TOWARDS AN IN-DIRECT METHOD FOR LOW FREQUENCY SOUND TRANSMISSION

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ABSTRACT

This paper describes the development and testing of an alternative method of sound transmission measurement, ideally suited to low frequencies. The standard approach to measuring sound transmission (detailed in ISO 10140) relies on the assumption of a diffuse field from which radiated sound power can be estimated. While adequate for higher frequencies, this assumption doesn't hold at low frequencies due to the presence of modal effects. The proposed method avoids this assumption and thus has the potential to provide a low frequency sound transmission measurement with reduced uncertainty. This is achieved by a) representing the radiated sound field by an equivalent array of monopole sources (i.e. volume velocities) which are independent of the room's modal characteristics and b) applying a synthesised incident diffuse field to a measured vibro-acoustic FRF of the partition. Preliminary results demonstrate that the equivalent field representation is both invariant of the rooms modal characteristics, and able to accurately reproduce the sound field radiated from a partition.

1 INTRODUCTION

The laboratory measurement of sound transmission, according to ISO 10140 [1], is based on the spatially averaged level difference between two reverberant chambers that surround the test object. Underlying this method is the assumption that within each chamber, the sound field constitutes that of a diffuse field. It is this assumption that allows us to relate the spatially averaged pressure levels to the incident and radiated power across the partition, and so estimate sound transmission.

The diffuse field assumption holds well in the mid-high frequency range (above approx. the Schroeder limit). However, at low frequencies this assumption is no longer valid; well separated modes lead to large spatial variations in the pressure field. Indeed, it is widely recognised that these variations lead to large uncertainties in the ISO standard result [2], and in fact limit its low frequency application. For this reason, there is great interest in alternative methods, particularly suited to low frequencies, that avoid the uncertainties associated with the diffuse field assumption. In this paper, we present our work towards such a method.

For conciseness, we do not provide a detailed review on the sound transmission literature here. Rather, we will discuss only the most relevant study to the work presented in this paper, that by Roozen et al.[3]

Roozen et al. [3] in 2018 presented a mobility-based method for measuring sound transmission that entirely avoids use of the diffuse field assumption to approximate incident or radiated power. Rather, radiated power is obtained by first measuring the partition's structural velocity using a scanning Laser Doppler Vibrometer (LDV), before an evaluation of the Rayleigh integral is used to predicted the radiated pressure, and so estimate radiated power. Importantly, the structural velocity measured is not due to an incident sound field upon the partition. Instead, it is due to a series of point force excitations made across the partition's incident side. In effect this yields a mobility measurement across the partition. A synthesised diffuse field with known power is subsequently applied (numerically) to the measured mobility. The result is an indirect measurement of sound transmission that avoids the diffuse field uncertainties of ISO 10140.

Though a promising approach, there are some important limitations to this method. Firstly, the need for a scanning LDV to measure structural velocity. Scanning LDVs are costly (in excess of £100,000) and, whilst available within most R&D facilities, are not necessarily so in commercial test houses. Secondly, with the point-by-point measurement of the LDV, and the numerous point-force excitations required, the experimental campaign becomes quite costly. Thirdly, being based on structural velocity, the radiated power can not be predicted for any systems that contribute through acoustic paths, for example louvres and vents. Similarly, the method is not able to account for acoustic leaks, and would be challenging to apply to partitions with complex (non-planar) geometry.

In this paper we propose an alternative method, based on a similar synthesised diffuse field approach, that avoids the above limitations. In short, the principle difference is that rather than measuring *structural* velocity and using this to estimate power, we instead define an array of monopole sources that equivalently represent the partition, and estimate power from their *volume velocities*. Importantly, these volume velocities are obtained indirectly by measuring the partitions radiated sound field. In this sense, the proposed method is able to account for any acoustic paths, as these are implicitly captured by the volume velocities. As will be shown, the volume velocities obtained are in fact independent of the receiver room's modal characteristics [4]. And so the effects of low frequency modes are avoided and a *free field* transmission loss can in theory be obtained. In addition to the advantages described above, being based on a structural excitation (as opposed to an acoustic excitation), the proposed method could be used to evaluate sound transmission in situations where flanking contributions would otherwise be unacceptable.

