Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

characterisation of structure borne sound sources from measurement in-situ

Andrew Elliott and Andy Moorhouse

University of Salford, Acoustic Research Centre, Newton Building, M5 4WT Salford, UK
a.s.elliott@pgr.salford.ac.uk

A method is outlined which allows the activity of a structure-borne sound source to be characterised from measurements made in-situ, i.e. where the source is connected to a receiver structure. The blocked force of a beam source was measured in-situ when coupled to a receiver beam. This blocked force was validated by predicting the coupled velocity of the source mounted on a different receiver beam. Excellent agreement with measurement was obtained. Importantly, no separation of the source and receiver structure is required in order to obtain the blocked force, so this method could be used in the many practical situations where a source cannot be separated from a receiver structure. An extension of the method was also tested which allows remote measurement positions on the receiver structure to be used, i.e. positions away from the contact points. This method gave even better agreement, perhaps because it allows us to over-determine the problem. Such a method could also be beneficial where access to contact points is difficult.

1 Source Characterisation

A vibrating machine will excite a receiver structure at the points where the two connect. In some cases this may cause a structure borne noise problem.

In order to quantify the mechanical power transmitted from a vibration source to receiver we may carry out a process of source characterisation. The quantities chosen to characterise the source must describe the activity of the source and its ability to transmit this activity to the connected structure. The focus of this paper is how to obtain a representative description of source activity.

To describe source activity, the free velocity v_{sf} or blocked force F_{bl} may be used. Blocked force and free velocity are related to source mobility Y_s and source impedance Z_s by,

$$\{F_{bl}\} = [Z_s]\{v_{sf}\} \qquad \{v_{sf}\} = [Y_s]\{F_{bl}\} \tag{1}$$

Essentially, the free velocity is the operational velocity of the unconstrained source and the blocked force is the force that would be required to prevent the operating source from moving. Neither quantity is particularly easy to measure directly without compromise.

Mobility and impedance are passive properties of the source and are not the main concern here. Nevertheless, passive properties are required and will be discussed later. .

1.1 In-situ source characterisation

It has been suggested that it may be useful to investigate how source characterisation data might be recovered from measurements performed in-situ. In-situ characterisation measurements are those carried out on the source and receiver whilst coupled.

Previous works have investigated the possibility of performing in-situ source characterisation measurements. Moorhouse and Gibbs, for example, characterised resiliently mounted machines in-situ [1]. Heng Yi Lai introduced the concept of an in-situ measured synthesized force [2]. A method for measuring mobility and free velocity in-situ was outlined by Pavic and Elliott in [3]. Further investigation of this method and an alternative method which characterised a source in terms of the blocked force was presented in [4]. This alternative method characterised source activity in terms of in-situ measured blocked force. Although not recognised at the time the synthesized force used in [2] was in fact also the blocked force.

It is hoped that by characterising a source in-situ we may be able to account for the confines on the source resulting from its connections to the receiver. It is also likely that measurements made using the in-situ method described here will be easier to carry out, particularly when characterising source activity under realistic operating conditions.

In this paper a method for obtaining the blocked force purely from in-situ measurements is described and results from laboratory validation measurements are presented. A validation of conventionally measured data is also shown as a comparison. First we address conventional source characterisation measurements.

2 Conventional method

The standard method of characterising structure-borne sound source activity is through the free velocity [ISO 9611:1996]. Additional information is required about the passive properties, so typically, a source would also be described by its mobility. The receiver would just be described by its mobility. All these quantities would be measured independently i.e. when source and receiver are separate. It is useful to begin with a few basic relationships.

When a source and receiver are rigidly coupled the velocity of the operating vibration source and its receiver can be related to the free velocity of the source,

$$\{v_s\} = \{v_{sf}\} + [Y_s]\{F_s\} \tag{2}$$

$$\{v_r\} = [Y_r]\{F_r\} \tag{3}$$

Here, the source and receiver velocities, v_s and v_r, are equal and will from here on be referred to as the coupled velocity v_c. F is the force and Y the mobility, and the subscripts s, r and c are used to denote source, receiver and coupled respectively.

