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NOISE CONTROL FOR A BETTER ENVIRONMENT

In-situ characterisation and prediction of heavy impact-generating events in buildings.

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ABSTRACT

There is a growing need to better understand and predict the effect of impact sources within new-build and existing constructions. This paper presents application of a novel measurement technique to characterise dropped-weight sources in a manner which permits data use in environments other than that in which it was tested. A case study demonstrating use is presented where the vibration performance at a receiver location is predicted using a combination of characterisation data and Transfer Accelerance Frequency Response Functions. The results from the prediction exercise are then subsequently compared to measurement data. The findings of this exercise show promise in predicting noise and vibration effects in buildings and may be of use to suppliers responsible for providing data for use by engineering consultants.

Keywords: Noise, Environment, Annoyance
I-INCE Classification of Subject Number: 41, 43

1. INTRODUCTION

The increase in urban densification in recent years has led to a notable increase in the number of fitness/gymnasium facilities located in shared mixed-use developments alongside residential spaces (homes, hotels, apartments), places of work and study (offices, educational buildings) or places of leisure (cinemas, restaurants, retail). This rise has led to a greater need in predicting the effects that heavy-impact sources, would have on the noise and vibration climate in sensitive adjacencies [1].

A model seeking to address this issue must account for the behaviour of source, the transmission path and receiver. In existing structures, the latter two are relatively easy to describe however in new build schemes – or those in the process of design, more sophisticated means of simulation would be required. In either case, accounting for the source term remains an issue, as it is potentially affected by numerous factors which tend to modify the force or power injected into the transmission path.

In existing developments, it is possible to undertake in-situ testing via the process of dropping-test weights, however the degree of testing required may be prohibitive.

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The lack of clarity on an agreed methodology is, in part, driven from a lack of guidance on prediction methodologies and criteria that can be relied upon. If target criteria is broadband in nature or, more critically set with respect to national Building Regulations [2] then there is a possibility that the significance of the low-frequency content could be overlooked as standard assessments often start from 100 Hz. Though this paper is not intended to address the issue of acceptability, it does highlight the fact that robust measures for capturing low-frequency vibration/vibroacoustic behaviour is essential, as it is usually this region which typify noise complaints.

The purpose of this paper is to focus on the source mechanism, which is an impact of a falling mass upon a structural floor. Though the physical properties of a falling mass are well defined, the method detailed herein shows promise for use on less regular geometries – thus reducing uncertainties by oversimplification of dynamical systems. The principle term of investigation presented is that of blocked force, a quantity usually derived for the purposes of characterising machines on foundations or supports in-situ, negating the need for decoupling and avoiding free-velocity measurements. An independent characterisation procedure will be described to derive the blocked forces of the source which are, in theory, transferable to a similar-receiver. The paper begins with a discussion of current measurement and prediction limitations, serving as preamble from which the benefits of the method proposed can be described and understood.

2. MOTIVATION

2.1 Assessments via prediction

When predicting noise and vibration arising from impacting objects, it is common to use first-principle dynamical and energy relationship equations to determine the behaviour and force load of the falling mass. Time-domain loading functions typically centre upon assumption regarding impactor shape, drop height and contact stiffness of the receiving structure [3,4,5]. In reality – impactor shapes are rarely ideal and contact stiffness can become non-linear, resulting in vibration spectra which do not follow predictions based on idealised conditions. By example, **Figure 1** illustrates the single-sided acceleration amplitude for a half-sine and rectangular each pulse (same transient peak magnitude and duration). Scales have been removed for clarity so as to illustrate the general behaviour. Though the duration and magnitude of the pulses are similar, the resulting FFT vary noticeably. Comparing this further to a FFT spectra for a typical kettlebell-drop (**Figure 2**), the differences are greater still. Consequently, when utilising FFT data for the purpose of predicting 1/3-octave band noise and/or vibration, for example in power-based Statistical Energy Analysis (SEA) approaches, considerable care must be used to ensure that the excitation source and the associated signal processing are properly accounted for.

