl}}$ is the force on the receiver structure $\mathbf{f'_R}$.

In the companion paper[1] the blocked force measurements of a complex real-world vibration source are validated in detail. The next logical step is therefore to validate Equation 5 as part of the combined source characterisation and sub-structuring methodology. The validation of equation 5 and the subsequent prediction of structure borne noise or vibration by equation 3 are therefore the main focus of this paper.

3. MEASUREMENT SETUP

As reported in the companion paper[1] the vibration source used for the case study was an air generation and treatment unit (AGTU) to be installed on a train. Measurements were performed on the AGTU under two different configurations on a bespoke test bench constructed by the equipment manufacturer Faiveley. The two test configurations, free and rigidly coupled are shown in Figure 1.

In the free configuration, #1, the source mobility $\mathbf{Y_S}$ was measured together with the source free velocity, $\mathbf{v_{S,fr}}$. In practice however, the source can only be considered free above the mounted resonance of the assembly (which is one reason why the in-situ blocked force approach is favoured). In the companion paper it is shown that the blocked force measured in both configurations are the same when six degrees of freedom at each coupling point are taken into account; i.e. $\mathbf{f_{S,bl}} = \mathbf{Y_C^{-1} v_C} = \mathbf{Y_S^{-1} v_{S,fr}}$ where $\mathbf{Y_s}$ is the source mobility and $\mathbf{v_{S,fr}}$ is the free velocity. This demonstrates that the same blocked forces can be obtained from two extreme mount conditions, experimentally validating equation 1.

To complete the methodology it therefore only remains to validate Equation (5) by accurately predicting $\mathbf{H'_C}$ and to make a prediction of the structure borne noise $\mathbf{p'_C}$ or test bench vibration using the blocked force together with the source and receiver mobilities, as in Equation 3. Most importantly this should be done for a configuration other than the one in which the source of vibration was characterised. For this reason, the results presented in the paper take the blocked force and source mobility from configuration #1 (free) and the receiver mobility (without the equipment installed) and combine them by sub-structuring to make a prediction of the source's installed behaviour in configuration #2. Because there was no compartment available on the test bench for sound pressure measurement without a strong contribution from the airborne component, the vibration acceleration is used for validation purposes here rather than the sound pressure. The only difference is that $\mathbf{H_R}$ is a set of transfer mobilities between the interface degrees of freedom and a reference position rather than a set of vibro-acoustic frequency response functions; i.e. the vibration of the test bench is predicted rather than structure borne noise.