Having introduced the context of this paper, its remainder is organised as follows. Section 2 will present the background theory, including the equivalent volume velocity representation and the formulation of a sound transmission estimate. Section 3 will describe an experimental study conducted within the University of Salford's UKAS accredited transmission suite, before section 4 presents the results obtained. Finally, section 5 will draw some concluding remarks.

2 THEORY

In this section we detail the theory behind the proposed indirect measurement of sound transmission.

2.1 Sound field reconstruction

According to the equivalent field theorem described by Bobrovnitskii [4], the response field within an acoustic domain can be reproduced exactly by an equivalent differential velocity excitation across the exciting interface (i.e. the radiating partition). Point-like discretisation of this continuous area excitation yields the following relation[5],

$$\mathbf{p}_b \approx \mathbf{H}_{Cbc}\tilde{\mathbf{q}}_c \tag{1}$$

where $\mathbf{p}_b \in \mathbb{C}^M$ is a vector of M complex sound pressures measured within the receiver at locations b, $\tilde{\mathbf{q}}_c \in \mathbb{C}^N$ is the vector of equivalent volume velocities defined along the separating interface c, and $\mathbf{H}_{Cbc} \in \mathbb{C}^{M\times N}$ is the matrix of acoustics transfer functions relating $\mathbf{q}$ to $\mathbf{p}$, whose entries are defined as $H_{ij} = p_i/q_i|_{q_{n\neq j}=0}$. Importantly, it can be shown that the equivalent volume velocities $\tilde{\mathbf{q}}$ are in-fact invariant of the receiving domain, and so unaffected by the modal behaviour of the room.

The approximation of equation 1 comes from its discretisation, and so its validity relies on the usual points-per-wavelength requirements. At low frequencies it is expected that such a requirement can be satisfied and so equation 1 can be used as an alternative representation of the sound field generated by a radiating surface.

In the current context, the volume velocities $\tilde{\mathbf{q}}_c$ are unknown, and so we treat equation 1 as an inverse problem, the solution to which is obtained as,

$$\tilde{\mathbf{q}}_c = \mathbf{H}^+_{Cbc}\mathbf{p}_b \tag{2}$$

where $\square^{+}$ represents a generalised matrix inverse. Once obtained, the free volume velocity can be used to predict the pressure response at a new location r,

$$\mathbf{p}_r = \mathbf{H}_{Crc}\tilde{\mathbf{q}}_c \tag{3}$$

or estimate the total radiated power, as described below.

2.2 Radiated power

In addition to predicting sound pressure level at a single point, we are interested in estimating the total radiated power from the equivalent volume velocity representation, as this is required for the estimation of sound transmission.

Considering our equivalent volume velocity representation, the time averaged radiated power from the partition is given by,

$$\Pi_{rad} = \frac{1}{2}\Re\left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{p}_c\right) = \frac{1}{2}\Re\left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{Z}_{rad}\tilde{\mathbf{q}}_c\right) \tag{4}$$

where $\mathbf{p}_c$ is the surface pressure, $\mathbf{q}_c$ is the volume velocity with $\square^{\mathrm{H}}$ denoting conjugate transpose, and $\mathbf{Z}_{rad}$ the complex radiation impedance matrix (relating $\mathbf{p}_c$ and $\mathbf{q}_c$).

It is convenient to instead express the radiated power using the real part of the radiation impedance as so,

$$\begin{aligned}
\Pi_{rad} =& \frac{1}{4}\left[\left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{Z}_{rad}\tilde{\mathbf{q}}_c\right) + \left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{Z}_{rad}\tilde{\mathbf{q}}_c\right)^{\mathrm{H}}\right] && (5)\\
=& \frac{1}{4}\left[\left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{Z}_{rad}\tilde{\mathbf{q}}_c\right) + \left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\mathbf{Z}_{rad}^{\mathrm{H}}\tilde{\mathbf{q}}_c\right)\right] && (6)\\
=& \frac{1}{4}\tilde{\mathbf{q}}_c^{\mathrm{H}}\left(\mathbf{Z}_{rad} + \mathbf{Z}_{rad}^{\mathrm{H}}\right)\tilde{\mathbf{q}}_c && (7)\\
=& \frac{1}{2}\tilde{\mathbf{q}}_c^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\tilde{\mathbf{q}}_c && (8)
\end{aligned}$$

