ICA 2019 AACHEN

PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Combining Structural Modification with In-Situ Transfer Path Analysis to Solve Noise and Vibration Problems

Andrew ELLIOTT[1]; Nezam SANEI[2]; Martin GLESSER[2]

[1] University of Salford, Greater Manchester, M5 4WT, United Kingdom.

[2] Alstom Rolling Stocks & Components, 48 Rue Albert Dhalenne, 93400, SAINT-OUEN, FRANCE

ABSTRACT

In-situ TPA measurements provide blocked forces that can be used to diagnose structure borne noise problems in vehicles. One of the main advantages of in-situ TPA, also known as blocked force TPA, is that all measurements are made with the source and receiver in a coupled state making measurements easier and ensuring representative operation of the vibration source. Perhaps the greatest advantage however is that the blocked forces obtained, unlike contact forces, are an intrinsic property of the vibration source which means they remain valid for modified or completely different receiver structures. In the paper, real world practical examples that exploit the advantages of in-situ TPA in terms of structure borne noise prediction and structural modification are presented. The first example is of a complex vibration source coupled at multiple points through six degrees of freedom per interface to a test bench that is subsequently built into a new assembly for which structure borne noise predictions are made. A further example is then used to demonstrate how structural modifications can be made to the receiver side of an assembly for the purposes of troubleshooting noise and vibration problems using in-situ TPA.

Keywords: Transfer Path Analysis, Structure-Borne Noise, Sub-Structuring

1. INTRODUCTION

In-situ transfer path analysis (iTPA) and conventional transfer path analysis (TPA) bear many similarities in terms of their application but the former has two distinct advantages. The first advantage is that to implement an iTPA it is not necessary to separate the source and receiver structures during the measurement of frequency response functions because the assembly is kept in the coupled state for all measurements. The second advantage is that the iTPA approach yields blocked forces, an intrinsic property of the source, whereas conventional TPA provides the operational forces at the source-receiver interface. This subtle difference is perhaps the most significant advantage overall because modifications to the receiver structure can be made and the blocked forces, by definition, remain valid. Interface forces (from conventional TPA), on the other hand, are a property of the assembly and could therefore change significantly with only minor alterations to a receiver structure.

Beyond TPA, this freedom to transfer blocked forces from one assembly to another presents further benefits because it allows one to characterize the vibration activity of a source on a test bench and to use the same blocked force dataset to virtually excite modelled systems obtained by experimental sub-structuring, FEA, SEA or hybrid methods [1].

In this paper two case studies are presented to (a) illustrate the application of the blocked force methodology combined with sub-structuring for the prediction of structure borne noise in a train and (b) to demonstrate the application of structural modification as a noise/vibration control measure.

For (a) an air generation and treatment unit (or AGTU) is characterized in terms of its blocked forces using measurements on a test bench. This data is then combined with frequency response functions of the AGTU and the train to predict structure borne noise. Comparisons are then made to actual measurements of the structure borne noise with the AGTU installed on a train. Case study (b) then demonstrates how design changes can be investigated by sub-structuring simple idealized elements to this system using the combined methodology.

[1] a.s.elliott@salford.ac.uk

[2] nezam.sanei@alstomgroup.com

2. THEORY

In this section of the paper the theory of in-situ transfer path analysis (iTPA), sub-structuring and structural modification are outlined setting out the key terms and relationships used throughout the paper. Useful references for the interested reader include [2-7].

2.1 In-situ Transfer Path Analysis

The blocked force, $\mathbf{f}_{\mathbf{S,bl}}$, of a structure borne sound source can be obtained from measurement in-situ using the equation,

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

where **f**, **Y** and **v** are **force vectors**, **mobility matrices** and **velocity vectors** respectively.

Here, the uppercase subscript, **S**, denotes a property of source structure alone and, **C**, a property of the coupled source and receiver assembly. The additional lower-case subscript, **bl**, indicates a blocked condition. It is important to note here that blocked forces are a property of the source, **S**, and not the assembly, **C**, even though the source and receiver are coupled during measurements [2,3].