The forces acting on the source and receiver, F_s and F_r, are equal but opposite in direction and sign; rearranging Eqs. 2 and 3 and substituting to eliminate these forces we obtain the relationship,

$$\{v_c\} = [Y_r][Y_r + Y_s]^{-1}\{v_{sf}\} \quad (4)$$

Eq. 4 will prove to be useful for validation purposes as power transmission from a vibration source to a receiver is difficult to measure with absolute certainty. Thus, Eq. 4 is used here to test the validity of independently measured characterisation data.

A previous study highlighted a requirement for simple validation tests [4]. A simple validation test structure was designed which consisted of two beams. The upper, source, beam was fitted with two 3cm square feet; each with a threaded hole in the centre. The source and receiver could then be connected rigidly by screws through the receiver beam into the source at two points.

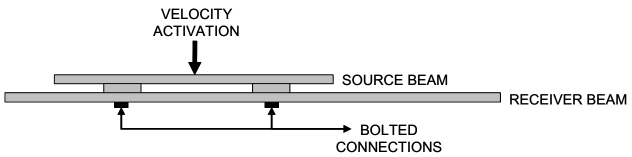

Fig.1 Laboratory test setup

As our primary aim is to validate descriptions of source activity; a stable and repeatable source activity was required. For this purpose a hammer blow was used to activate the vibration source. Although the hammer user cannot apply a repeatable activating force to the source, resulting velocities can easily be normalised by the measured applied force. This is in effect a mobility but may be considered as being equivalent to broadband frequency excitation by shaker. The benefit is that the obstructions and inconvenience caused by a shaker attachment are avoided.

As discussed, characterisation data was found using independent measurements. The source mobility was measured at both contact points, then the normalised activity at these contact points was measured (source mobility and free velocity). The receiver mobility was then measured at the points where the source attaches. Finally, the source and receiver were bolted together and the normalised coupled velocity was measured as a validation reference.

The coupled velocity was predicted from the independently measured characterisation data using Eq. 4. This prediction was then compared to the measured “true” coupled velocity. This is shown in Fig. 2.

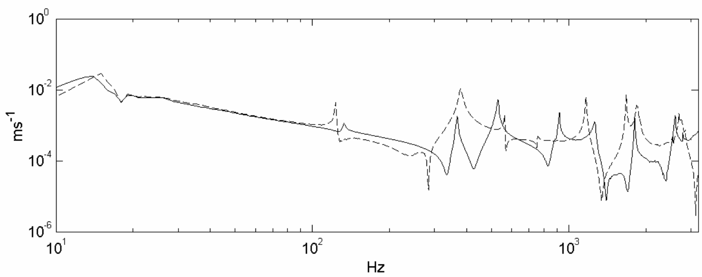

Fig. 2 Coupled velocity: Directly measured (solid line) and predicted from source and receiver mobilities and free velocity “conventional method” (dashed line)

The source characterisation data used here included only one degree of freedom; translation in the axis perpendicular to the beams. Source excitation was in the same direction. The prediction of coupled velocity shown in Fig. 2 is poor. In the following section we investigate the reason for the poor agreement, which requires an understanding of the role of the mobilities in Eq, 4.

2.1 Discussion of conventional results

In the given example, the passive properties of the source and receiver were characterised by measuring the mobility at each of the points where the source coupled to the receiver for one degree of freedom only. The mobility could however have been measured for all axes of vibration and for rotations about these axes. This may or may not have been necessary. The extent to which mobility data is required may be investigated by considering the coupled mobility Y_c.

$$[Y_c] = \left[[Y_s]^{-1} + [Y_r]^{-1}\right]^{-1} \quad (5)$$

Eq. 5 states that the impedance of the coupled structure is equal to the sum of the source and receiver impedances. Here however, we measure mobility rather than impedance. It has long since been known that mobility is invariant whereas impedance is not [5]. In part, mobility is favoured because of this. An unfortunate consequence, however, is that a mobility matrix which does not include all elements of structural importance may not invert to a representative impedance matrix. Thus, when evaluating Eq. 4 an error will result if degrees of freedom are not included.

We suspect that the poor agreement in Fig 2 is due to the fact that in-plane mobilities were not included. In order to investigate this we modify the contact conditions so as to allow the two beams to slide over each other. This is done by resting the source beam on the receiver beam, held lightly in place with wax. Shown in Fig.2 is a prediction of the coupled mobility given by Eq. 5 compared to that which was directly measured.