where we use the fact that for a complex symmetric matrix $\Re(\mathbf{A}) = \frac{1}{2}\left(\mathbf{A} + \mathbf{A}^{\mathrm{H}}\right)$. Using the cyclic property of the trace operator, $\mathrm{Tr}(\mathbf{ABC}) = \mathrm{Tr}(\mathbf{BCA}) = \mathrm{Tr}(\mathbf{CAB})$, and noting that the radiated power is a scalar and so its trace is equal to itself,

$$\Pi_{rad} = \frac{1}{2}\mathrm{Tr}\left(\tilde{\mathbf{q}}_c^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\tilde{\mathbf{q}}_c\right) = \frac{1}{2}\mathrm{Tr}\left(\tilde{\mathbf{q}}_c\tilde{\mathbf{q}}_c^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\right) = \frac{1}{2}\mathrm{Tr}\left(\mathbf{G}_{qq}\Re\left(\mathbf{Z}_{rad}\right)\right) \tag{9}$$

the radiated power can be expressed in terms of the cross-spectral volume velocity matrix $\mathbf{G}_{qq} = \tilde{\mathbf{q}}_c\tilde{\mathbf{q}}_c^{\mathrm{H}}$.

The elements of the radiation impedance matrix $\mathbf{Z}_{rad}$ are obtained by considering the half field Green's function,

$$p(r) = \overbrace{\frac{\omega^2\rho_0}{2\pi c_0}\left(\frac{ie^{-ikr}}{kr}\right)}^{Z_{rad}(r)} q \tag{10}$$

where $p(r)$ is the pressure level at distance r from the volume velocity q. The terms ω, k, ρ_0 and c_0 adopt their usual meanings as radian frequency, wave number, air density and speed of sound, respectively. The real part of the radiation impedance is then,

$$\Re\left(Z_{rad}(r)\right) = \frac{\omega^2\rho_0}{2\pi c_0}\left(\frac{\sin(kr)}{kr}\right). \tag{11}$$

When considering the collocated pressure and volume velocity, such that $r \to 0$, the limit of equation 11 becomes,

$$\lim_{r\to 0}\Re\left(Z_{rad}(r)\right) = \frac{\omega^2\rho_0}{2\pi c_0}. \tag{12}$$

From equation 11 and 12 we can construct the full radiation impedance matrix by

$$\Re\left(Z_{rad,ij}\right)\begin{cases}\frac{\omega^2\rho_0}{2\pi c_0} & \text{if } i=j\\ \frac{\omega^2\rho_0}{2\pi c_0}\left(\frac{\sin(kr_{ij})}{kr_{ij}}\right) & \text{if } i\neq j\end{cases} \tag{13}$$

where r_{ij} is the distance between the pressure at point i and the volume velocity at point j. Equation 9 and 13 will be used later to indirectly estimate the sound transmission loss through a partition.

2.2.1 Diffuse field power

The ISO methods for measuring sound power and sound transmission in a diffuse field are fundamentally based on the equation [6],

$$w=\frac{\langle p^2\rangle}{\rho_0 c_0^2}=\frac{4\Pi}{c_0 A} \tag{14}$$

where w is the spatial average energy density, $\langle p^2\rangle$ is the spatial average of squared RMS pressure, ρ_0 is the density of air, c_0 is the speed of sound, A is the total absorption area, and Π is the sound power.

From equation 14 the power level is related to the spatially averaged rms pressure by,

$$\Pi=\frac{\langle p^2\rangle A}{4\rho_0 c_0}. \tag{15}$$

In a diffuse field, the absorption area A is typically approximated using Sabine's equation as,

$$A=0.161\frac{V}{T60} \tag{16}$$

where V is the room volume, and $T60$ is the reverberation time.