When performing an iTPA it is usual to measure a further set of frequency response functions, $\mathbf{H}_{\mathbf{C}}$, at the same time as measuring, $\mathbf{Y}_{\mathbf{C}}$, which relate forces at the source-receiver interface to a target location (e.g. sound pressure or floor vibration). For the case of sound pressure, $\mathbf{p}_{\mathbf{C}}$, we may write,

$$\mathbf{p}_{\mathbf{C}} = \mathbf{H}_{\mathbf{C}}\mathbf{f}_{\mathbf{S,bl}} \tag{2}$$

The combined dataset then allows one to investigate contributions to the interior noise from different paths by setting elements of the blocked force vector to zero and repeating the calculation; thereby eliminating contributions from one or more paths [7]. This in turn allows one to identify the strongest paths, the strongest forces and their combined contributions to a vehicles interior noise.

For example, in some cases just one source-path combination may dominate and, once identified, measures can potentially be taken to resolve the issue by structural modification. The advantage of iTPA with respect to conventional TPA is then that changes to, $\mathbf{H}_{\mathbf{C}}$, can be investigated without any concerns regarding the potential effect on the interface forces (which are likely to be quite sensitive to changes made to the receiver structure).

2.2 Sub-structuring and Structural Modification

The mobility of the source-receiver interface, $\mathbf{Y}_{\mathbf{C}}$, is a combination of the passive properties of the source and receiver sub-structures, $\mathbf{Y}_{\mathbf{S}}$ and $\mathbf{Y}_{\mathbf{R}}$ respectively. $\mathbf{Y}_{\mathbf{C}}$ can expressed as the inverse of sum of the source and receiver impedances $\mathbf{Z}_{\mathbf{S}}$ and $\mathbf{Z}_{\mathbf{R}}$, where $\boldsymbol{Z} = \boldsymbol{Y}^{-1}$, i.e.

$$\boldsymbol{Y}_{\boldsymbol{C}} = \left[\boldsymbol{Y}_{\boldsymbol{S}}^{-1} + \boldsymbol{Y}_{\boldsymbol{R}}^{-1}\right]^{-1} = \left[\boldsymbol{Z}_{\boldsymbol{S}} + \boldsymbol{Z}_{\boldsymbol{R}}\right]^{-1} \tag{3}$$

Similarly, the mobility of a structurally modified assembly, $\boldsymbol{Y'}_{\boldsymbol{C}}$, or receiver, $\boldsymbol{Y'}_{\boldsymbol{R}}$,can be obtained by sub-structuring using the equations,

$$\boldsymbol{Y'}_{\boldsymbol{C}} = \left[\boldsymbol{Y}_{\boldsymbol{C}}^{-1} + \boldsymbol{Y}_{\boldsymbol{M}}^{-1}\right]^{-1} = \left[\boldsymbol{Z}_{\boldsymbol{C}} + \boldsymbol{Z}_{\boldsymbol{M}}\right]^{-1} \tag{4}$$

$$\boldsymbol{Y'}_{\boldsymbol{R}} = \left[\boldsymbol{Y}_{\boldsymbol{R}}^{-1} + \boldsymbol{Y}_{\boldsymbol{M}}^{-1}\right]^{-1} = \left[\boldsymbol{Z}_{\boldsymbol{R}} + \boldsymbol{Z}_{\boldsymbol{M}}\right]^{-1} \tag{5}$$

where the dash denotes a structurally modified component or assembly and, $\boldsymbol{Y}_{\boldsymbol{M}}$, is the matrix of elements that are used to make the modification. For example, this could be a matrix of ideal mass or stiffness elements or more complex components such as beams, plates or resonant absorbers. The key point to note is that the blocked forces from equation (1) can again be used to excite these modified structures because blocked forces are an intrinsic property of the source. For example, equation 4 in combination with Equation 1 can be used to predict vibration levels at the source-receiver interface of a modified assembly using data describing the individual sub-structures.