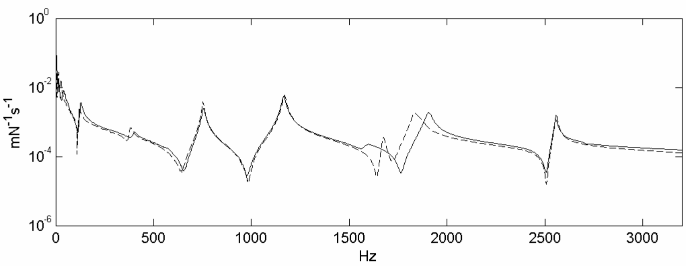

Fig. 3 Measured (solid line) and predicted (dotted line) coupled mobility for two beams connected by two sliding square contacts. One of two contact points shown.

As there were two contact points the prediction shown in Fig. 2 was computed using 2×2 source and receiver matrices. Only one of the possible six degrees of freedom was included. In this case Eq. 5 yields an excellent prediction of the coupled mobility. This suggests that the inversions from mobility to impedance were valid for this problem. This may have been expected since the sliding contact condition should only allow the source and receiver to interact through the one degree of freedom which was accounted for.

We now return to the original bolted contact, i.e. the configuration for which the velocities were shown in Fig. 1. The measured coupled mobility of the bolted source and receiver is shown in Fig. 4. The prediction from independently measured mobilities in one degree of freedom is also shown (which is the same as that in Fig 3).

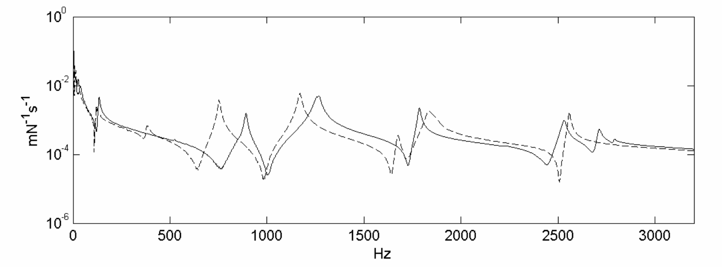

Fig. 4 Measured (solid line) and predicted (dotted line) coupled mobility for two beams connected by two bolted square contacts. One of two contact points shown.

The discrepancies in Fig. 4 are clearly due to the bolted connections which cause a stiffening of both structures, one by the other. This in-plane coupling was not accounted for and thus, the coupled mobility prediction from Eq. 5 is a rather poor reflection of reality. This explains why the predicted velocities in Fig. 2 are in poor agreement with the measured values.

Perhaps if in plane mobilities were included for our bolted connection cases better results would have been obtained. Unfortunately however in plane excitation was not possible due to the geometry of the problem. This will often be the case in reality. It is also interesting that in terms power transmission; it is possible that in plane activity may not be of importance but one may still be forced to measure in plane to account for structural stiffening. Thus, in practice it is difficult or impossible to account for all degrees of freedom when using the conventional mobility approach, yet such omissions can result in significant errors.

It is hoped that by characterising a source in-situ, using a receiver that applies similar restraints on the source, we may be able to account for such effects. We will now consider the in-situ measurement of source data.

3 In situ method: Basic measurement

In this section we investigate a method for obtaining blocked forces from in-situ measurements. Since the contact conditions can be accurately reproduced in such a test it is argued that all significant degrees of freedom are included including those which could not be measured in the conventional approach.

By substituting the free velocity from Eq.1 into Eq.2 we have,

$$\{v_c\} = [Y_s]\{F_{bl} + F_s\} \tag{6}$$

Then by combining Eq.3 and Eq.6 and rearranging,

$$\{F_{bl}\} = [Y_s]^{-1}\{v_c\} - [Y_r]^{-1}\{v_c\} \tag{7}$$

Finally, if we gather the inverted source and receiver mobility terms we can substitute for the coupled mobility from Eq.5 giving,

$$\{F_{bl}\} = [Y_c]^{-1}\{v_c\} \tag{8}$$

Thus the blocked force can be found from in-situ measurements of the coupled velocity and coupled mobility.

The thinking behind the in-situ method is that a source could be characterised in a way which accounts for degrees of freedom and perhaps other coupling effects that we wish to avoid measuring. The experiment presented here is designed to enable us to characterise the source in terms of blocked force in one direction only.