2.3 Indirect measurement of sound transmission

The transmission loss is defined by the ratio of the power incident on (Π_{inc}) and radiated from (Π_{rad}) the partition,

$$TL=10\log_{10}\left(\frac{\Pi_{inc}}{\Pi_{rad}}\right). \tag{17}$$

Assuming a diffuse field on either side of the partition, equation 17 reduces to the classical equation for sound transmission (given here in its simplest form without its various correction factors),

$$TL=L1-L_2+10\log\left(\frac{S}{A}\right) \tag{18}$$

with L_1 and L_2 representing the averaged sound pressure levels (in dB) of, respectively, the source and receiver rooms, S being the surface area of the separating partition and A the absorption area of the receiver room. As already discussed, equation 18 is subject to considerable uncertainty in the low frequency range, where the assumption of diffusivity is not met. Hence, we are interested in an alternative formulation for TL that *avoids the estimation of power based on a spatially averaged pressure levels*.

For a diffuse incident field, the power incident on a partition of area S is given by [7, 3],

$$\Pi_{inc}=\frac{\langle p_e^2\rangle S}{4\rho_0 c}=\frac{\langle p_{inc}^2\rangle S}{8\rho_0 c} \tag{19}$$

where $\langle p_e^2\rangle$ is the spatially averaged pressure level within the diffuse field, and $\langle p_{inc}^2\rangle$ is that over the partition, now accompanied by a factor of 1/2 to account for the doubling of pressure due to the hard boundary. Equation 19 can be substituted into equation 17, leaving us to determine the radiated power Π_{rad} as a function of the incident pressure $\langle p_{inc}^2 \rangle$.

For an incident diffuse field on a rigid wall the cross-spectral incident pressure matrix $\mathbf{G}_{p_i p_i} = \langle \mathbf{p}_{inc} \mathbf{p}_{inc}^{\mathrm{H}} \rangle$ is given by,

$$\mathbf{G}_{p_i p_i} = 2\langle p_e^2 \rangle \frac{\sin(k_0 r_{ij})}{k_0 r_{ij}} = \langle p_{inc}^2 \rangle \frac{\sin(k_0 r_{ij})}{k_0 r_{ij}} = \langle p_{inc}^2 \rangle \mathbf{G}_{dd} \tag{20}$$

where k_0 is wave-number, r_{ij} is the distance between positions i and j and $\mathbf{G}_{dd}$ represents the normalised cross-spectral matrix describing the frequency/spatial correlation across the partition.

The incident pressure field $\mathbf{p}_i$ can be interpreted as an array of equivalent point-like external forces, such that $\mathbf{f}_i = \mathbf{S}\mathbf{p}_i$, where $\mathbf{S}$ is a diagonal matrix of patch areas with $\mathrm{Tr}(\mathbf{S}) = S$. We can then relate $\mathbf{G}_{p_i p_i}$ to a cross-spectral matrix of external forces $\mathbf{G}_{f_i f_i} = \langle \mathbf{f}_i \mathbf{f}_i^{\mathrm{H}} \rangle$,

$$\mathbf{G}_{f_i f_i} = \mathbf{S}\mathbf{G}_{p_i p_i}\mathbf{S}. \tag{21}$$

The pressure response in the receiver room due to the external force is given by,

$$\mathbf{p}_b = \mathbf{H}_{bi}\mathbf{f}_i \tag{22}$$

or in cross-spectral form,

$$\mathbf{G}_{pp} = \mathbf{H}_{bi}\mathbf{G}_{f_i f_i}\mathbf{H}_{bi}^{\mathrm{H}} \tag{23}$$

where $\mathbf{H}_{bi}$ is a vibro-acoustic (force to pressure) FRF. Recalling that the radiated pressure is inversely related to the equivalent volume velocity array (see equation 2), we have,

$$\tilde{\mathbf{q}}_c = \mathbf{H}_{bc}^{+}\mathbf{H}_{bi}\mathbf{f}_i \quad \text{or} \quad \mathbf{G}_{qq} = \mathbf{H}_{bc}^{+}\mathbf{H}_{bi}\mathbf{G}_{f_i f_i}\mathbf{H}_{bi}^{\mathrm{H}}\mathbf{H}_{bc}^{+\mathrm{H}} \tag{24}$$

where $\mathbf{H}_{bc}$ is an acoustic (volume velocity to pressure) FRF.