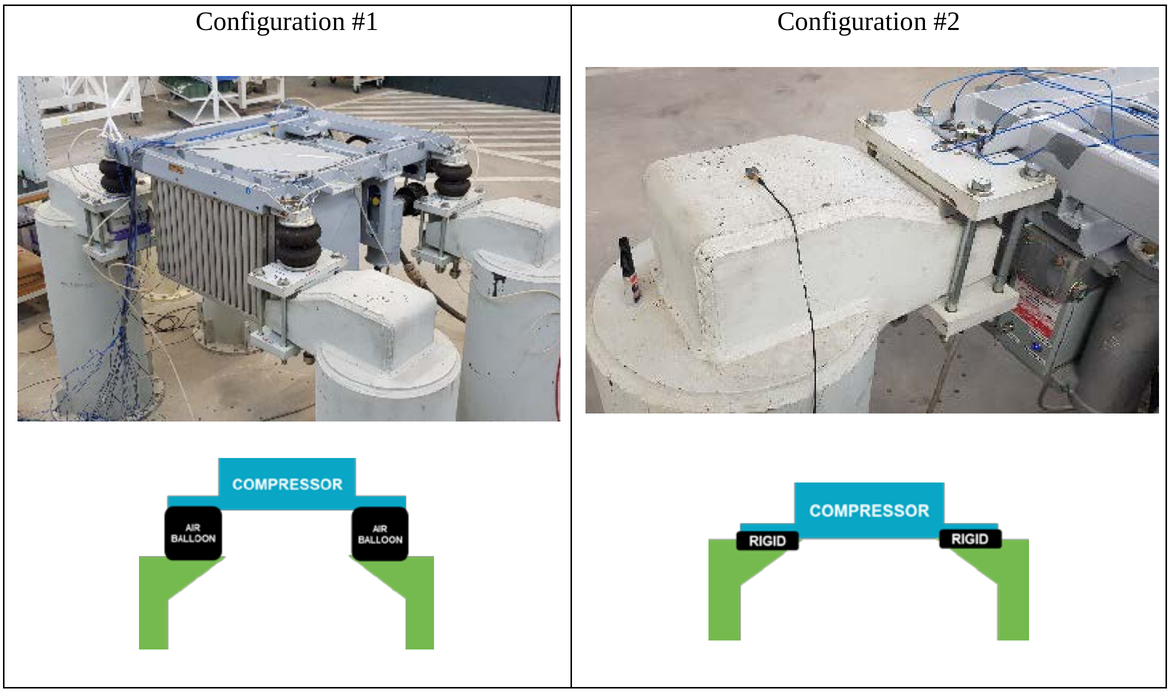

Fig. 1 – AGTU mounted on test rig according two different boundary conditions: 'freely' mounted on air balloons named configuration #1 (left photo) and rigidly named configuration #2 (right photo).

To summarise, the source and receiver characterisation and prediction methodology is as follows:

- Source mobility and source velocity measured in configuration #1
- Blocked forces of the source calculated
- Receiver mobility measured for the test bench alone
- Source and receiver mobilities combined by sub-structuring (Equation 5)
- Prediction of test bench vibration in configuration #2
- Comparison with directly measured test bench vibration from configuration #2

In order to capture six degrees of freedom at each connection point the method outlined in reference[3] was used together with the test arrangement described in the companion paper[1]. The experimental arrangement for one of the connection points in configuration #2 is shown in Figure 2.

It can be seen in Figure 2 that seven accelerometers are used to capture six degrees of freedom at each connection point when in principal only six should be required. This is done for convenience because using this arrangement moments/rotations about the x and y axes can be easily determined using the finite difference method[3]. Alternatively, each contact position can be considered as multiple points in translation thereby taking into account moments and rotations without having to define them explicitly[3]. This is the approach used to obtain the results presented in the paper.

