Finite element simulation of a laboratory reception plate for structure-borne sound power measurements

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ABSTRACT

Structure-borne power from machinery into a heavyweight structure can be characterised using the laboratory reception plate method described in EN 15657-1. When designing a new reception plate for a specific kind of machinery it is potentially useful to have a prediction model to assess its dynamic behaviour before it is built. This paper concerns the development and validation of Finite Element Models (FEM) for a concrete reception plate installed horizontally on resiliently supports. Two FEM models were considered: an idealised model for an isolated plate with free boundary conditions, and a more detailed model for the reception plate in the laboratory at Stuttgart which incorporates the viscoelastic material around the boundaries which is used to increase the damping. Experimental Modal Analysis (EMA) was carried out to validate the FEM models. The degree of correlation between mode shapes derived from the numerical model and EMA was assessed using the Modal Assurance Criterion (MAC). For the first 13 modes, high MAC values and close agreement in eigenfrequencies was achieved with the more detailed FEM model. The direct injected power and the reception plate power were compared for both FEM models to assess errors for single excitation points on the reception plate.

Keywords: Experimental Modal Analysis, Finite Element Method, structure-borne sound power, reception plate

I-INCE Classification of Subjects Number(s): 21.7, 42, 75.3

1. INTRODUCTION

In heavyweight buildings there are many sources of structure-borne sound that propagate in a structure which, when reradiated as sound, can cause annoyance for the building occupants. This research concerns the characterisation of building machinery that is fixed in a heavyweight building. The preferred approach in the laboratory to quantify the structure-borne sound power is to use an isolated reception plate [1] as described in EN 15657-1 [2]. This can be used to provide input data for the prediction model EN 12345-5 [3]. In actual heavyweight buildings each wall/floor is rigidly connected to other walls/floors and there are errors in trying to estimate the structure-borne sound power by measuring the vibration and structural reverberation time of the wall/floor to which the machinery is attached (i.e. by treating the wall/floor as a coupled reception plate) [4,5].

This paper focuses on the development of two Finite Element Models (FEM) of the reception plate: a) an idealised model for an isolated plate with free boundary conditions and b) a more detailed model for the reception plate in the laboratory at Stuttgart which incorporates the viscoelastic material around the edges that is used to increase the damping. The FEM models incorporate measured damping from structural reverberation time and mobility measurements and are validated against Experimental Modal Analysis (EMA) on a concrete reception plate. Natural frequencies and mode shapes from EMA were used to assess the percentage error between two natural frequencies and correlation between mode shapes. An assessment of the reception plate is made by comparing direct injected power and reception plate power for point force excitation with harmonic excitation at different positions on the plate surface.

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2. LABORATORY MEASUREMENTS

2.1 Reception plate

The heavyweight reception plate test rig consists of three, decoupled, perpendicular concrete plates (Figure 1). These 100 mm thick plates are supported around the edges by viscoelastic material with a high internal loss factor. The area of the plates is in the range from 5.34 to 6.85 m². The vertical plates are restrained by six anchoring supports on each plate. Structural reverberation time measurements of each plate have shown that the loss factor of all three plates is similar. In this paper, FEM models and experimental validation are only considered for the horizontal reception plate.

Figure 1 – Reception plate test rig at Stuttgart

2.2 Material properties

Material properties required for the FEM model include the Young's modulus, spring stiffness and damping coefficient of resilient material.

The quasi-longitudinal wave velocity of the concrete plate was measured at eight different positions using time-of-flight. Figure 2 shows an example of the measurement results where the velocity is calculated from the ratio of the distance between accelerometers and the time between nominally identical points on the initial rising slope of the response [6,7]. Hence, the Young's modulus of the concrete plate is calculated according to:

$$E = c_{\mathrm{L}}^{2}\rho\left(1-\nu^{2}\right) \tag{1}$$

where c_{L} is the quasi-longitudinal wave velocity, ρ is the density and ν is Poisson's ratio. This gave a Young's modulus with a value of 25.9E09 N/m².

