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Structure borne noise characterization of an air generation and treatment unit (AGTU) for a train by using blocked forces method.

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ABSTRACT

Interior noise is a challenge for Rolling Stock manufacturers in the search for a comfortable travel experience. To achieve interior noise levels respecting customer requirements, it is necessary to allocate noise and vibration targets to the different train equipment. Airborne source characterization is quite standardized in the railway industry but it is not the case for structure borne sources. An air generation and treatment unit has been installed on a supplier's test rig, a full structure borne characterization has been performed for three different kind of boundary conditions. Rotational degrees of freedom have been also considered thanks to a specific instrumentation. Blocked forces have been obtained thanks to advanced signal processing and computations; they have been then validated via comparison with direct vibration measurements. The novelty of the work presented is the full validation of the methodology for a real train equipment including all possible degrees of freedom and in the close collaboration between rolling stock manufacturer, supplier and academia. The learnings from this work will help to establish new standards for the methodology of structure borne noise characterization of equipment. The work presented here has been performed in the frame of European research project FINE1 in the context of the Shift2Rail JU.

Keywords: Structure Borne Noise, Test, Characterization
I-INCE Classification of Subject Number: 11

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1. INTRODUCTION

It has been introduced previously[1,2] that for airborne sound sources the sound power is the most widely accepted standard measure for acoustic 'source strength' because it is relatively straightforward to measure and because the receiving medium (air) does not vary significantly. For structure borne sound sources however few such standard methods currently exist and this is in part because the vibration power transmitted to a receiver structure is highly dependent on the properties of the receiver itself as well as the vibration source. Consequently, the amount of structure borne noise produced by a vibration source cannot be predicted using the source strength alone.

For the prediction of structure borne noise it is generally accepted that a characterization quantity that is not dependent on the mount condition is required and, although other options may exist, the most commonly referred to quantities are the free velocity and the blocked force. Together with the mobilities or impedances of the source and receiver structures (or of the coupled assembly) predictions of structure borne noise and vibration can then be made.

The following figure shows how free velocities and blocked forces can be used to predict the vibrations or the structure borne sound pressure at a reference point, e.g. a listener position. The theory describing the calculations is presented in section 2.

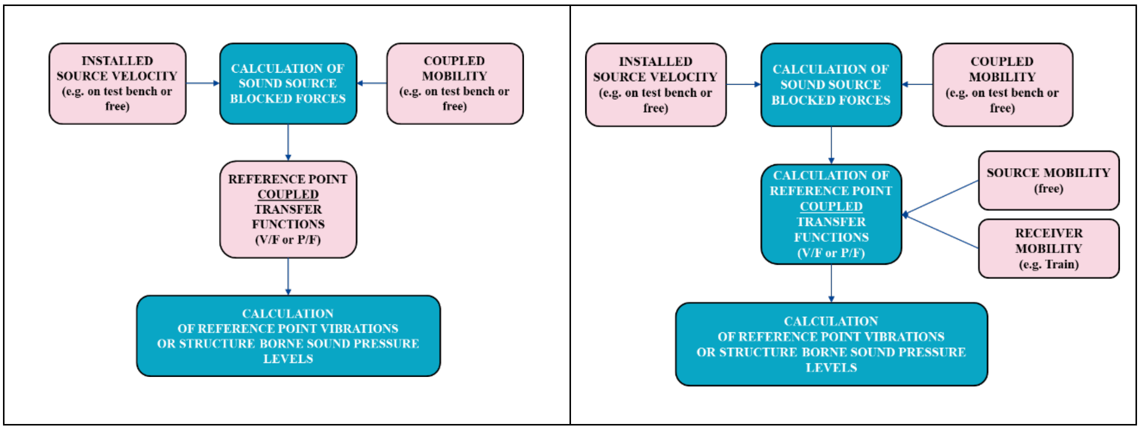


Fig. 1 – General workflow using blocked forces methodology to predict structure borne noise and vibration. Left – simplified methodology where the coupled source and receiver can be measured together. Right – Full prediction methodology.

The free velocities of a vibration source are the velocities of the mount points (in multiple degrees of freedom) when no external force or moment acts on them (f = 0) and the blocked forces of a vibration source are the 'hypothetical' forces required to block the motion of the vibration source so that the velocity of the source contact points is zero in each relevant degree of freedom (v = 0). To measure these quantities directly, the vibration source might be freely suspended using resilient elements or blocked by a heavy and stiff support respectively. Neither of which is generally practicable over the full frequency range of interest.

The advantage of the blocked force and free velocity methodologies is the possibility to predict the vibration or the structure borne sound pressure level due to a source as if the source is installed on its final supporting structure. As we can see in figure 1, the only information needed from the final receiving structure - the train in our case - are its mobilities at the connection points to the source and its transfer functions (v/F or P/F) to the reference point (vibration or sound pressure levels inside the train compartment in our case).