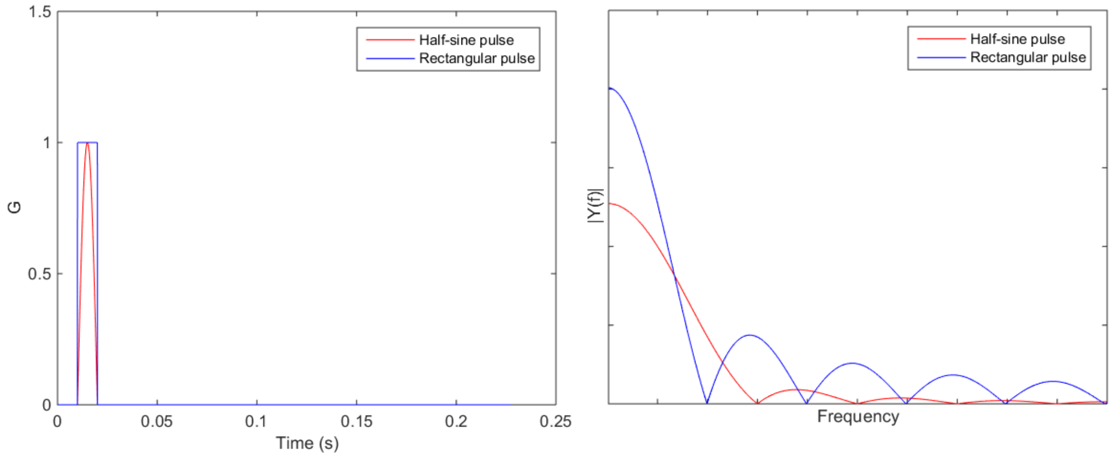

Figure 1: (Left) Half-sine and rectangular pulses (Right) 1-sided FFT amplitudes for half-sine and rectangular pulses.

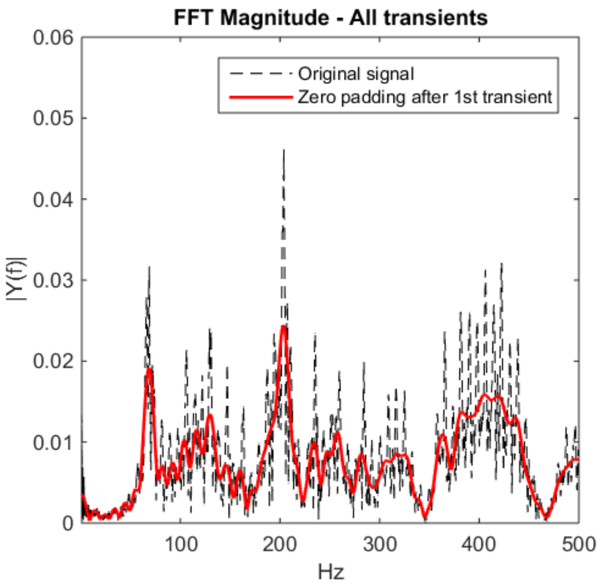

Figure 2: 1-sided FFT amplitudes for typical kettlebell weight drop

2.1 Assessments via measurement

In a number of countries, impact sound insulation performance is rated in accordance with ISO 717-E:2013 [6] . This document stipulates that the necessary measurement values, obtained in accordance with ISO 10140-3 [7] shall be assessed at frequencies ranging from 100 Hz to 3150 Hz. Generally, the application of this is intended to replicate sources human in nature such as footfall. Referring to the example previously presented, impacting source can readily produce components of low frequency vibration below 100Hz.

In terms of quantifying or estimating the effects of repeated heavy impact sources, such as those in gymnasium facilities, an approach attempted by consulting engineers is to attend site and undertake tests involving dropped weights. This approach has a number of limitations. Firstly, the engineer is likely to bring a select number of weights which are convenient to transport to and from a site and are likely to be of limited mass to allow repeated testing. By subscribing to this method, one limits the ability to undertake a wide-ranging test campaign and may fail to understand the potential adverse impact that some heavier gym (or other heavy impact source) equipment may cause. Additionally, the effects of varying impactor shapes, may also be poorly defined.

In addition to limited test equipment, the engineer is likely to test in a number of spaces to gain a reasonable understanding as to the behaviour of the receiving structure. This would involve repeated weight drops at each location – possibly resulting in superficial damage in efforts to achieve a suitable signal to noise ratio in receiver areas of interest. This is often coupled with the engineer testing upon a range of flooring materials for the purpose of comparing their respective vibration isolation properties in situ. This further complicates and lengthens the procedure.