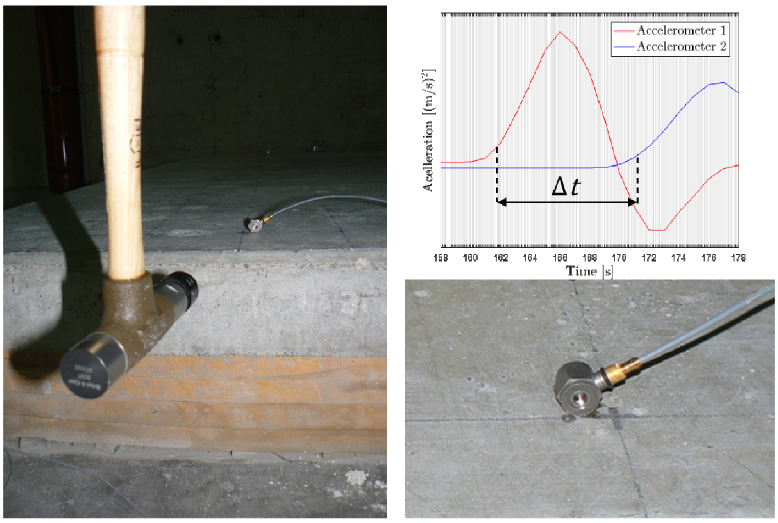

Figure 2 – Measurement setup for the quasi-longitudinal wave velocity

The dynamic stiffness of the resilient material (Sylomer HD 30) is obtained by measuring the mass-spring resonance frequency according to EN 29052-1 [8] – see Figure 3. To simulate the load of the reception plate the load mass was a concrete cube with an edge length of 0.1 m. The overall height of the resilient material was 0.1 m (comprising 8 Sylomer layers of 12.5 mm thickness) which also formed a cube. From the measured resonance frequency the dynamic stiffness of the resilient material was determined using:

$$k = 4\pi^2 m f_{\mathrm{ms}}^2 \qquad (2)$$

where f_{ms} is the resonance frequency and m the mass of the concrete cube (2.5 kg). The value of the calculated spring stiffness is 271004 N/m. The resonance frequency of the measured driving-point mobility is also used to gain the loss factor of the resilient material using the half-power bandwidth method. Hence, the damping coefficient is obtained from [7]:

$$R = \eta\sqrt{km} \qquad (3)$$

where η is the loss factor of the resilient material determined at the mass-spring resonance frequency, k is the spring stiffness of the resilient material (N/m) and m the mass of the used concrete cube (kg). Using this equation leads to a damping coefficient of 497.4.

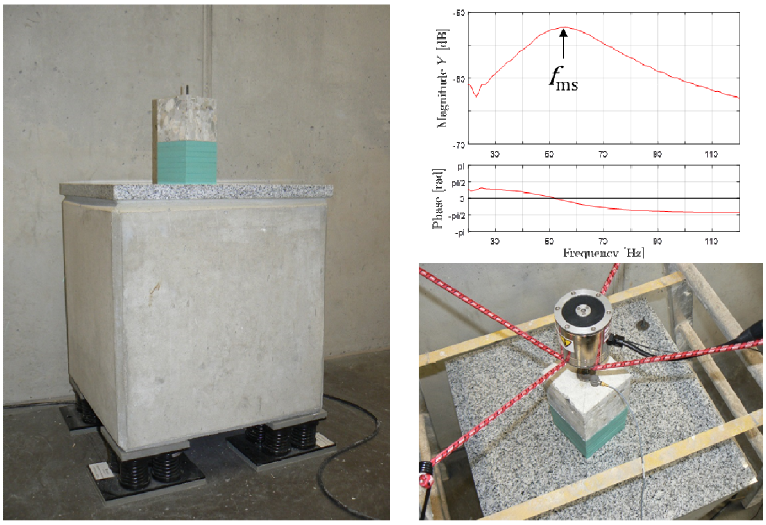

Figure 3 – Measurement setup for dynamic stiffness of the resilient material

2.3 Experimental Modal Analysis (EMA)

EMA was carried out on the horizontal reception plate using the modal test software PULSE MTC Type 7753. Frequency response functions were determined using roving hammer excitation and stationary multiple reference responses to ensure that closely coupled modes or repeated roots are also resolved. A 21 by 29 point measurement grid was used over the surface of the horizontal reception plate (size: 2.0 m by 2.8 m) giving a total of 609 grid points.

The post processing of the vibration data was carried out with the modal analysis software package ME'scope VES. The mode shapes and natural frequencies of the horizontal reception plate are obtained by multiple reference curve fitting of all measured sets of frequency response functions. The curve fitting method was the MDOF polynomial fit method.

3. MODELLING USING THE FINITE ELEMENT METHOD (FEM)

FEM models are created with ABAQUS. To see the influence of the resilient supports around the edges, two FEM models were made of the horizontal reception plate (see Figure 4): a) an idealized representation using an isolated plate with free boundary conditions (referred to as FEM FFFF) and b) a more accurate representation of the plate incorporating the resilient material around the boundaries (referred to as FEM Sylomer) are created using thin shell elements (STRI3 – 3-node triangular facet thin shell elements). Element dimensions are < $\lambda_B/8$ over the frequency range of interest.