Presented in the paper is a case study concerning the application of the in-situ blocked forces methodology[2] to a complex machine to be installed on a train. The first purpose of the paper is to compare the calculations of the blocked forces of this sound source, an air generation and treatment air unit (AGTU) measured under 2 different mounting conditions (freely mounted and rigidly mounted to a test bench). By definition the blocked forces obtained should be the same from both test setups (see section 2) and this test is therefore used to validate the measurement methodology. The second purpose of the paper is to compare predicted vibration levels obtained from these blocked forces and a measured frequency response functions of the test rig (i.e. the left flow diagram in figure 1) to those actually measured on the test bench while the source was in operation. The complete methodology (figure 1, right) including sub-structuring of the source and receiver structure mobilities is presented in a companion paper[3] also submitted to Internoise 2019.

In a final section of the paper the sensitivity of the results will also be investigated according to the following parameters: measurement phase and number of number of degrees of freedom included at the interface.

2. THEORY

The blocked force $\mathbf{f}_{\mathbf{S,bl}}$ of a structure borne sound source can be determined in-situ[4,5,6] according to,

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

where **f**, **Y** and **v** are force, mobility and velocity respectively. Here, the uppercase subscript, **S**, denotes the vibration source structure alone and **C** the coupled source and receiver assembly. The lower case subscript, **bl**, indicates a blocked condition.

What is notable about Equation 1 is that the blocked force of a vibration source, **S**, can be obtained when the vibration source is installed within any assembly, **C**, and this in turn allows predictions of structure borne noise or vibration to be made for assemblies other than the one in which it has been characterised. An extreme case of this is when the vibration source is freely suspended with no external forces acting on it, Equation 1 then becomes,

$$\mathbf{f}_{\mathbf{S,bl}} = \mathbf{Y}_{\mathbf{S}}^{-1}\mathbf{v}_{\mathbf{S,fr}} \tag{2}$$

where $\mathbf{Y}_{\mathbf{S}}$ is the mobility of the free source and $\mathbf{v}_{\mathbf{S,fr}}$ is its free velocity.

The reason for characterising a vibration source in terms of its blocked force or free velocity is generally to allow one to make a prediction of structure borne noise or vibration produced by the source when installed in different environments and, as such, for a perfect measurement the blocked forces obtained from Equation 1 or 2 should be the same. This has been demonstrated previously for idealised components in simple assemblies[4,5] and will be further evidenced later in this paper for a complex machine.

To predict structure borne noise using the blocked force or free velocity we may then use the equations,

$$\mathbf{p'}_{\mathbf{C}} = \mathbf{H'}_{\mathbf{C}}\mathbf{Y}_{\mathbf{C}}^{-1}\mathbf{v}_{\mathbf{C}} = \mathbf{H'}_{\mathbf{C}}\mathbf{Y}_{\mathbf{S}}^{-1}\mathbf{v}_{\mathbf{S,fr}} = \mathbf{H'}_{\mathbf{C}}\mathbf{f}_{\mathbf{S,bl}} \tag{3}$$

Where $\mathbf{H}_{\mathbf{C}}$ is a set of vibro-acoustic frequency response functions relating the degrees of freedom at the source-receiver interface to a reference point within the assembly, **C**, and

$\mathbf{p}$ 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 was characterised. For example, $\mathbf{H'_C}$, could be from a measurement of the source installed on a train and $\mathbf{Y_C^{-1}v_C}$ or $\mathbf{Y_S^{-1}v_{S,fr}}$ could be obtained from a test bench according to the methodology defined in Figure 1.

Finally, to complete the prediction methodology we must also consider the case where the assembly, $\mathbf{H'_C}$, (i.e. train + vibration source) does not yet exist. In this case it is convenient as an interim step to determine the forces on the train (which we shall refer to as the receiver, **R**) so that we may write,

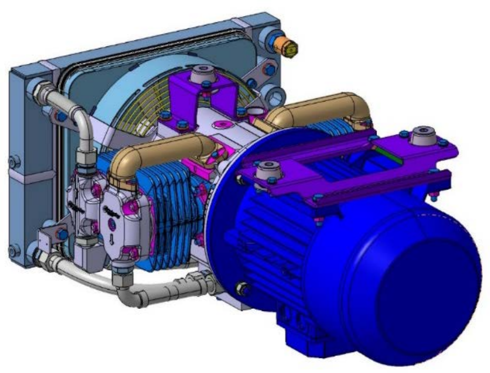
$$\mathbf{p'_C} = \mathbf{H_R}[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S}\mathbf{f_{S,bl}} \tag{4}$$

where the blocked forces, $\mathbf{f_{S,bl}}$,can be obtained from equation (1) or (2), **R** denotes the receiver structure and $[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S}\mathbf{f_{S,bl}}$ is the force on the receiver $\mathbf{f'_R}$.

Thus, the structure borne sound pressure inside the train can be predicted before assembly with measurements of the mobility and vibro-acoustic frequency response functions of the train in isolation together with the source mobility and blocked force or free velocity. At earlier stages in the design process it should also be possible to obtain $\mathbf{H_R}$ and $\mathbf{Y_R}$ from numerical models if desired.

3. THE SOUND SOURCE

The sound source considered in our study is an air generation and treatment unit – AGTU - equipped with Buran 5 oil free piston compressor designed and manufactured by the rolling stock supplier Faiveley Transport. The main characteristics of this sound source are given in figure 2.