Substituting the cross-spectral matrices of equations 21 and 20 we obtain,

$$\mathbf{G}_{qq} = \mathbf{H}_{bc}^{+}\mathbf{H}_{bi}\mathbf{S}\mathbf{G}_{dd}\mathbf{S}\mathbf{H}_{bi}^{\mathrm{H}}\mathbf{H}_{bc}^{+\mathrm{H}}\langle p_{inc}^2 \rangle = \mathbf{H}_{cp_i}\mathbf{G}_{dd}\mathbf{H}_{cp_i}^{\mathrm{H}}\langle p_{inc}^2 \rangle \tag{25}$$

where $\mathbf{H}_{cp_i} = \mathbf{H}_{bc}^{+}\mathbf{H}_{bi}\mathbf{S}$ is an acoustic FRF between the incident pressure field excitation, and the equivalent volume velocity representation.

Using equation 9 and 25, the radiated power from the partition due to the diffuse incident pressure field $\langle p_{inc}^2 \rangle$ is given by,

$$\Pi_{rad} = \frac{\langle p_{inc}^2 \rangle}{2} \mathrm{Tr}\left(\mathbf{H}_{cp_i}\mathbf{G}_{dd}\mathbf{H}_{cp_i}^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\right). \tag{26}$$

Substituting equation 19 and 26 into equation 17 yields an indirect estimation of the transmission loss,

$$TL = 10\log_{10}\left(\frac{S}{4\rho_0 c}\frac{1}{\mathrm{Tr}\left(\mathbf{H}_{cp_i}\mathbf{G}_{dd}\mathbf{H}_{cp_i}^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\right)}\right) \tag{27}$$

or equivalently,

$$TL = 10\log_{10}\left(\frac{S}{4\rho_0 c}\right) - 10\log_{10}\left(\mathrm{Tr}\left(\mathbf{H}_{cp_i}\mathbf{G}_{dd}\mathbf{H}_{cp_i}^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\right)\right). \tag{28}$$

In the special case that the same discretisation is used for both the volume velocity and force excitations, such that all patch areas are equal, then $\mathbf{S} = \frac{S}{N}\mathbf{I}$ and,

$$TL = 10\log_{10}\left(\frac{S^3}{4\rho_0 c N^2}\right) - 10\log_{10}\left(\mathrm{Tr}\left(\mathbf{H}_{cp_i}\mathbf{G}_{dd}\mathbf{H}_{cp_i}^{\mathrm{H}}\Re\left(\mathbf{Z}_{rad}\right)\right)\right) \tag{29}$$

with $\mathbf{H}_{cp_i} = \mathbf{H}_{bc}^{+}\mathbf{H}_{bi}$.

Equation 28 is the main result of this paper. Importantly, it avoids the estimation of incident and radiated power based on spatially averaged sound pressure levels. The incident power is obtained by considering a diffuse incident field and applying this as an artificial excitation to the partition through the cross-spectral matrix $\mathbf{G}_{dd}$. This excitation is subsequently propagated through the partition by a pair of measured transfer functions yielding a set of equivalent volume velocities from which the radiated power can be determined.

3 METHODOLOGY

In this section we describe the experimental set-up and methodology used to validate the invariance and sound field reconstruction capability of the equivalent volume velocity representation.

Figure 1: (Left) An image of the receiver room in the acoustic domain experiment. (Right) An image of the source room in the acoustic domain experiment.

3.1 Experimental Setup

The experimental validation was performed in a UKAS accredited sound transmission suite at the University of Salford. The partition understudy was a simple dual leaf plasterboard construction, with mineral wool infill. The test procedure was as follows:

1. A 10×5 grid of points were marked on both the incident and radiating side of the partition.
2. An array of 15 microphones were randomly positioned across the receiver room (see figure **??**).
3. Using a volume velocity source, the acoustic FRF (volume velocity to pressure) between each (radiating side) grid point and the microphone array was measured. The resulting FRF matrix is that of $\mathbf{H}_{Cbc}$ in equation 2.
4. Using an instrumented force hammer, the vibro-acoustic FRF between each (input side) grid point and the microphone array was measured.
5. A dodecahedron loudspeaker was positioned within the source room and driven by pink noise. The response across the microphone array was measured. This test was repeated for three different source positions.