3. IMPACT SOURCE CHARACTERISATION

Upon consideration of the issues identified in the previous sections, it follows that it would be of benefit to develop of means of reducing uncertainty attached to the characterisation of heavyweight sources. Further, it would be of use if the characterising of such sources were transferable to structures so as to assess their suitability, or to devise a more robust means of mitigation, bespoke to the structure under examination.

Source characterisation is a common practice within automotive industry, as part of well-defined Transfer Path Analysis (TPA) assessments. In particular, the in-situ characterisation approach [8,9] is suitable to the current problem at hand.

The in-situ approach consists of a two-part test. Firstly, the Frequency Response Functions (FRFs) (e.g. mobility (velocity/force) or accelerance (acceleration/force)) of the coupled source-receiver assembly are measured. Next, under the action of the active source, the operational response of the receiver is measured.

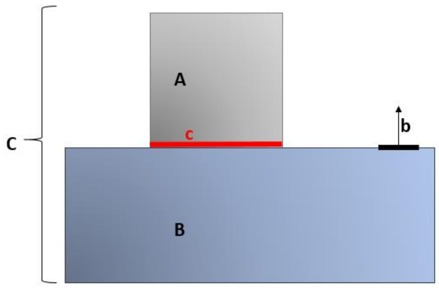

Figure 3: Source-receiver representation of a dynamic system, source (active component) labelled A is coupled to the receiver (passive component), labelled B at the source receiver interface (red), labelled c, during impact. At this point A and B form the assembly, labelled C.

In the current study, as the floor impedance is relatively higher than that of a mass, the FRF's can be measured on the receiver directly while the operational responses can be measured upon the impact of a falling mass (to be characterised).

It can be shown [8,9,10] that the relationship between the acceleration experienced at a receiver and the applied blocked force from the source is:

$$f_{bl} = [A]^{+}\{a'\} \qquad \textit{Equation 1}$$

In Equation 1, and with reference to **Figure 3,** $[A]$ is the accelerance matrix linking the contact point (shown as c in the figure) to all at all receiver locations. '+' denotes the Moore-Penrose inverse which means that the solution is overdetermined. The accelerance matrix is assembled thus:

$$[A]_{i\,xj} = \begin{bmatrix} {a_1}/{f_1} & \cdots & {a_1}/{f_j} \\ \vdots & \ddots & \vdots \\ {a_i}/{f_1} & \cdots & {a_i}/{f_j} \end{bmatrix}$$ *Equation 2*

The quantity $\{a'\}$ in E*quation 1* represents the vector of operational acceleration values at the receiver location(s).

$$\{a'\} = \begin{Bmatrix} a'_1 \\ \vdots \\ a'_i \end{Bmatrix}$$ *Equation 3*

Finally, and similar to the above, the blocked force (f_{bl}) also a complex vector quantity, assigned to each contact location.

An illustration of the procedure is shown in **Figure 4** for the proposed test methodology. First, FRFs are generated at a series of response locations at which operation accelerations are also measured. The blocked force derived is that of the force exerted during contact, though may include double strikes, rebounds or settlement, depending on the test arrangement and associated signal processing. When studying a single impact, it is often advantageous to utilise more response locations than sources (in this paper, a single impact source is considered) and as such, overdetermine the system.

An added benefit is that the derived blocked-force can be checked for quality via comparison between direct measurement and prediction of velocities/displacements or accelerations at a trial reception location during the characterisation process. This, known as on-board validation, serves as a test to validate the measured blocked forces.