Air flow (after dryer):	500 l/min @9bar
Nom. power:	6,3 kW
Nom. current:	11,5 A
Batt. supply:	110 V
Work. pressure:	8,5 ÷ 9,5 bar
Weight:	235 kg

Fig. 2 – Main characteristics of the air generation and treatment unit equipped with Buran 5 oil free piston compressor.

All measurements carried out on the AGTU were performed at the supplier's facility. The AGTU was installed on the test rig thanks to a frame that has 4 connection points with the test rig.

The AGTU was characterised according to two different mounting conditions: freely mounted thanks to air balloons as shown on figure 3 and rigidly mounted on the test rig. The Coupled mobility and operational velocity (required for equation 1) and the source mobility and free velocity (equation 2) could then be measured in the rigidly mounted and free cases respectively. This in turn allows the blocked forces from the two configurations to be compared (in theory they should be the same if the source operates in the same way) and the blocked forces from one configuration can be used to predict the test rig reference vibration for the other configuration. If both of these are successful the measured blocked forces would then be considered validated and suitable for making predictions of sound and vibration from the AGTU when installed on a train.

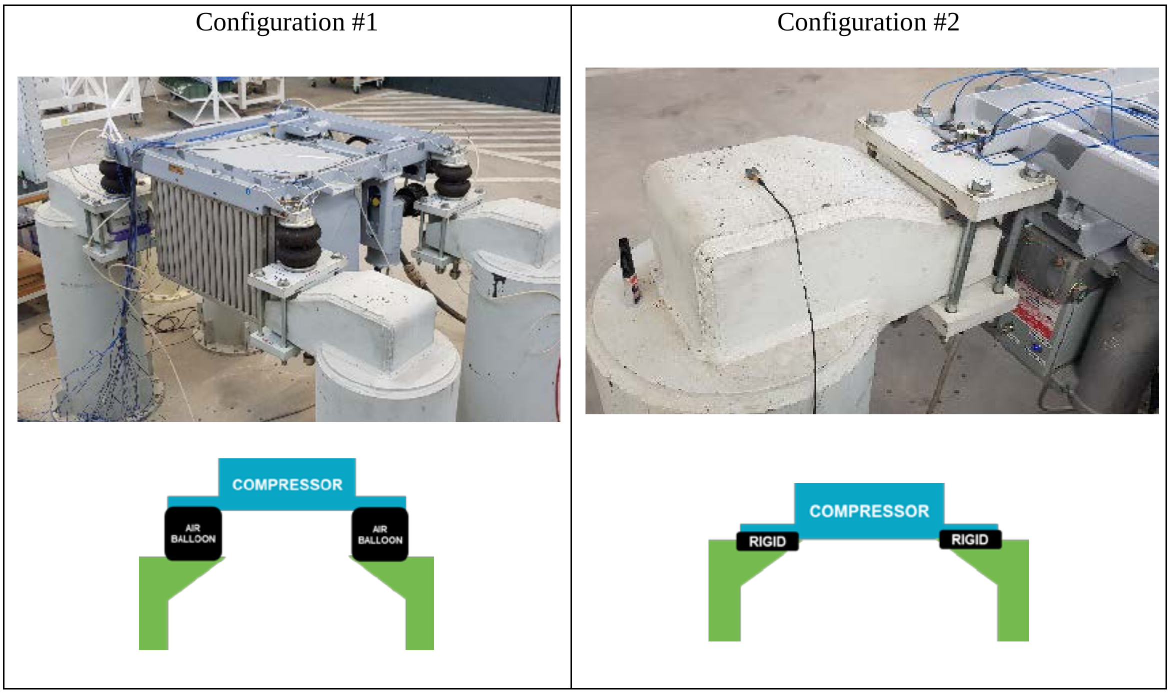


Fig. 3 – AGTU mounted on test rig according two different boundary conditions: freely thanks to air balloons named configuration #1 (left photo) and rigidly named configuration #2 (right photo).

4. INSTRUMENTATION

In order to measure all the degrees of freedom, i.e. 3 translations and the 3 rotations, each connection point was instrumented with 7 mono-axial accelerometers using a method similar to that described in[7,8,9]. In principal 6 accelerometers per contact could have been used to obtain 6 degrees of freedom but the arrangement used is convenient in terms of calculating rotational and translational components of vibration at common point. It is also possible using this approach to treat the contact as 6 (or 7) points in translation, simplifying the calculations further by avoiding the requirement to determine the rotational components altogether. Again, see reference[8,9] for further details.

Figure 4 shows the instrumentation of one of the 4 connection points. The principle of the instrumentation is the following:

- 4 mono-axial accelerometers in the vertical direction Z,
- 2 mono-axial accelerometers in the longitudinal direction Y,
- 1 mono-axial accelerometer in the longitudinal direction X.

In addition to these 28 (=4 connection points x 7 mono-axial) accelerometers a further accelerometer was installed on the test bench as shown in figure 5. This tri-axial accelerometer was installed on one of the four pillars of the test rig and is considered as the reference point for validation purposes. See also figure 3 (right photo).