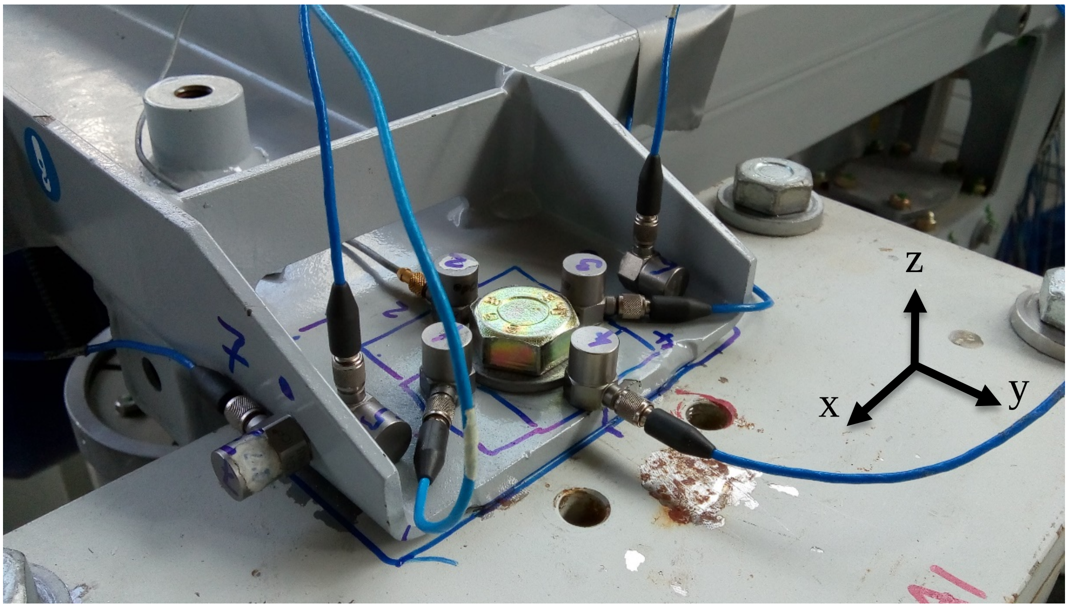

Fig. 2 – Instrumentation of AGTU connection point

4. SUB-STRUCTURING

As set out above the first aim of the paper is to validate equation 5 using the passive measurements of the source and receiver structures when decoupled, i.e. $\mathbf{Y_S}$, $\mathbf{Y_R}$ and $\mathbf{H_R}$. Because the blocked forces have already been validated in the companion paper, the velocity of the test rig when the source is operational can then be predicted by pre-multiplying with the estimated $\mathbf{H_C}$ matrix according to equation 3.

Shown in Figure 3 are measured and predicted elements of the $\mathbf{H_C}$ matrix corresponding to excitation in the z, y and x directions with responses at the reference location in the z, y and x directions respectively. It can be seen that a fair agreement has been obtained between the measured and predicted coupled transfer accelerances of the test bench with the AGTU installed. Better agreement has previously been obtained when taking into account 5 degrees of freedom between idealised sub-structures in the laboratory[4,5]. The example in reference[4,5] however was designed specifically to make the measurements on the source and receiver structures as straightforward as possible. The real configurations studied here are considerably more challenging because six degrees of freedom were taken into account and because the coupling points had a less convenient geometry, especially when exciting and measuring responses in the x and y directions, see Figure 2.

Note that in order to predict the transfer accelerances shown in figure 3 some regularisation of the matrix inverse was performed to reduce noise. This was done by means of a singular value discarding with the 4 smallest singular values being set to zero. The physical justification for this is that 7 accelerometers were used to describe 6 degrees of freedom at 4 connection points, i.e. one singular value was discarded per connection point. This method was also used to obtain the good predictions of the passive properties of a coupled assembly presented in reference[4,5].

In the following section predictions of the test bench acceleration due to excitation from the operational AGTU are made using the sub-structured accelerances $\mathbf{H}_C$ and the blocked forces reported in the companion paper[1].