Perhaps more usefully however, the frequency response function, $\mathbf{H}_{\mathbf{C}}$, from equation (2) which relates forces at the interface to a point of interest can also be obtained by sub-structuring using the equation,

$$\mathbf{H_C} = \mathbf{H_R}[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S} \tag{6}$$

where, $\mathbf{H_R}$, is a vibro-acoustic frequency response function for the receiver structure alone Similarly, we may also write,

$$\mathbf{H'_C} = \mathbf{H'_R}[\mathbf{Y_S} + \mathbf{Y'_R}]^{-1}\mathbf{Y_S} \tag{7}$$

Where, $\mathbf{H'_C}$, is a vibro-acoustic frequency response function of an assembly where the receiver structures mobility has been modified using equation (5). Note that $[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S}\mathbf{f_{S,bl}}$ is the actual force applied to the original receiver structure, $\mathbf{f_R}$, and that this will not be the same force applied to modified assembly, $\mathbf{f'_R}$, because,

$$[\mathbf{Y_S} + \mathbf{Y_R}]^{-1}\mathbf{Y_S} \neq [\mathbf{Y_S} + \mathbf{Y'_R}]^{-1}\mathbf{Y_S} \tag{8}$$

Note also that because, $\mathbf{H_R}$, may no longer be equal to, $\mathbf{H'_R}$, the vibro-acoustic frequency response functions relating forces at the interface to a response location might also be changed. A discussion regarding how $\mathbf{H'_R}$ may be obtained in practice is given later in the paper.

3. Prediction of Structure Borne Noise

In this section of the paper a case study is presented that demonstrates the real-world application of equations 1, 2 and 6 for the prediction of structure borne noise within a train. This involved the measurement of source blocked forces, source mobility, receiver mobility and a set of vibro-acoustic frequency response functions for the train (without the vibration source installed). The passive FRF data was then combined to make an experimental model of source-receiver assembly and this model was excited using measured blocked forces to predict structure borne noise within the train carriage.

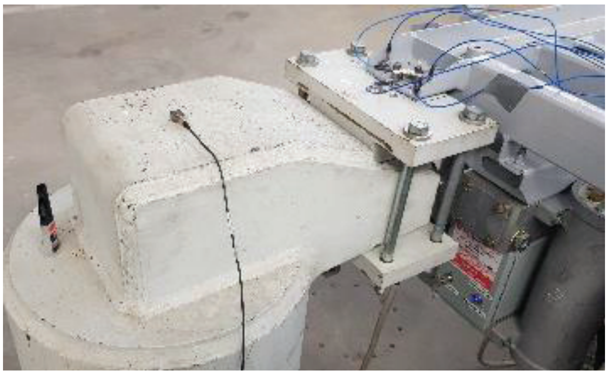
3.1 Blocked Force Measurements

An air generation and treatment unit (AGTU) was characterized in terms of its mobility and blocked forces taking into account six degrees of freedom at each connection point (three translational and three rotational) with the AGTU supported on air springs as shown in figure 1. In order to take into account six degrees of freedom at each connection point four accelerometers were oriented in the vertical z direction in order to capture translation in the z axis and rotation about the x and y axes. Two further accelerometers oriented in the x direction then capture translation in the x direction and rotation about the z axis. A single accelerometer was the oriented in the y direction to capture the remaining degree of freedom. A description of the method used can be found in [8].

After performing measurements with the source resiliently mounted on air springs the source was then rigidly coupled to the test bench as shown in figure 1b. In this configuration an additional accelerometer was installed at a remote location on the test bench. The measurements were then repeated but this time obtaining $\mathbf{Y_C}$ and $\mathbf{v_C}$ to satisfy equation 1. The combination of measurements in the free and rigidly coupled conditions on the test bench allowed the blocked forces to be validated using two methods:

1. The blocked forces from the free and rigidly coupled test setups were compared for each degree of freedom to confirm they were not affected by the boundary condition, and
2. The blocked forces obtained from the freely suspended condition were used to make a prediction of the test bench vibration at a remote location away from the interface.