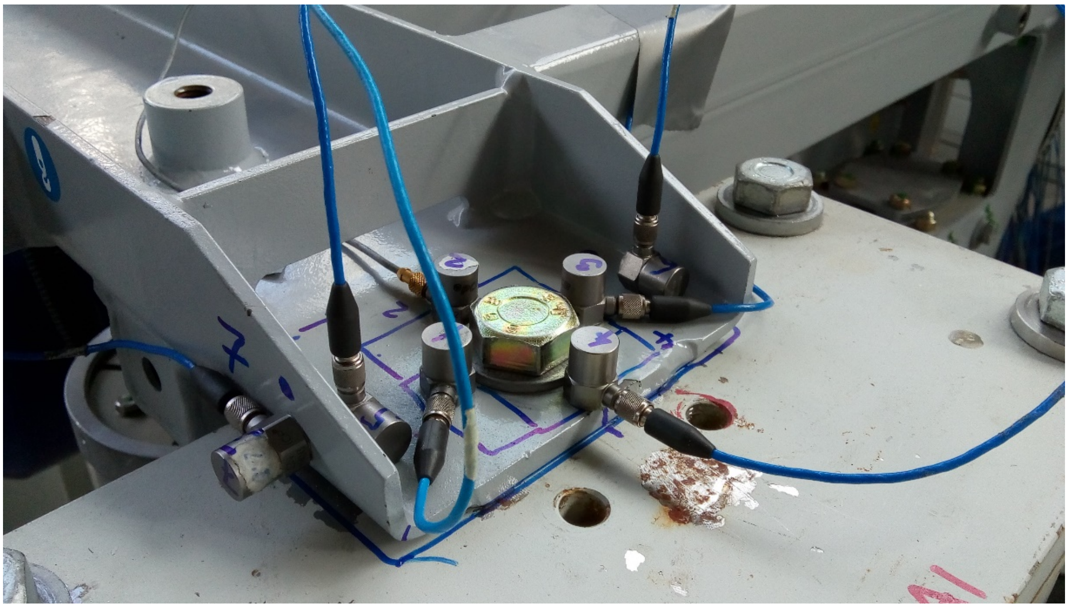


Fig. 4 – Instrumentation of AGTU connection point

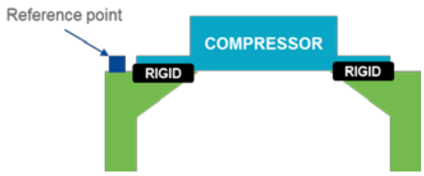


Fig. 5 – Position of the reference point vibration

5. BLOCKED FORCES CALCULATIONS & COMPARISON

The mobilities have been measured thanks to an impact hammer near each accelerometer and according to the direction of the accelerometer. The "operational" velocities were measured according to two different excitations:

- Artificial excitation 'pseudo operational' thanks to an impact hammer on the body of the air compressor,
- Real excitation of the air compressor when running under load.

The purpose of the artificial excitation is to test the quality of the mobility data without the uncertainty associated with an irregular or unrepeatable real source operation. By exciting the structure with an instrumented hammer the blocked forces due to a unit force excitation of the source can be calculated from the velocities at the interface with reliable phase information that is referenced to the measured hammer excitation. In this way, if the artificial excitation gives good agreement in terms of the blocked forces from the different configurations but that is not found to be the case for the real operation it is likely that the errors are then due to the operational behaviour of the source rather than the degrees of freedom included in the mobility matrix or the matrix inversion process.

In the following sub-sections the blocked forces measured at one of the connection points in the x, y and z directions are compared for configurations #1 and #2. In theory the two configurations should yield the same blocked forces in all degrees of freedom for both the artificial excitation and the real operation of the AGTU.

5.1 Use of artificial excitation

Blocked forces have been computed following equations (1) and (2) for the two configurations; the freely mounted configuration #1 and rigidly mounted configuration #2 respectively. Figure 6 below shows the comparison of the blocked forces obtained from the two configurations.