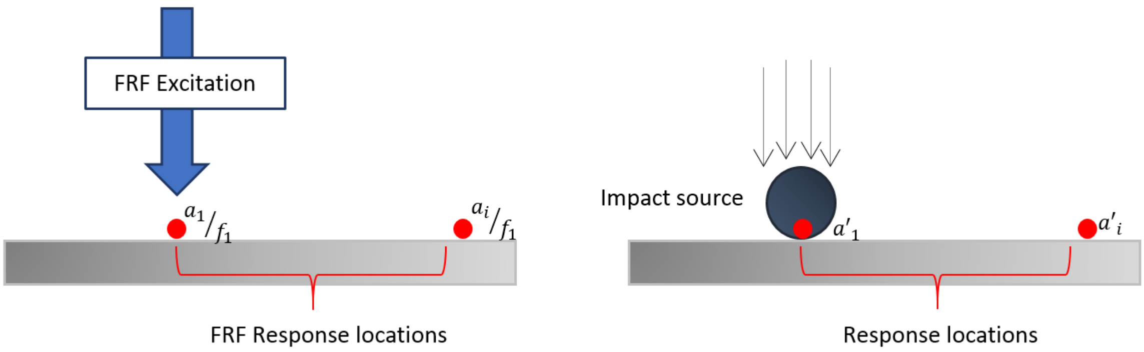

Figure 4: FRF capture and operational test elements.

4. TEST DETAILS

A series of tests were undertaken in a room with approximate plan dimensions of 2.5m x 3.5m. A 10kg kettlebell was chosen as the impact source, dropped at a single location from a height of 10cm, 15cm and 20cm. Three drops were performed to permit a statistical view of the blocked force. A total of 5 response locations were taken with 3 locations used to derive the blocked forces of the impacting kettlebell. The remaining two positions were reserved for use as on-board validation locations. FRFs (accelerance) were obtained between source and respective response points, determined via force hammer excitation. Following the acquisition of FRFs, a series of operational acceleration measurements were taken via the approach detailed in the previous section.

Figure 5: 10kg kettlebell used in tests.

5. VALIDATION

The predicted vertical acceleration level at the two receiver locations, referred to as Position 1 and Position 2 was compared to direct measurement data for each drop height at the same location. Only the vertical component of acceleration normal to the floor was considered.

The results from each of the drops, for each height, are provided in **Figure 6** (10cm) **Figure 7** (15cm) **and Figure 8** (20cm). The subplot left-right pairings in each row correspond to receiver location 1 and 2 respectively.

In each case, it can be seen that the measured and predicted curves show good agreements particularly at frequencies above 50Hz. Deviations below 50Hz were, in general, due to time-domain artefacts, other than the dominant transient(s) such as settling, rocking etc affecting the resulting spectrum derived from the FFT process and manifesting as additional low-frequency components of noise. Knowledge of this is especially important if results are being used to predict short-duration transient effects rather than a encapsulating the full measurement window.