In theory both of the above should be satisfied because equations 1 and 2 are known to be exact for linear, time invariant systems. However, experimental uncertainty and the number of degrees of freedom included in the model are known to affect the agreement between blocked forces measured in different states and this in turn affects the accuracy of any subsequent sound or vibration predictions. Furthermore, in some cases it is possible that source operation could be affected by the mounting condition, i.e. the source's behavior can be altered. Thus, by making checks 1 and 2 above the reliability of the blocked force data for structure borne noise predictions on the train can be assessed.



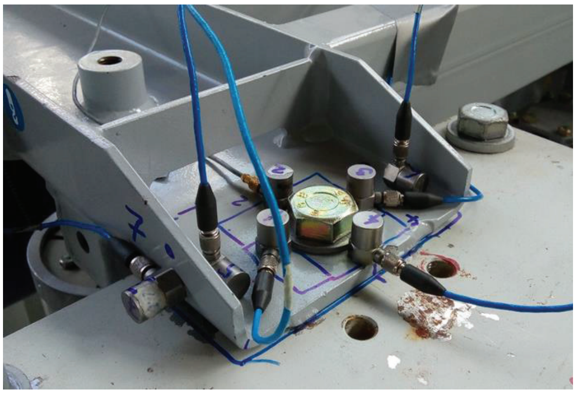


Figure 1: (a) Air compressor installed on test bench supported by air springs (top left) (b) air compressor installed on test bench by rigid coupling, showing also the position of the validation reference sensor (top right) and (c) instrumentation of the interface used to capture 6 degrees of freedom (bottom left).

Shown in figure 2 is a comparison of the blocked forces measured in the free and rigidly coupled states for one of the AGTU connection points in the vertical z direction. It can be seen that blocked forces measured under both mounting conditions agree well over the majority of the frequency range shown (20-2000Hz). Note that the operation of the AGTU was found to vary from one day to the next by a similar order of magnitude, perhaps due to variations in environmental conditions (as observed in acceleration measurements made on the core of the compressor).

Shown in figure 3 is the reference vibration level measured on the test bench with the AGTU operational (blue line) when mounted as shown in figure 1b. This is compared to a prediction of the vibration acceleration obtained using the blocked forces measured in the free condition (data check 2 above). Except for a few tonal peaks the agreement between measurement and prediction is very good, especially when the repeatability of the AGTU's operational behavior is considered.

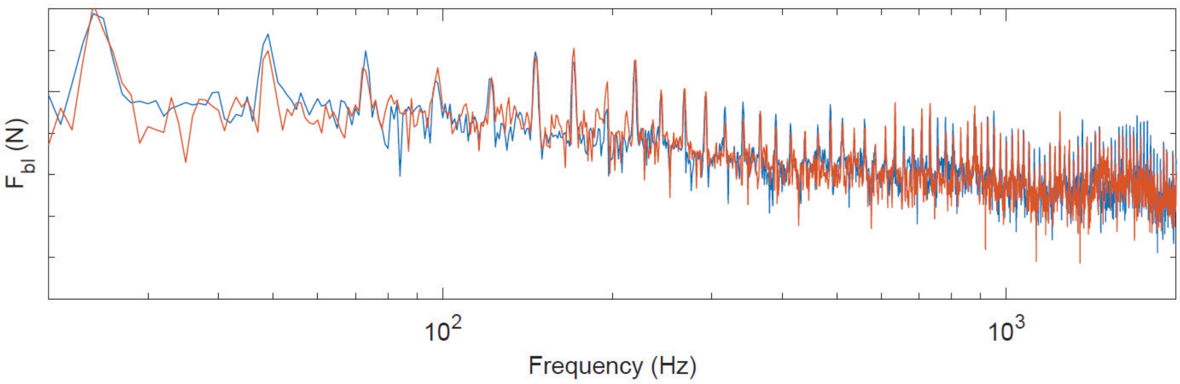


Figure 2: Comparison of blocked forces measured on the test bench under two different boundary conditions - rigidly coupled (blue) and mounted on air springs (red). The blocked forces obtained under both boundary conditions are in good agreement despite the different mount conditions demonstrating that the data is independent of the installation condition [9].