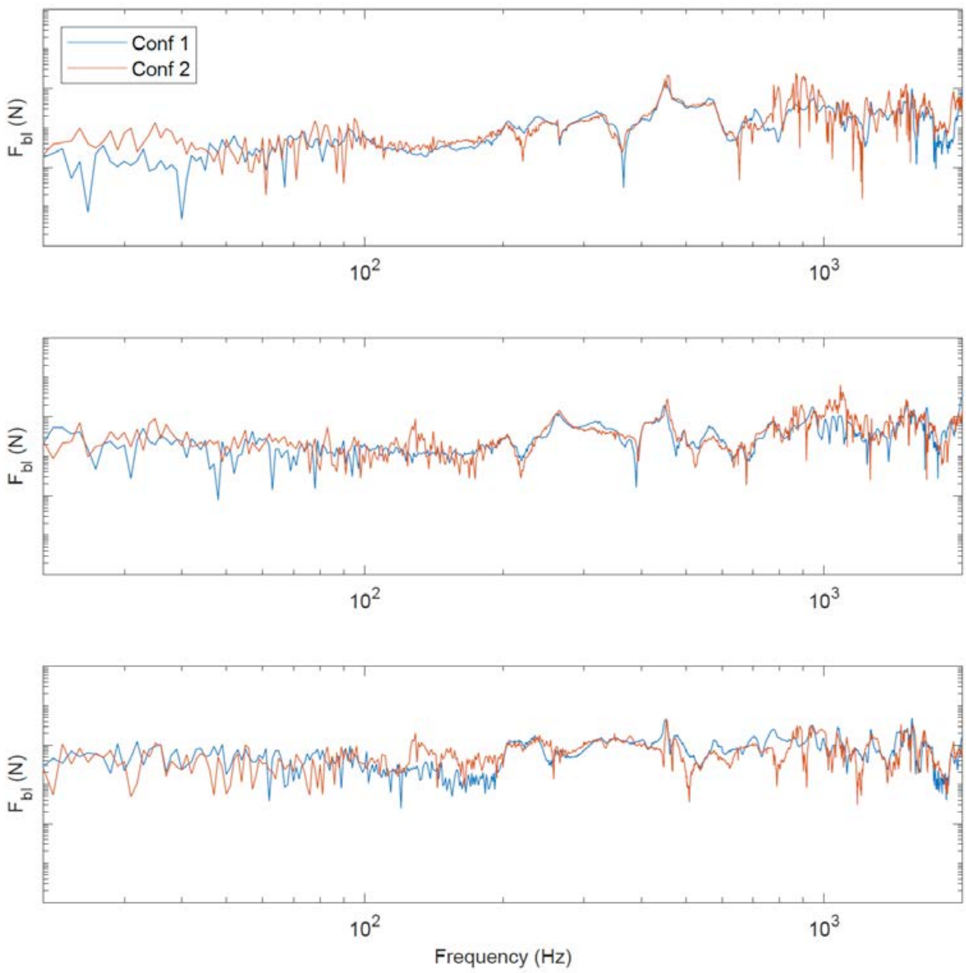


Fig. 6 – Comparison of blocked forces between configuration #1 and #2. Top, middle and bottom plots correspond to responses in the z, y and x directions at attachment point 1 respectively (artificial excitation).

It can be seen that the blocked forces obtained from the two extreme boundary conditions of the source are in good agreement with some errors at low frequency due to noise. Note that in order to cover a wide frequency range a plastic hammer tip was used with 100mV/g accelerometers. To optimise results in specific frequency ranges softer or harder hammer tips can be used together with different sensitivities of accelerometers.

5.2 Use of real excitation

With the passive FRF data validated as described above the same calculations were then made for the case of the real operation of the AGTU. The figure below shows a comparison of the blocked forces from the two configurations with the AGTU operating under load as it would do on a train after a 10 minute warm up period. To account for phase in the operational measurements complex Fourier spectra were used rather than time averaged auto-spectra and cross-spectra because coherence between sensors at the interface was poor. In this way the phase information in the operational data is preserved as it was recorded and the blocked forces obtained are complex Fourier spectra also.

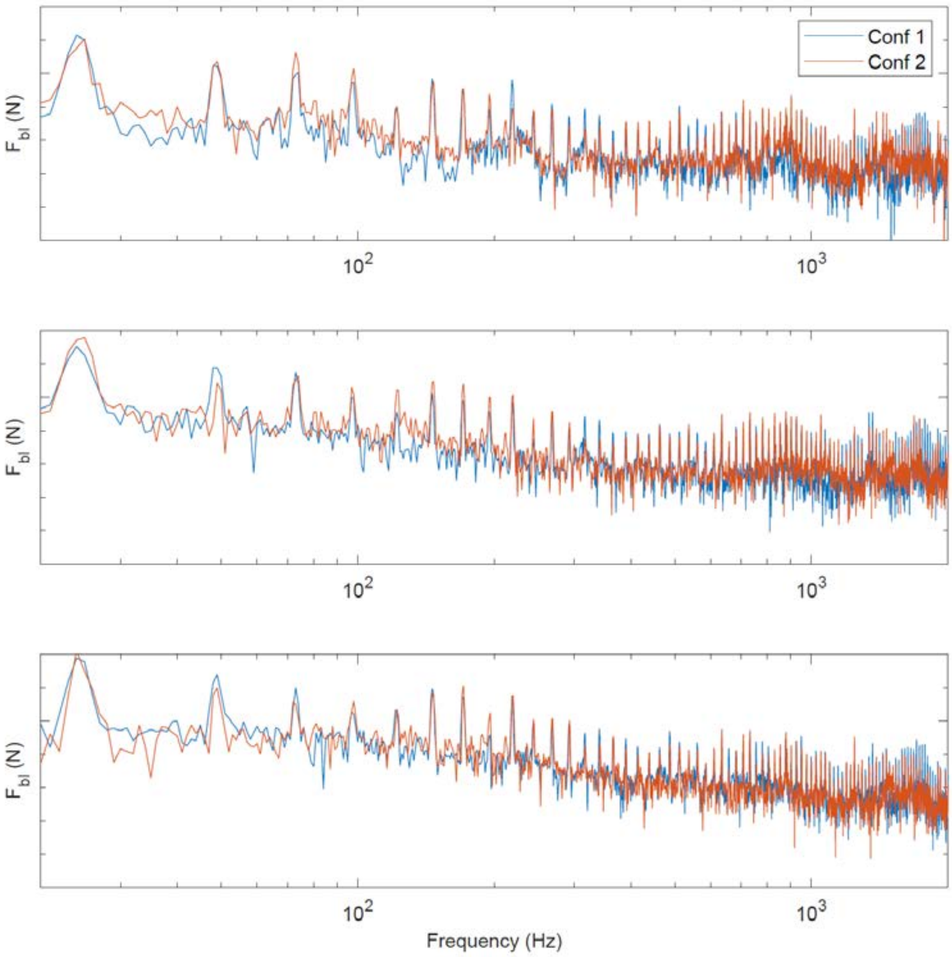


Fig. 7 – Comparison of blocked forces between configuration #1 and #2. Top, middle and bottom plots correspond to responses in the z, y and x directions at attachment point 1 respectively (AGTU operational).