To be clear, here we aim to validate the blocked force measurement only. In order to obtain the blocked force from Eq. 8 we must measure the coupled mobility and coupled velocity using a receiver beam which is different from that for which we wish to make our predictions. The test would otherwise be cyclical. An alternative receiver beam, which we shall refer to as the reference beam, was used for characterising the blocked force of the source. We required this reference beam to have a have a different mobility to the receiver beam to allow for a fair test whilst confining the source as it would be on the receiver beam.

To demonstrate that the mobility of the receiver beam Y_r and the mobility of the reference beam Y_r' were sufficiently different to provide a fair test; both mobilities are plotted in Fig.5.

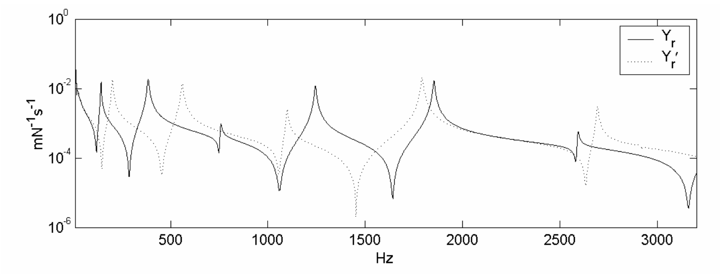

Fig. 5 Receiver mobilities: Receiver mobility (solid line) and reference beam mobility (dotted line)

All dimensions other than the receiver and reference beam lengths were the same. They were also both of the same material. It is likely therefore that the in plane mobility of the two beams were very similar. This was in fact intended, although, the in plane mobility was not measured to confirm this.

In brief, the measurement procedure was:

1 Measure the coupled velocity on the reference beam.

2 Measure coupled mobility on the reference beam.

3 Use measurements 1 & 2 to calculate the blocked force using Eq. 8.

4 Measure the coupled mobility of the coupled source and receiver beam.

5 Using the blocked force from 3 and the coupled mobility from 4, use Eq. 8 to predict the coupled velocity.

Shown in Fig. 6 is a comparison of the measured and predicted coupled velocities for one of the two points.

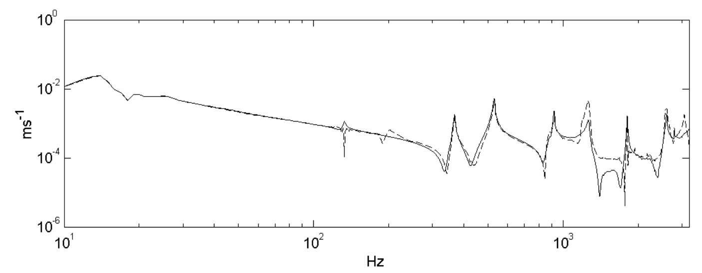

Fig. 6 Coupled velocity: Directly measured (solid line) and predicted from blocked force and coupled mobility (dashed line)

The measured coupled velocity shown in Fig. 6 is the same as that shown in Fig. 4. The prediction using the blocked force appears excellent up to 1 kHz after which the predicted velocity is still reasonable and a considerable improvement on that obtained by the conventional method.

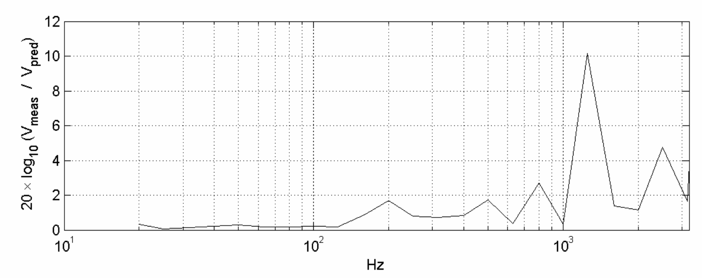

Fig. 7 Third octave band plot of error in spatially averaged coupled velocity prediction.

Shown in Fig.7 is the ratio of measured and predicted coupled velocity. This plot takes into account both connection points using a spatially averaged velocity. Spatially averaged velocities were calculated for both measurement and prediction which were then converted into third octave bands. The error shown is the dB error in the third octave band spectra of the velocity prediction. The error is less than 3dB below 1 kHz.