On completion of the above, equation 2 and 3 can be implemented to first obtain the volume velocities of the partition, before predicting the response at a remote location. As described below, this was done for three different excitation scenarios; a volume velocity excitation, a point-force, and an acoustic excitation.

3.2 Invariance and sound field reconstruction

To validate the invariance and reconstruction capabilities of the equivalent volume velocity array, we consider 3 different excitation scenarios. For each, we compute an array of volume velocities and a) compare their spatial average to that of the sound pressure level from which they were determined (to illustrate invariance), and b) use them to predict the pressure response at some new location within the receiver domain. The three excitation scenarios are described below.

1) A simple volume velocity excitation within the receiver room, adjacent to the partition (see figure 2a). As the volume velocity excitation is constant with frequency, we should not expect to see any modal characteristics in its spatial average.
2) A point force excitation on source side of partition (see figure 2b). With the partition having its own modal characteristics, we would expect to see some modal features in the spatial average of volume velocity.
3) An acoustic excitation within source room (see figure 2c). With both the source room and partition now being excited, we would expect to see significant modal features in the averaged volume velocity.

Note that the volume velocity modal features present within scenarios 2) and 3) are not related to those of the receiver room; these have been removed through the inverse procedure. For each scenario, we consider 3 different excitation locations.

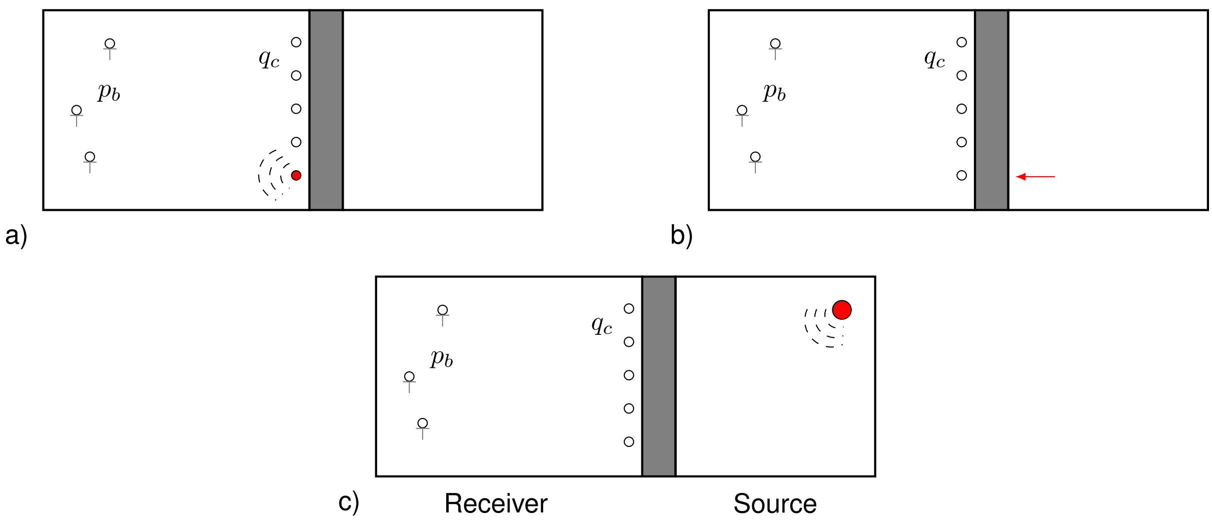

Figure 2: Illustration of sound field reproduction cases. a) volume velocity excitation. b) point force excitation. c) acoustic excitation.

4 RESULTS

In this section we present the results of the invariance and sound field prediction validation. For each excitation scenario we present 4 plots. In each case these plots show the following: top left - spatial average of 50 volume velocities, bottom left - spatial average of 15 sound pressure levels, top right - directly measured and predicted pressure response at a new location in the receiver room, bottom right - absolute error between the measured and predicted sound pressure level in top right figure.

4.1 Volume velocity excitation

The invariance of the volume velocity representation is immediately evident by comparing the spatially averaged volume velocities and sound pressures in figure 3. The spatially averaged sound pressure presents a highly modal response, with clear and well separated modes in the low frequency range. In contrast, the average volume velocity response is remarkably flat. The modal characteristics of the receiver room have been removed entirely. The flat volume velocity response is expected in this case as the excitation itself was a volume velocity, which has a flat frequency response. Note that the y-axes limits are adjusted to present both sound pressure and volume velocities over the same range for succinct comparisons to be made.