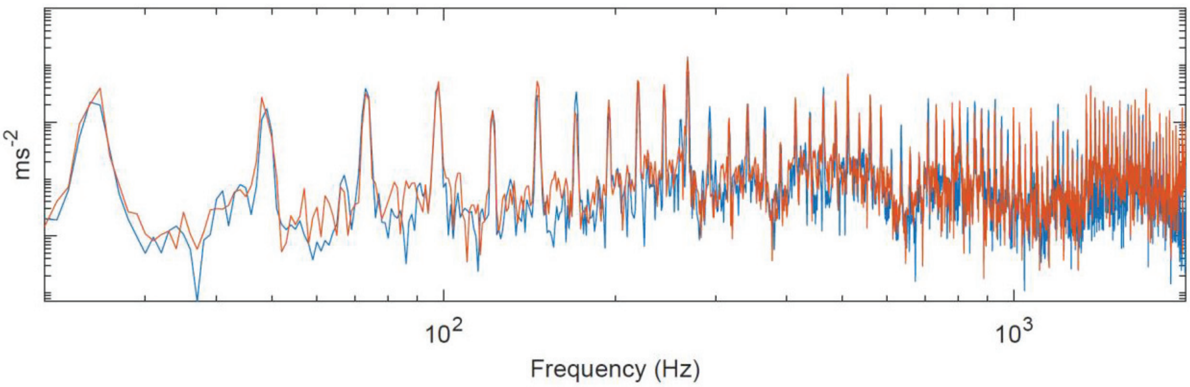


Figure 3: Prediction of test rig reference vibration levels in the vertical z direction with the AGTU operational. The blue line shows the actual vibration level measured on the test rig when the source and receiver were rigidly coupled, and the orange line was predicted using in-situ measured blocked forces obtained when the source was freely mounted [9].

3.2 Sub-Structuring

With the blocked forces of the compressor validated as described above a further measurement campaign was carried out to validate the full prediction methodology. In order to do so frequency response function measurements were made on a train with and without the compressor installed and the sound pressure inside the train with the air compressor operational was measured. A photograph of the AGTU installed on the train is shown in figure 4 below.

Figure 4: The air generation and treatment unit (AGTU) installed on the train.

In order to make a prediction of structure borne noise in the train it was first necessary to perform measurements of the train mobility at the degrees of freedom where the AGTU was to be mounted and of the transfer functions relating the interface degrees of freedom to the interior sound pressure. This was done by instrumenting the train using the same accelerometer arrangement as shown in figure 1c but with an additional three microphones in the train carriage. This test setup allowed the simultaneous acquisition of the train mobility and the vibro-acoustic frequency response functions by exciting, one by one, all the interface degrees of freedom. Once these measurements had been completed the AGTU was reinstated and the interior structure borne noise was measured for validation purposes.

The final result of this section is therefore a comparison of the train interior noise with a prediction of the structure borne component of the interior noise obtained using equations 6 and 2 (see figure 5). Note that the measurements on the train were performed in a reverberant space (a factory) and that the measured train interior noise can be expected to include both the structure borne component and a flanking airborne paths, e.g. through door seals and windows, so one would not expect a perfect comparison. Nevertheless, the prediction result is very encouraging with most of the frequency range shown displaying a good agreement between the measured and predicted response (the difference to in the overall A-weighted sound level was 2.5dBA). The under prediction in the frequency range 1000-2000Hz is thought to be in part due to airborne transmission. Recall also that the source repeatability may not be perfect, for example it can be seen that the operational speed of the AGTU on the train was slightly lower than on the test bench.