The blocked forces from the two configurations are again in good agreement and appear improved at low frequency, this may be due to a stronger excitation from the source in this frequency range. The results in Figures 6 and 7 therefore partially validate the measured blocked forces from the two different test configurations and suggest that the source operation is not affected by the mount condition. In the following section these blocked forces are further validated by making predictions of the vibration acceleration of the test bench in configuration #2 using blocked forces measured in configuration #1. For clarity the predictions are again made for both the artificial excitation and the for the actual operation of the AGTU.

6. VALIDATION

The acceleration of the reference point (Figure 3) were calculated from the calculated blocked forces from the freely mounted configuration (Equation 2) and the measured transfer functions of the rigidly mounted configuration (Equation 3). The blue and orange lines in Figure 8 correspond to the actual vibration measured at the reference point and the predicted level from Equation 3 respectively. The predicted vibration in the x, y and z directions were all found to be in good agreement with those measured.

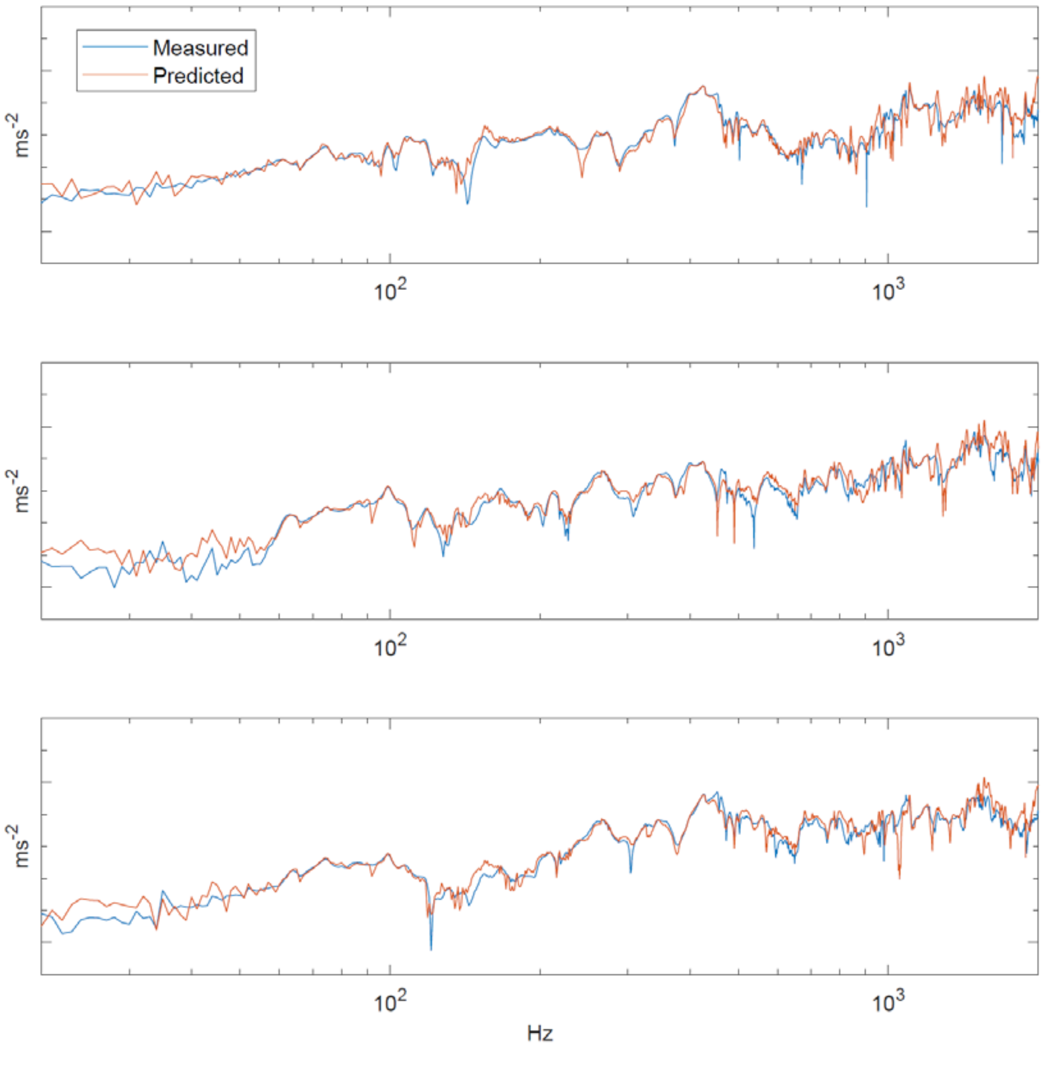


Fig. 8 – Prediction of test rig reference vibration levels in the x, y and z directions (top, middle and bottom respectively) for an artificial excitation of the AGTU. The blue line shows the actual vibration level measured on the test rig when the source and receiver were rigidly coupled (#2). The orange line was calculated using in-situ measured blocked forces obtained when the source was freely mounted (#1).