This result can be considered as a validation of the blocked force as measured on the separate reference beam. For the full potential of the method to be realised a validation of the coupled mobility is required. For completeness and clarity this requirement is acknowledged but not addressed here. It is suggested however, that such a measurement could be performed in-situ during source characterisation on the reference structure.

4 In-Situ Source Characterisation Using Remote Measurements

A further development of the method allows the blocked force to be found using remote measurement positions. This may simplify measurements where access to coupling points poses a problem. Another benefit is that using this new formulation it is possible to over-determine the problem.

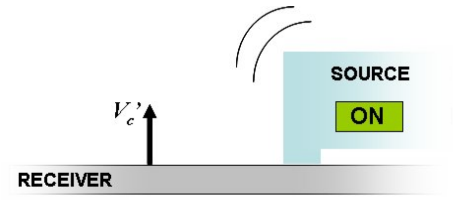

Fig. 8 Remote sensed coupled velocity.

First a coupled velocity measurement, at any point on the receiver structure, is made while the source is operating. Here we shall call this measurement v_c' where the dash indicates that the measurement is not made at a contact point.

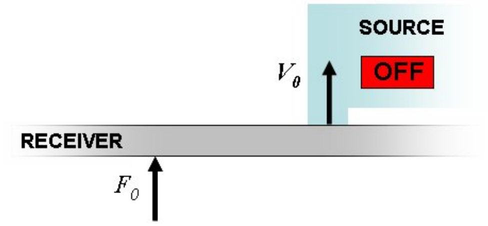

Fig. 9 Coupled transfer mobility measurement.

This velocity must then be related by transfer function to the source' and receiver's coupling point, as shown in Fig.9. The velocity v_0 divided by the applied force F_0 is then the coupled transfer mobility Y_{ct}.

It can be shown that from these two measurements the blocked force of the source can be found by solving Eq. 9.

$$\{v_c'\} = [Y_{ct}]\{F_{bl}\} \qquad (9)$$

If blocked forces at N contact points were required v_c' must be a vector of at least N remote velocities and Y_{ct} would be an N × N matrix. However, this formulation will also allow us to over determine the problem if desired. In which case Y_{ct} would then consist of N columns and the number of rows in Y_{ct} and v_c may then be any number greater than or equal to N. It is also interesting to note that the remote coupled velocity could in theory be replaced by a sound pressure, for example, providing the transfer function Y_{ct} related force to a sound pressure rather than a velocity.

For validation of the remote measurement method the same basic approach as that described in Sec.3 was used. However, here we make use of the possibility to over determine the measurement.

The measurement procedure was as follows:

1 The coupled velocity was measured at seven positions with the source coupled to the reference beam. (giving a vector of 7 velocities)

2 The coupled transfer mobility was then measured to relate these seven points to the points where the source and reference beam coupled. (giving a 2 by 7 matrix of mobilities)

3 Eq.9 was then solved to find the blocked force.

4 The coupled mobility of the coupled source and receiver beam was measured as described before.

5 Using the blocked force from 3 and the coupled mobility from 4, Eq. 8 was used to predict the coupled velocity.

Steps 1, 2 and 3 only, differ from the basic measurement described previously by the use of measurements at remote positions rather than at contact points. Thus, here, we use an alternative measurement of the blocked force combined with the same coupled mobility as used for the validation in Sec. 3.

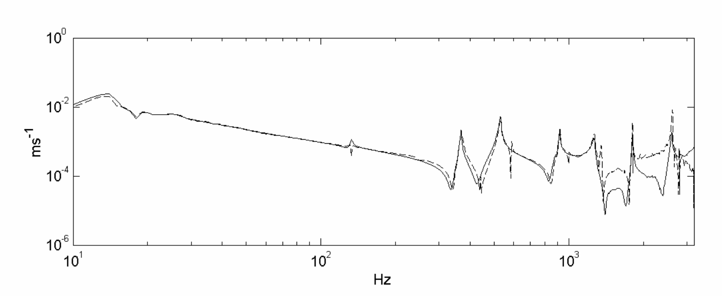

Fig. 10 Coupled velocity: Directly measured (solid line) and predicted from blocked force and coupled mobility (dashed line)

Shown in Fig. 10 is a comparison of the measured and predicted coupled velocities. The narrow band spectra of measured and predicted coupled velocity magnitudes compare very well. Comparing Figs. 6 and 10 the basic and remote measurement techniques appear to yield similar results. The validation results shown for the basic and remote methods are from a first trial and are not optimised or smoothed. A spatially averaged result for the remote measurement is shown in Fig.11.