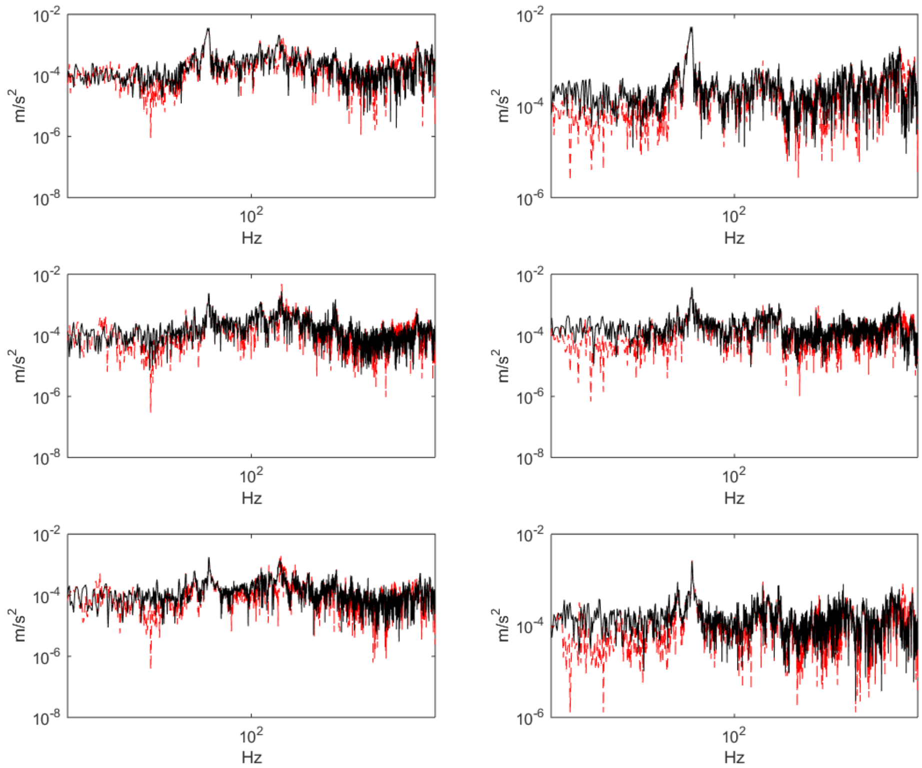

Figure 6: Results for the 10kg kettlebell drop from a height of 10cm. Measured curves shown black, predicted values shown red. Top (L,R) show drop 1 results at receiver 1 and receiver 2 respectively. Middle (L,R) drop 2. Bottom (L,R) drop 3.

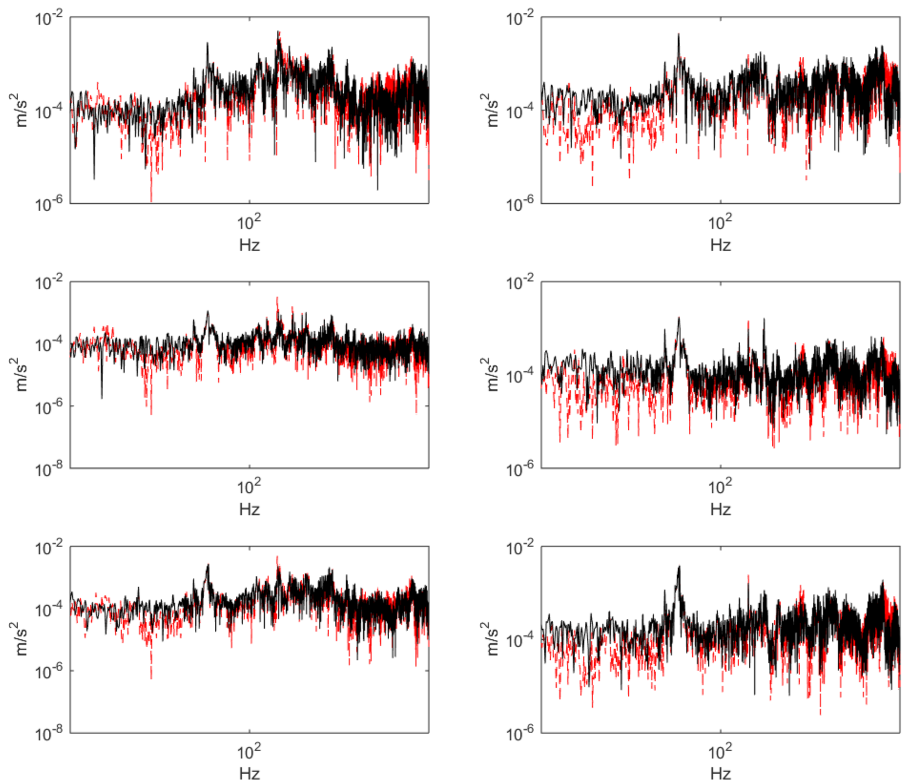

Figure 7: Results for the 10kg kettlebell drop from a height of 15cm. Measured curves shown black, predicted values shown red. Top (L,R) show drop 1 results at receiver 1 and receiver 2 respectively. Middle (L,R) drop 2. Bottom (L,R) drop 3.