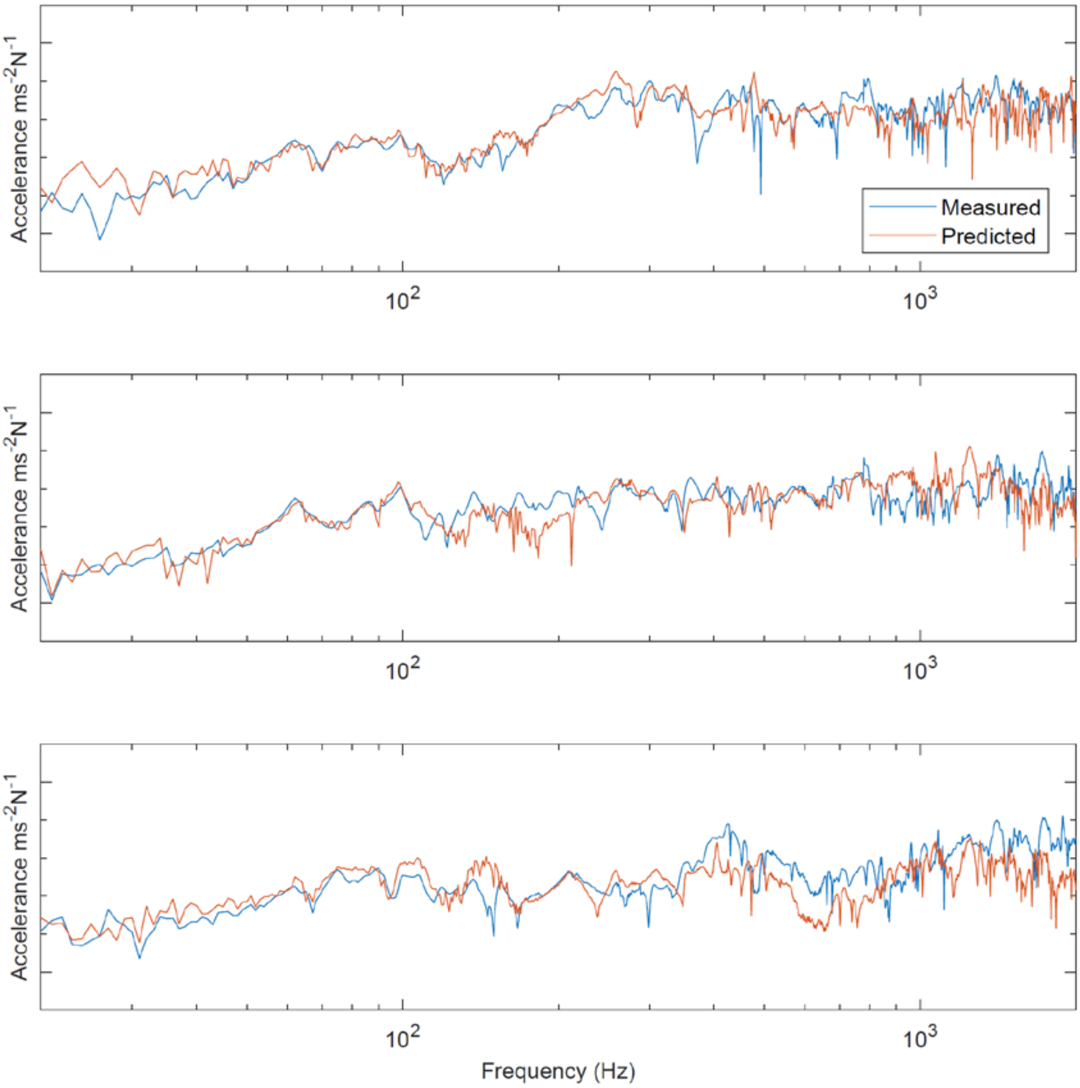

Fig. 3 – Measured (blue) and predicted (orange) transfer frequency response function (accelerance) between the interface degrees of freedom at connection point one to the reference position. Top, middle and bottom plots correspond to excitation in the z, y and x directions with responses in the z, y and x directions respectively. The range between minor ticks on the y-axis is a factor of 10.

5. THE VIRTUAL ACOUSTIC PROTOTYPE

In this section of the paper results from the full methodology, combining sub-structuring with in-situ measured blocked forces, are presented. This combined approach is sometimes referred to as virtual acoustic prototyping[6] or, more recently, component transfer path analysis[7]. Figure 4 below shows the measured and predicted vibration of the reference (validation sensor) position on the test bench for the frequency range 20-2000Hz.