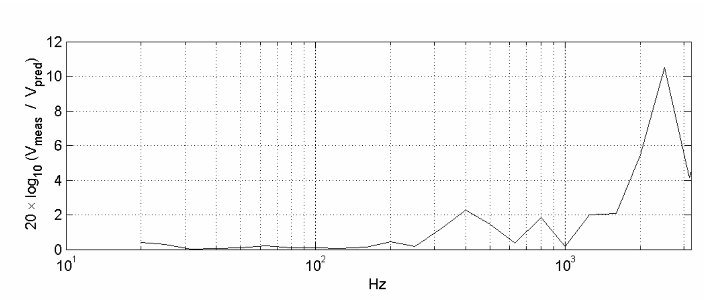

Fig. 11 Third octave band plot of error in spatially averaged coupled velocity prediction.

The error shown in Fig.11 is the dB error in the third octave band spectra of the velocity prediction as described in Sec.3. The error was found to be less than 2.5dB below 1.5kHz and less than 6dB below 2kHz.

All results presented are from a single laboratory trial and do not represent a deep investigation of the methods. In this case, the remote mobility points considered to have poorer coherence could have been discarded, perhaps giving a better result. Also, alternative remote points outside of the z-dir could have been investigated. These are some issues, of many, which could potentially improve the prediction even further. The results are therefore promising.

5 Conclusion

Using a conventional method a source was characterised in terms of its mobility and free velocity. This characterisation data was used to predict the coupled velocity. Poor agreement with measured data was obtained. Further tests indicate that this may be due to insufficient degrees of freedom being considered, despite the test being a very simple one. Such errors will be very difficult to avoid with conventional source characterisation techniques.

A method was outlined which allows the activity of a structure-borne sound source to be characterised from measurements made in-situ. The method was tested by measuring the blocked force for a source beam whilst it was rigidly bolted to a reference beam. The blocked force so obtained was then validated by predicting the coupled velocity of the source mounted on a separate receiver beam. The agreement with the measured coupled velocity was within 3 dB of the true coupled velocity below 1 kHz (third octave bands spatially averaged). Importantly, no separation of the source and receiver structure is required in order to obtain the blocked force, so this method could be used in the many practical situations where a source cannot be run without being rigidly bolted to a receiver structure. An extension of the method was also tested which allows remote measurement positions on the receiver structure to be used, i.e positions away from the contact points. This method also allows us to over determine the problem. The blocked force gave a prediction of the coupled velocity within 2.5 dB of the true coupled velocity below 1.5 kHz (third octave bands spatially averaged). Such a method could be used where access to contact points is difficult.

Acknowledgments

The support of EPSRC (EP/D002109/1) is gratefully acknowledged.

References

[1] A. T. Moorhouse, B. M. Gibbs "Measurement of structure borne sound emission from resiliently mounted machines in situ", *Journal of Sound and Vibration* 180(1), 143-161 (1993)

[2] Heng-Yi. Lai, "Alternative test methods for measuring structure borne sound", *Inter-noise*, Hawaii (2006)

[3] G. Pavic, A. Elliott, "Characterisation of structure borne noise in situ", *Euronoise*, Finland (2006)

[4] A. Elliott, A.T. Moorhouse, G. Pavic, "Characterisation of a structure borne sound source using independent and in situ measurement", *ICA*, Madrid (2006)

[5] G. J. Ohara, "Mechanical impedance and mobility concepts", *Journal of the Acoustical Society of America* 41, 1180-1184 (1967)

[6] S. S. Sattinger, "A Method for experimentally Determining Rotational Mobilities of Structures", *Shock and Vibration Bulletin 50(2)*, 17-28 (1980)

[7] A. S. Elliott, G. Pavic, A.T. Moorhouse, "Measurement of force and moment mobilities using a finite difference technique", *Proceedings Acoustics 2008,* Paris (2008)