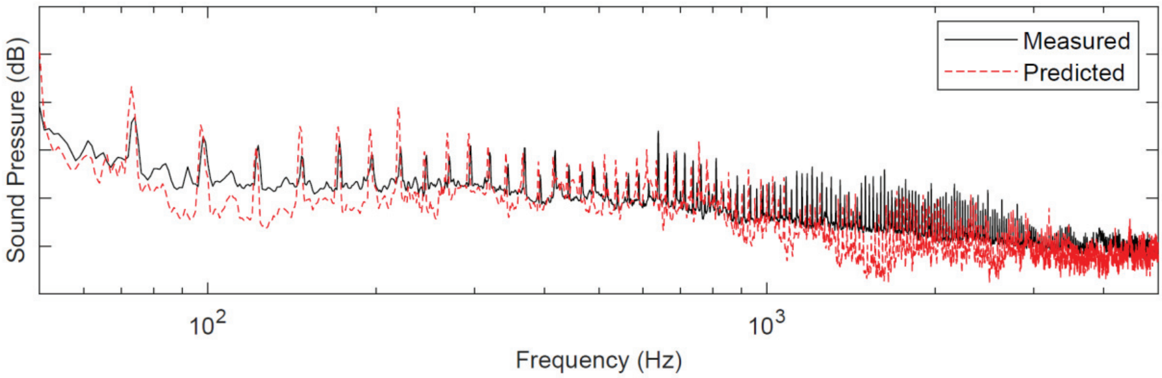


Figure 5: Prediction of structure borne noise in the train with the AGTU operational (dashed red line) compared to the actual interior noise (solid black line). The y-tick divisions each represent 10dB.

4. Structural Modification

As explained in the introduction and theory sections of the paper, one of the main advantages of blocked forces over contact forces is that they remain valid even after a modifications to a source receiver assembly (providing the modifications are made downstream of the interface). This was shown experimentally to be the case in figures 2 and 3 in the previous section. By means of an example it is therefore interesting to experiment with the possibility of sub-structuring simple elements or components to the coupled source-receiver assembly using equation (4). The purpose of doing so in real world applications would be to investigate the influence of structural modifications to an assembly to solve noise and vibration problems.

Shown in figure 6 is the accelerance of the z-direction at one of the interface points of the source-receiver assembly (blue line). To implement the structural modification approach, the accelerance of the z-direction degrees of freedom were modified by sub-structuring virtual lightly damped springs (of stiffness, $k=3x10^6$ Nm^{-1}) to each node of the 4 z-oriented nodes at each connection point. Applied in practice, this would have the effect of stiffening the receiver structure in the z-direction and rotationally about the x and y axes. It can be seen in the figure that the orange line (representing the modified assembly) now has a lower accelerance than the original source receiver assembly. It can be expected therefore that the vibration at the source receiver interface will also be significantly altered by this structural modification.

After artificially modifying the source-receiver interface the vibration response of the modified assembly was then predicted using equation (1). The resulting vibration level is shown in figure 7 with a comparison to vibration the vibration level at the same point prior to structural modification. It can be seen in the figure that the vibration acceleration at the interface (in the vertical z-direction) would be reduced significantly in the frequency range 0-800Hz by making such a change to the receiver structure. Similar plots could also be made for the force on the receiver or the transmitted power making it a useful tool for the investigation of noise and vibration mitigation measures. What is often required however is the vibration or sound level at a response position that is remote from the source-receiver interface.

As previously mentioned in section 2 of the paper, when the response at a remote location is required the process of artificial structural modification is somewhat more challenging because equation 7 might then be used and any alteration to the transfer function relating the remote response to the interface degrees must also be taken into account. This is inconvenient because additional measurement positions are required for every position on the system where a structural modification might be made. In such instances it is likely therefore to be more useful to either excite a numerically modelled system (e.g. obtained using SEA or FEA) or a modal model obtained by measurement. This is a promising area for further research.