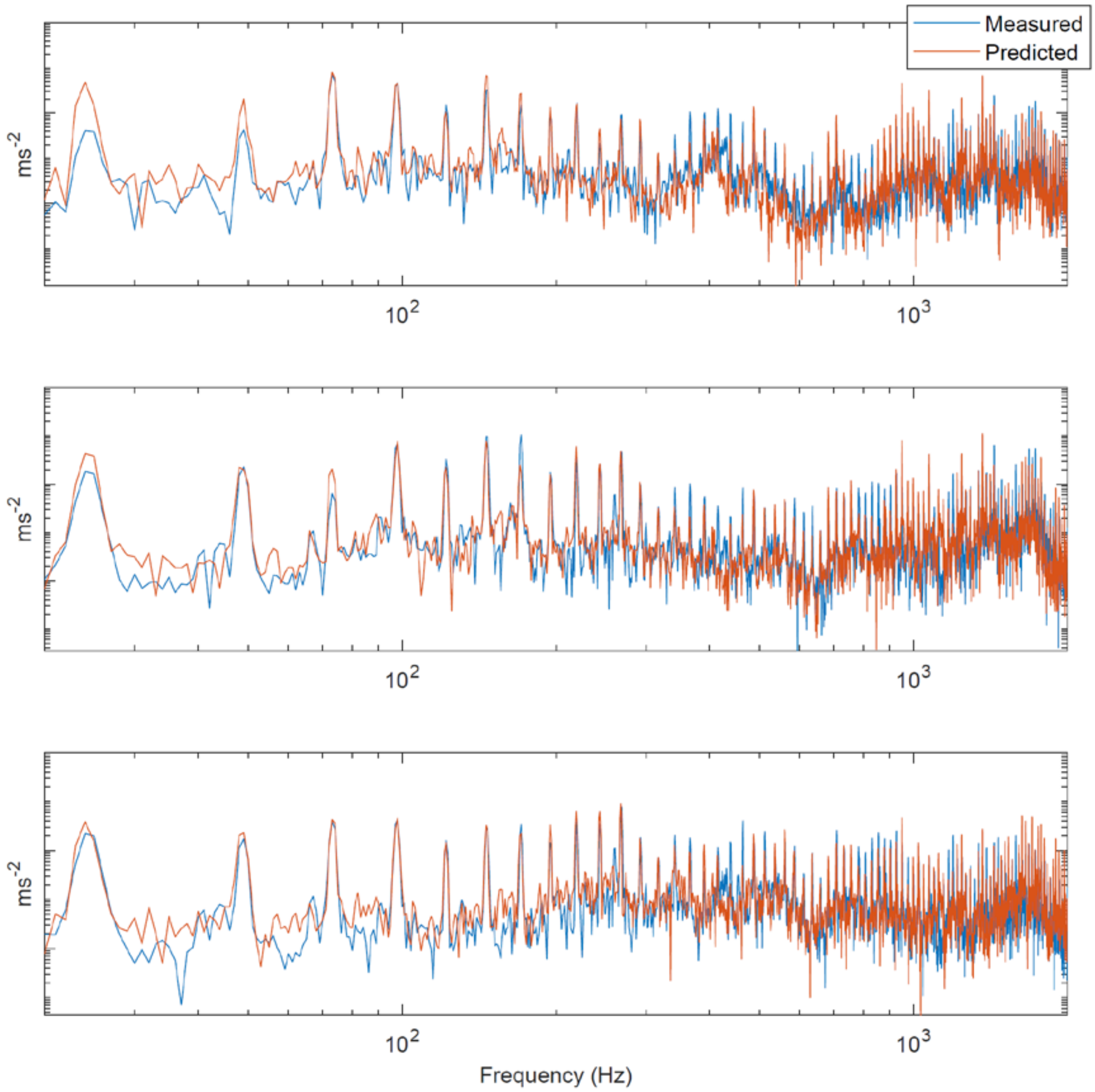

Fig. 4 – Measured (blue) and predicted (orange) acceleration of the test bench reference position in the x, y and z directions respectively. The range between major ticks on the y-axis is a factor of 100.

It can be seen in Figure 4 that the vibration acceleration of the test rig is generally predicted well with the majority of the peaks being in good agreement with the direct measurement. There is however a significant error in the prediction of the fundamental operational frequency in the x-direction. One reason for this may be the plastic hammer tip used for the FRF measurements. An alternative would have been to use a soft rubber tip to improve signal to noise at low frequencies but this would have been at the expense of data at higher frequencies (typically a plastic hammer tip offers a good compromise for structure borne noise sources). Figure 5 below shows the same result as in figure 4 for the x, y and z directions of the reference sensor position but this time presented in one third octave bands for clarity.