Following this a further prediction of the test bench vibration acceleration was made with the AGTU operating, again using Equations 2 and 3 as above. Due to the tonal nature of the source the agreement between the measured and predicted vibration accelerations of the test rig are more difficult to observe but again appear to be good over a wide frequency range (20-2000Hz shown). This indicates that the degrees of freedom taken into account at the interface adequately described the physics of the interface and that the source characterisation measurements have been successful.

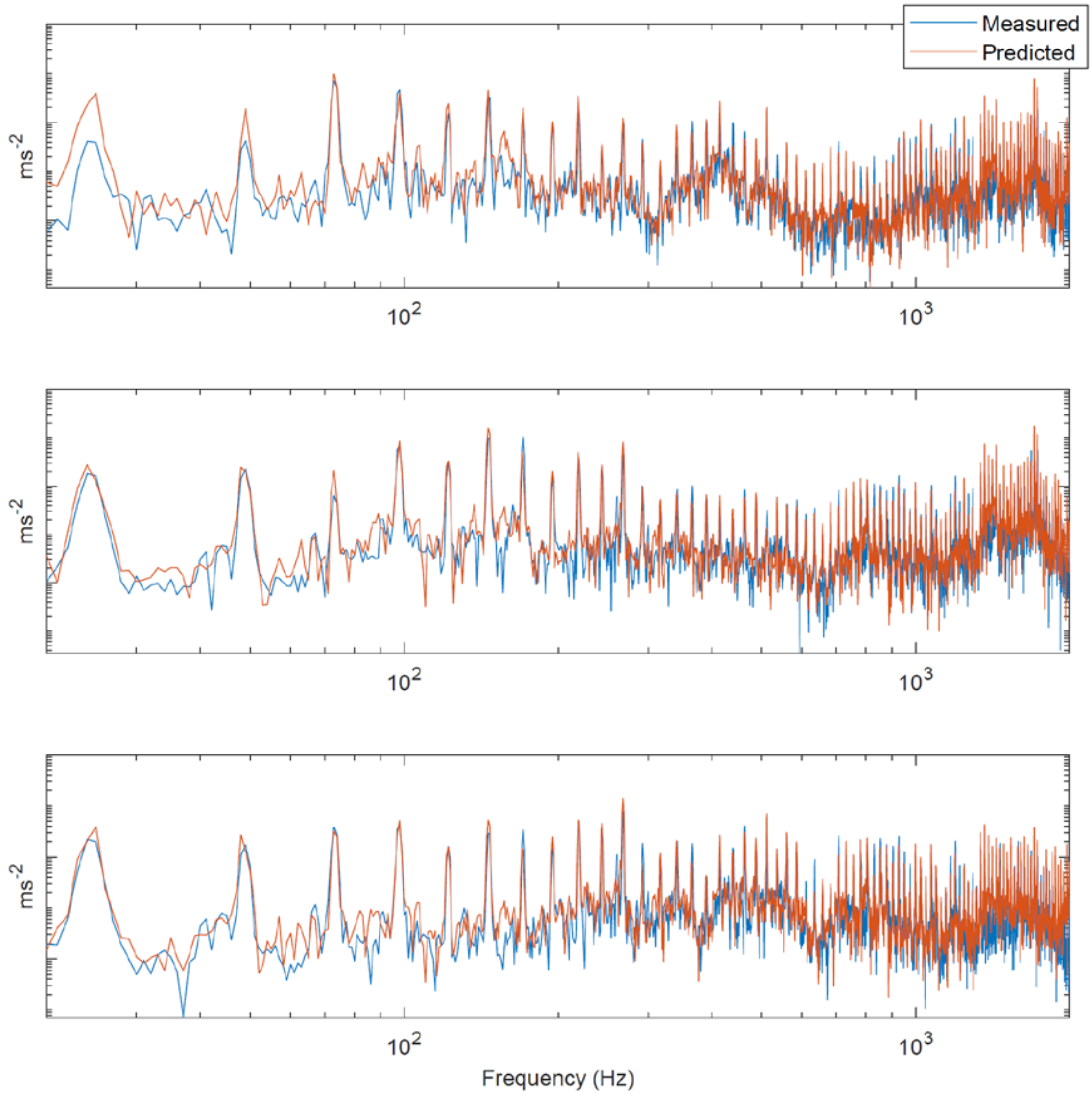


Fig. 9 – Prediction of test rig reference vibration levels in the x, y and z directions (top, middle and bottom respectively) with the AGTU operational. The blue line shows the actual vibration level measured on the test rig when the source and receiver were rigidly coupled (#2). The orange line was calculated using in-situ measured blocked forces obtained when the source was freely mounted (#1).