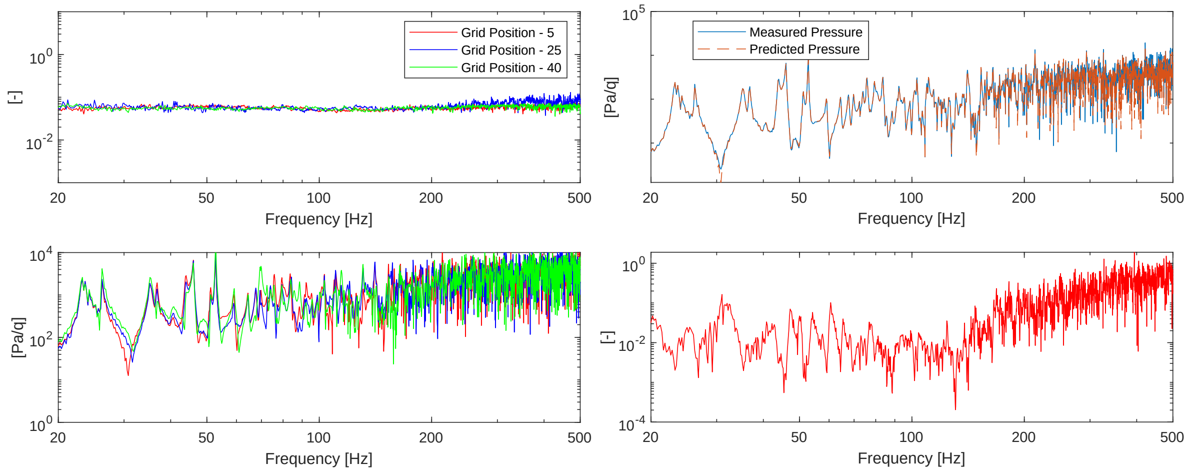

Figure 3: (Above) A pressure prediction compared with a measured pressure at a singular response position, from the volume velocity excitation. (Below) The normalised error between the predicted and measured spectra

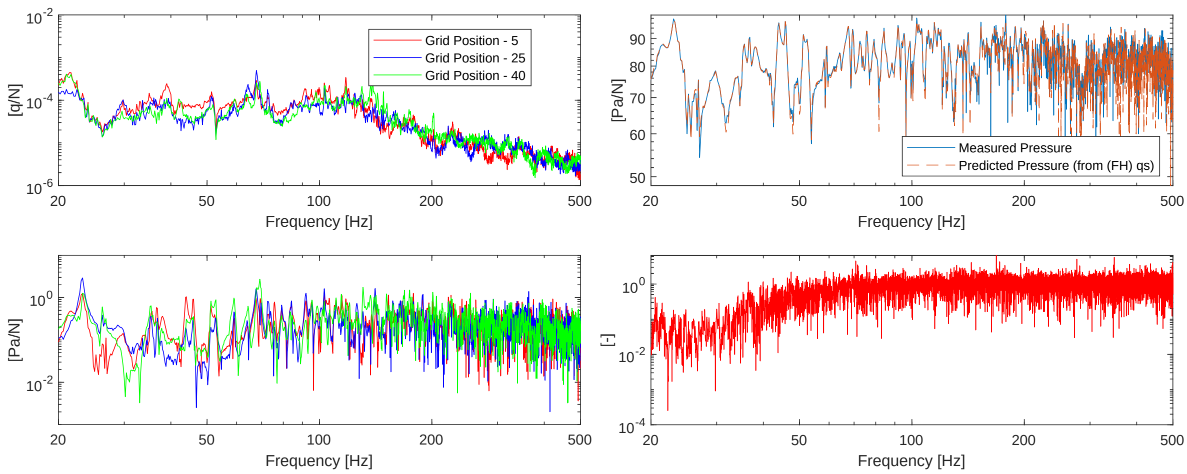

Figure 4: (Above) A pressure prediction compared with a measured pressure at a singular response position, from the force hammer excitation. (Below) The normalised error between the predicted and measured spectra

Figure 3 further illustrates that for the simple excitation considered, the volume velocity array is able to predict the sound pressure level at a new location with excellent accuracy, especially in the low frequency range. We see from the error plot below, that the relative error increases with frequency, as expected given the discretisations involved.