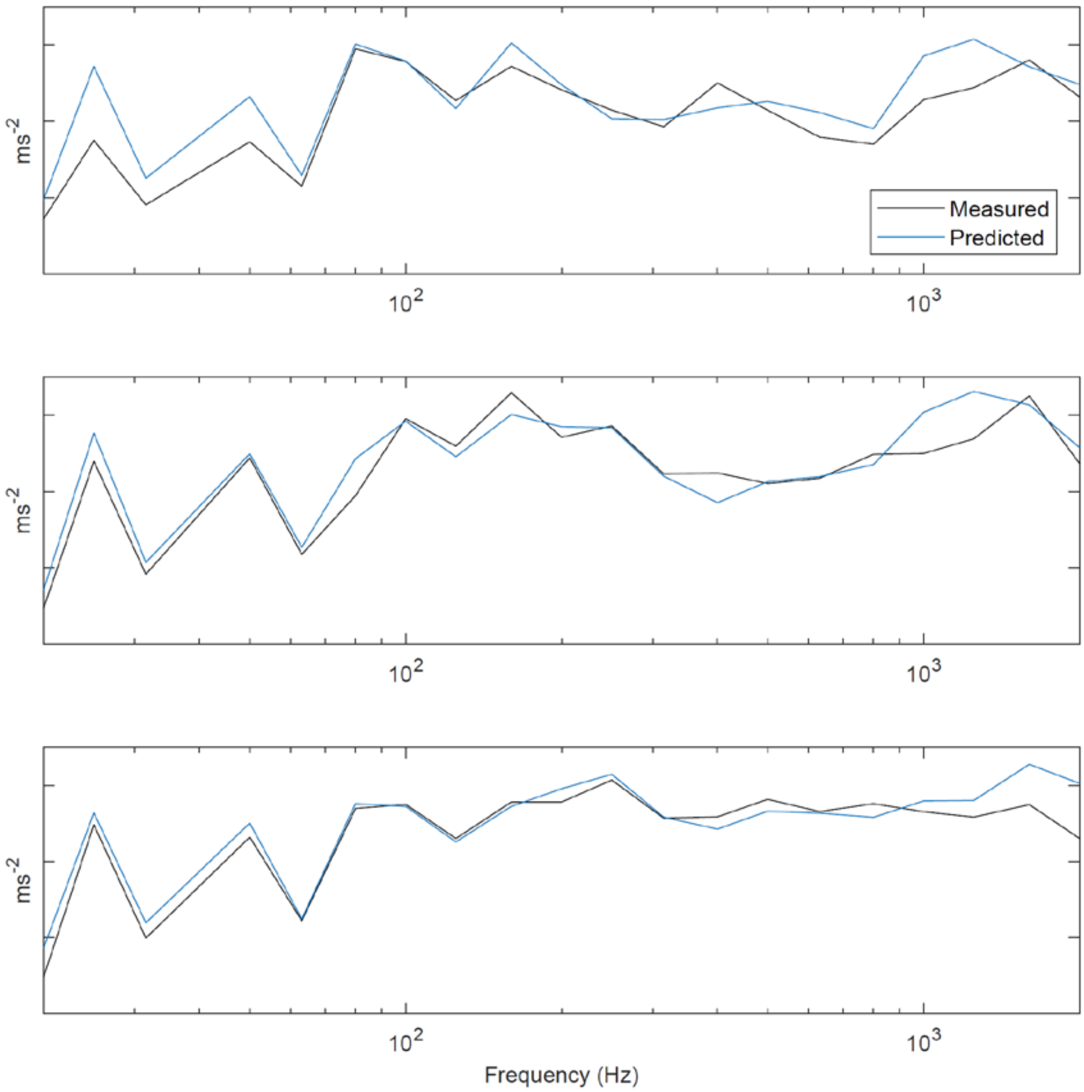

Fig. 5 – Measured (black) and predicted (blue) acceleration of the test bench reference position in the x, y and z directions respectively. The results shown are the same as those presented in Figure 4 but in one third octave bands. The y-axis scale covers a range of 70dB.

8. CONCLUDING REMARKS

Presented in the paper are the findings from a study into vibration source characterisation for the prediction of structure borne noise using the in-situ blocked force method in conjunction with sub-structuring. The subject of the case study was a real-world vibration source, an air generation and treatment unit, that is to be installed on a modern train. In characterising the source and receiver structures 6 degrees of freedom were accounted for at each connection point, i.e. 3 translations and 3 rotations.

The results presented in the paper show that the frequency response functions relating the source-receiver interface degrees of freedom to a reference position can be predicted by sub-structuring. It is then shown that these predicted frequency response functions can be used to predict the vibration acceleration of the test bench using blocked forces measured in-situ. The accuracy of the results obtained show that the method is suitable for making predictions of structure borne noise on a train.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

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