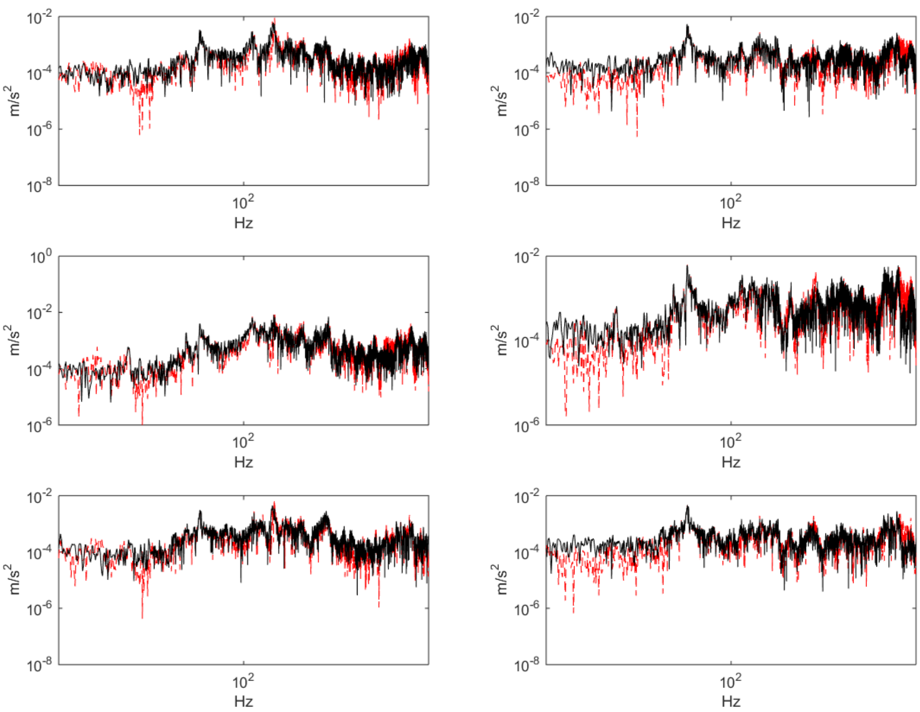

Figure 8: Results for the 10kg kettlebell drop from a height of 20cm. Measured curves shown black, predicted values shown red. Top (L,R) show drop 1 results at receiver 1 and receiver 2 respectively. Middle (L,R) drop 2. Bottom (L,R) drop 3.

6. POTENTIAL APPLICATIONS

The method proposed in this paper has applications for the prediction of noise within dwellings or noise sensitive spaces. This section provides a possible use for the method. Taking the 10kg kettlebell, dropped from a height of 20cm, the predicted vibration level has been used a means to predict the associated re-radiated noise component using the simplified Kurzweil equation:

$$L_p = L_a - 20log_{10}(f) + 37 \qquad \textit{Equation 4}$$

Where L_a is the floor acceleration normal to the surface (re 10^{-6} m/s^2). The results of the prediction exercise are shown in **Figure 9** which depict vibration levels, sound pressure levels (unweighted and A-weighted), and overall dB(A) noise values that could be derived from direct measurement of vibration at the reference location, compared to the same using the prediction method proposed herein. The curves represent an average level for the three-drops undertaken. The two response locations chosen are assumed to be representative of the room as a whole for the purposes of example though in reality, a greater number of points would be required to establish the mean response across a surface. For the purpose of demonstrating the potential offered by the method, the example is considered to be wholly adequate.

The presented third-octave spectra are taken from direct summation of the FFT magnitudes with frequency resolution of 0.1953Hz. Values are not scaled and care should be therefore used when utilising magnitudes for third-octave calculations as failing to account for frequency bin-widths, sample rates etc. may affect the overall third-octave values. Notwithstanding these aspects, and on the understanding that, in this case, such issues would only affect absolute scaling, it can be seen that the measured and predicted curves show good agreement. Reference point 2 experiences notable deviation in low frequency agreement below 50Hz due to diminishing coherence between excitation and receiver. This could be improved with use of a soft tip hammer to measure FRF’s in that frequency range. However, when it comes to the predicted overall A-weighted level, the agreement is excellent (within 1dBA).