4.2 Point-force excitation

Figure 4 shows the results of a point-force excitation. The average volume velocity response now presents some frequency varying characteristics. Careful comparison again the averaged sound pressure reveals that these characteristics are not of the receiver room, but of the partition itself, which is now being excited directly.

We see again that, even with a more complex excitation (the sound pressure in the receiver room is now being produced by the radiating partition), the volume velocity array is able to accurately reproduce the sound pressure level at a remote position.

4.3 Acoustic excitation

Finally, Figure 5 shows the result obtained with an acoustic excitation within the source room. Compared to the volume velocities obtained for the point-force, those of Figure 5 present significantly more resonant features. These additional features are due to the modal response of the source room, which is now being excited directly. Careful comparison against the averaged sound pressure, particularly in the range 20-65 Hz, confirms the absence of the source room's modal response.

We see that, even with this most challenging excitation (i.e. a complex pressure field over the entire incident side), the volume velocity representation is able to reproduce the sound pressure level at a remote location with impressive accuracy.

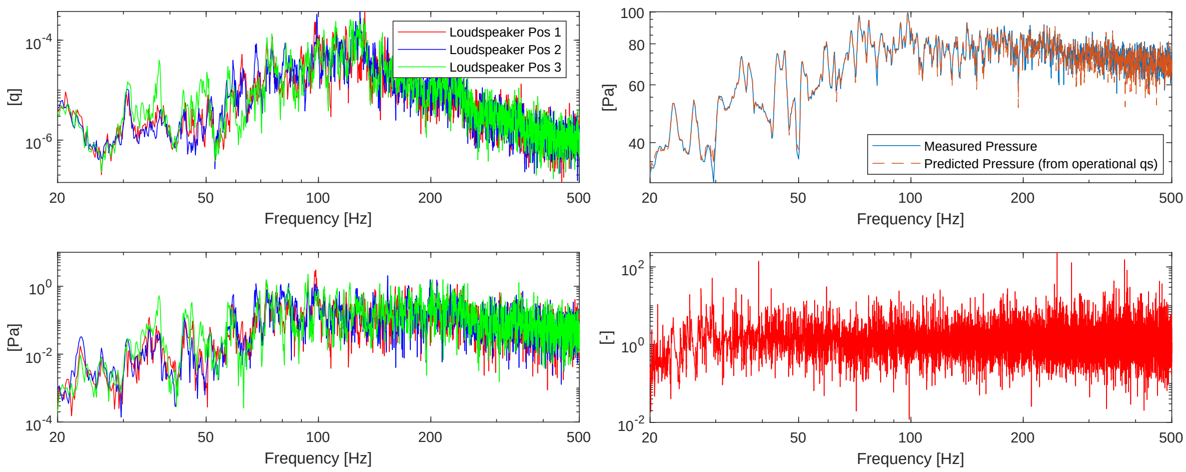

Figure 5: (Above) A pressure prediction compared with a measured pressure at a singular response position, from the operational excitation. (Below) The normalised error between the predicted and measured spectra

The results of Figures 3-5 clearly verify a) the invariance of the volume velocity representation and b) its ability to reconstruct the sound field within the receiver room.

5 CONCLUSIONS

In this paper we have introduced and proposed methodology for the indirect measurement of low frequency sound transmission. Based on an equivalent volume velocity representation of the radiated sound field, the proposed methodology avoids the estimation of power based on spatially averaged sound pressure levels, a main source of uncertainty in the ISO 10140 approach.

Key to the success of the proposed indirect method is a) the removal of the receiver room's modal characteristics from the equivalent volume velocities, and b) the ability to reconstruct the radiated sound field using said volume velocities. To this end we present a series of results that verify both of these capabilities for a range of increasingly complex excitation scenarios. These results provide confidence in the equivalent volume velocity representation, and will be used in future studies to estimate low frequency sound transmission, as per the proposed method.

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