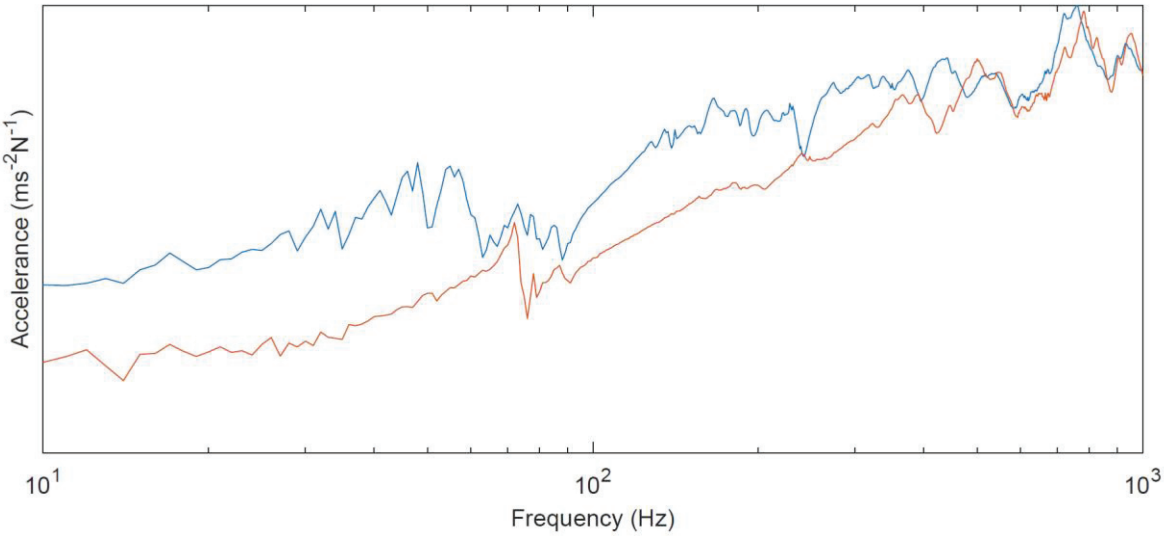


Figure 6: Example of modification to the accelerance of the coupled source receiver assembly in the vertical z-direction. The source receiver assembly was modified by sub-structuring damped springs of stiffness k=3x10^6 Nm^{-1} to each of the nodes oriented in the z direction (orange line). This is compared to the accelerance before structural modification (blue line).