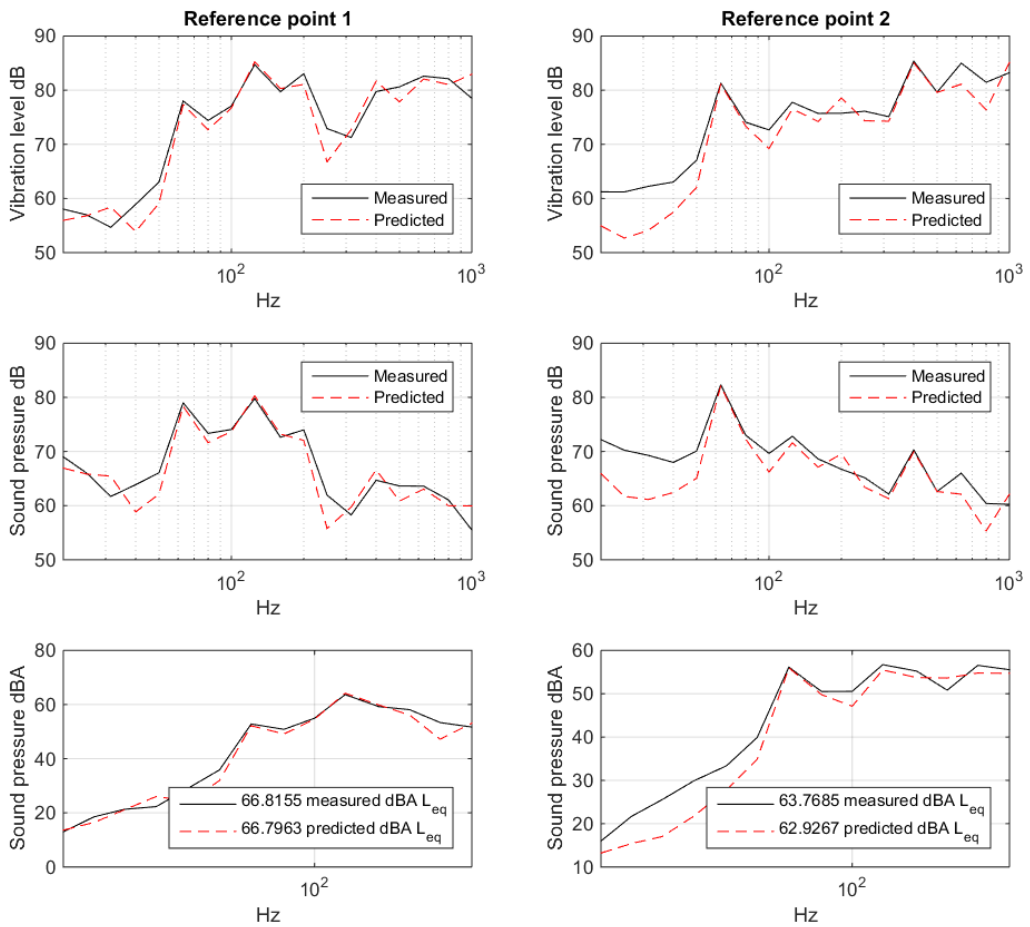

Figure 9: Predicted and measured third-octave values. Top – vibration level, acceleration dB re 10^{-6} m/s^2. Middle sound pressure level dB re $2x10^{-5}$Pa. Bottom, A-weighted sound pressure level dB re $2x10^{-5}$Pa. Bottom legend includes overall A-weighted noise level for each curve shown.

7. DISCUSSION

The method and potential application presented herein show promise for a standardised process to characterise impact sources, which can be utilised in predictions of vibration response in remote receivers. This is taken to be on the provision that the candidate structure is sufficiently similar to that of the test-floor and a well determined set of FRFs can be determined. This has implications for suppliers of heavy-equipment or those involved in mitigation, as the blocked force information could take the form of supplier-led factory testing, leaving only the structural FRFs to be determined as part of the assessment by a consultant. Suppliers could potentially use factory environments to test a greater variety of sources and heavier weight combinations than typically relied upon by consultants in the field.

An important issue in the characterisation process is vigilance with regards to the quality of the drop-test data. Spurious artefacts must be eliminated during the drop or via appropriate post-processing [12]. To this end, a reasonable number of drops should be performed so that a statistical impression can be determined. Further, if geometric forms are complex in relation to, for example, a perfect sphere, then multiple drop angles are also likely to be required so as to capture the variation in strike angle and the time-transient characteristics.

8. CONCLUSIONS

This paper has shown that it is possible to characterise the blocked force of heavy impact sources in-situ, and that the results are, in principle, appropriate for use as a means of prediction. Third-octave noise and vibration spectra in addition to overall (predicted) A-weighted levels of noise show good agreement to measurement data and suggest the data obtained could be of benefit to the consulting engineer wishing to undertake more robust predictions to avoid over-simplified prediction methods or inadequate testing strategies. Further, the methodology may be of use to suppliers of heavy equipment or mitigation systems to reduce the effects of shock/heavy impacts, as test facilities on site could be used to investigate a range of impactors that wouldn't be suited to field testing.

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