7. DEGREES OF FREEDOM AND PHASE

As a final note in the paper we look briefly at the sensitivity of structure borne noise and vibration predictions to the inclusion of phase information and the inclusion of rotational degrees of freedom at the interface. Figure 10 below shows three plots, the first of which is the 3rd octave band representation of the z-direction data presented in

Figure 9. The middle plot is the same result but for the case where phase is neglected in the calculations. The bottom plot is the case where moments are excluded. In each plot the black line is the actual measured vibration acceleration and in blue is the prediction from Equation 3.

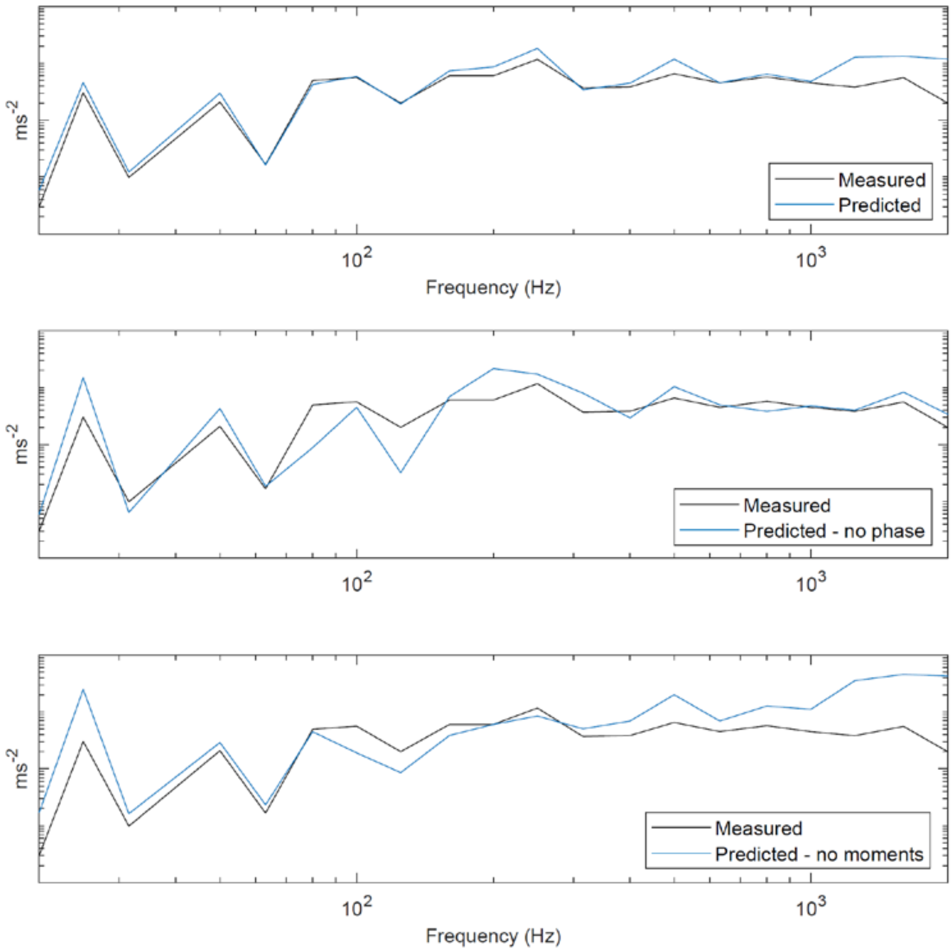


Fig. 10 – Prediction of test rig reference vibration levels in the z direction in one third octave bands. The top result is the same as that shown in Fig. 9 for the z direction. The middle figure shows the quality of the prediction when phase is not taken into account in the calculations. The bottom plot prediction does not include moments in the calculation, i.e. only translations in x, y and z are included.

Figure 10 shows that neglecting phase and rotational degrees of freedom in this case are both to the detriment of the predictions made. The results shown in Figure 10 therefore highlight the importance of properly accounting for the physics of the coupling between source and receiver when making predictions of structure borne noise for this item of equipment. It is important to note that the results shown here are only validations of the blocked force and not for the full prediction by sub-structuring source and receiver structures (figure 1, right schematic). This further step, the full prediction methodology, is addressed in a companion paper[3] also to be presented at Internoise 2019.

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. 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. Similar case studies have been reported in the past but here the vibration source was characterised taking account of 6 degrees of freedom at each connection point between source and receiver. This has not been previously reported experimentally for a complex real-world vibration source.

A number of validation results are provided in the paper to demonstrate that the blocked forces obtained using the in-situ method are (1) independent of the installation on which they are measured and (2) that they are suitable for making predictions of structure borne noise in assemblies other than the one in which they are characterised. For this to be the case the correct number of degrees of freedom must be taken into account at the source-receiver interface.

The results presented in the paper show that the blocked forces from two measurement configurations, free and rigidly connected, are independent of the configuration because closely matching blocked force magnitudes were obtained from both test setups. It was also shown that these blocked forces could be used to make predictions of the vibration acceleration of the test bench when the machine was installed in a condition other than the one in which it was characterised.

Finally, the sensitivity of the method to excluding moment excitations and phase in the calculations was investigated and it was shown that better results were obtained when moments and phase were included.

9. ACKNOWLEDGEMENTS

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