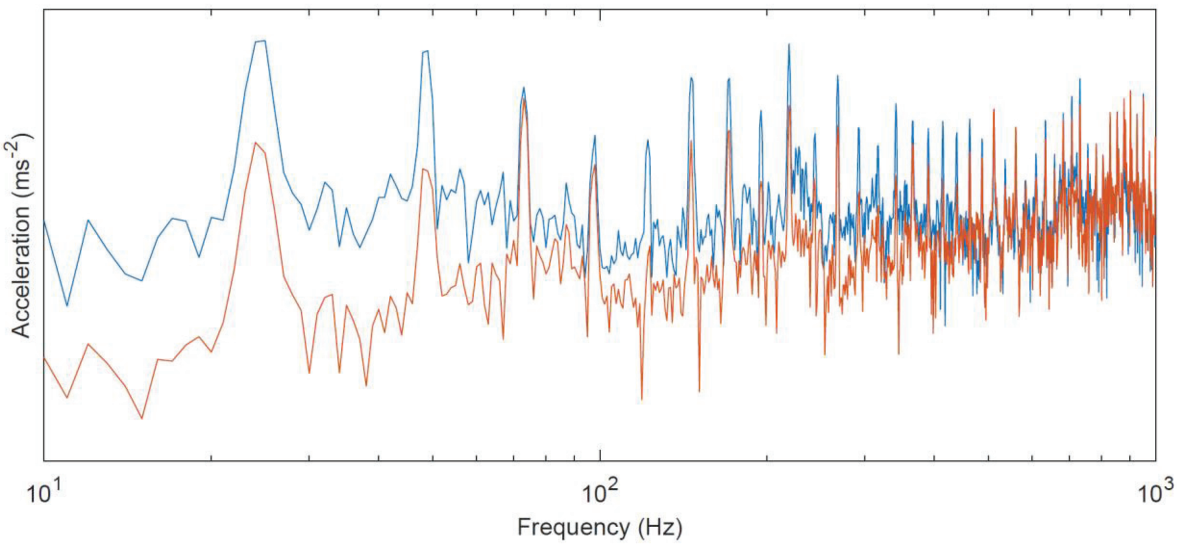


Figure 7: Example of the influence of artificially stiffening the source receiver interface on the vibration acceleration at the interface in the z-direction (orange line). The vibration level of the unmodified system is shown as a blue line.

5. CONCLUDING REMARKS

Described in the paper are two case studies that demonstrate the use of the in-situ blocked force approach in combination with sub-structuring, sometimes referred to as component TPA. The first case study describes measurements made to characterize a real-world vibration source on a test bench and the data checks that were carried out to ensure the blocked forces obtained were suitable for making predictions of structure borne noise. Six degrees of freedom were taken into account at each terminal of the source structure in these measurements which is unusual for a system of such complexity. The blocked force data was then used to make predictions of structure borne noise in a train and it was shown that the combined blocked force and sub-structuring methodology provide an estimate that agrees with measurements made on the train (within 2.5dBA overall).

The second case study presented uses the same source-receiver assembly but investigates the use of structural modification by means of a simple example. For this case study it is shown how the effect of stiffening of the receiver structure can be investigated by sub-structuring ideal springs to the source receiver interface. The combination of methods and techniques presented in the paper provide a useful toolset that can be employed for noise/vibration prediction, diagnostic testing and virtual prototyping.

ACKNOWLEDGEMENTS

We would like to thank Faiveley Transport in Turin (Italy) and also Alstom rolling stocks factory in Katowice (Poland) for providing the equipment case study and for their hospitality and support provided during the measurement campaigns. This contribution reflects the views of the authors.

REFERENCES

1. Clot, A, Meggitt, J.W.R, Langley, R.S, Elliott, A.S. and Moorhouse, A.T, 2019. Development of a hybrid FE-SEA-experimental model. Journal of Sound and Vibration, 452, pp.112-131.
2. Moorhouse, A.T, Elliott, A.S and Evans, T.A, 2009. In situ measurement of the blocked force of structure-borne sound sources. Journal of Sound and Vibration, 325(4-5), pp.679-685.
3. Elliott, A.S, Characterisation of structure borne sound sources in-situ. Thesis, University of Salford, 2009.
4. Klerk, D.D, Rixen, D.J. and Voormeeren, S.N, 2008. General framework for dynamic substructuring: history, review and classification of techniques. AIAA journal, 46(5), pp.1169-1181.
5. Mottershead, J.E, Kyprianou, A. and Ouyang, H, 2005. Structural modification. Part 1: rotational receptances. Journal of Sound and Vibration, 284(1-2), pp.249-265.
6. Klerk, D.D., Rixen, D.J. and Voormeeren, S.N., 2008. General framework for dynamic substructuring: history, review and classification of techniques. AIAA journal, 46(5), pp.1169-1181.
7. Elliott, A.S, Moorhouse, A.T, Huntley, T. and Tate, S, 2013. In-situ source path contribution analysis of structure borne road noise. Journal of Sound and Vibration, 332(24), pp.6276-6295.
8. Elliott, A.S, Moorhouse, A.T. and Pavić, G, 2012. Moment excitation and the measurement of moment mobilities. Journal of sound and vibration, 331(11), pp.2499-2519.
9. Nezam. S, Elliott. A, Glesser. M, Ferella. S. and Sapena J, 2019, Structure borne noise characterization of an Air Generation and Treatment Unit (AGTU) for a train by using blocked forces method, Internoise 2019, Madrid, Spain.