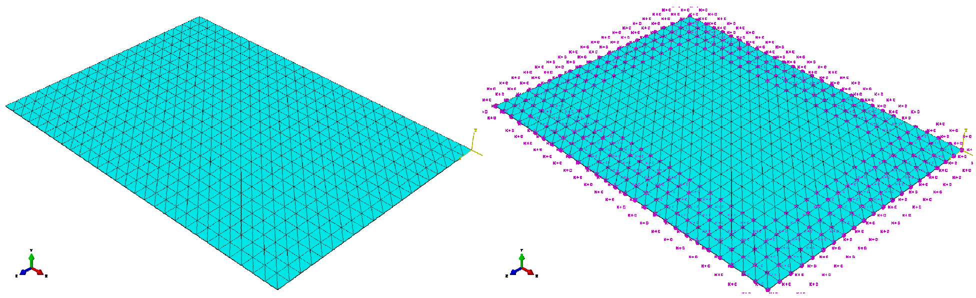

Figure 4 – FEM models: left – FEM FFFF and right – FEM Sylomer

Both FEM models incorporate the following material properties: the measured Young’s modulus (25.9E09 N/m²), the estimated Poisson’s ratio (0.3) [7], the measured density (2300 kg/m³) and the estimated internal loss factor for concrete (0.005) [7].

The FEM Sylomer model incorporates the resilient material around the boundaries as spring-dashpot elements with grounded connections to the concrete plate. The measured spring stiffness and damping coefficient values are divided by four because the dynamic stiffness is measured at the mid-point of the square corresponding to two triangular STRI3 elements. This gives spring-dashpot values for the spring stiffness with 67751 N/m and for the dashpot coefficient with 124.35 that are applied at each node in an area of 2.41 m² around the edges of the plate giving a total of 360 spring-dashpot elements.

In the FEM software ABAQUS two dynamic analysis procedures: a) direct solution and b) modal superposition can be used to solve steady-state dynamic vibration response in the frequency domain. These analysis procedures contain e.g. a) direct and b) mode based steady-state dynamic analysis type which can be applied for free and forced vibrations with damping. Both analysis types calculate the steady-state response of a system to a harmonic excitation. As the direct steady-state dynamic analysis (exact solution) is more accurate than the mode-based steady-state dynamic analysis (approximate solution) the direct analysis type is performed for the steady-state response with an applied harmonic load [9]. All models consider the *in vacuo* situation (i.e. no radiation coupling).

The reception plate method described in EN 15657-1 [2] is based on the principle that when a vibrating source is connected to a simple plate structure, under steady-state conditions, the source power equals the reception plate power. It is assumed that the plate is energized into bending vibration only. The reception plate power is determined by averaging single-frequency velocity data into one-third octave bands and calculated using

$$W_{\mathrm{rec}} = \omega m \eta \tilde{\overline{v}}^2 \tag{4}$$

where ω is the angular frequency, m is the mass of the reception plate, η is the total loss factor of the reception plate and $\tilde{\overline{v}}^2$ is the spatial-average mean-square velocity.

The losses of materials relate to the structural damping in both FEM models. The structural damping factor, γ, is equal to the internal loss factor, η_{int}, of the material and is defined as:

$$\gamma = \eta_{\mathrm{int}} = 2\zeta \tag{5}$$

where ζ is the critical damping ratio of the material.

Calculation of the reception plate power requires the total loss factor – see eq (4). For the FEM FFFF model where the reception plate has no energy losses at junctions or connections to other structures the total loss factor equals the internal loss factor of the concrete. However, for the FEM Sylomer model, the losses in the resilient material around the plate boundaries increases the total loss factor of the reception plate above the internal loss factor of the concrete. To estimate the total loss factor for the FEM Sylomer model, the loss factor is estimated at five randomly distributed positions using the half-power bandwidth method with the driving-point mobility. FEM analysis is carried out with a frequency resolution of 0.001 Hz to ensure accuracy.

In this paper the reception plate power is compared with the direct injected power at the driving-point:

$$W_{\text{inj}} = \frac{1}{2}\text{Re}\left[\underline{F}^{*}\underline{v}\right] \tag{6}$$

where $\underline{F}^{*}$ is the complex conjugate force at a single contact and $\underline{v}$ is the complex velocity.

4. RESULTS

4.1 Loss factor

For the FEM Sylomer model, Figure 5 compares the loss factors of the reception plate that are measured and simulated. The measurements are carried out using two different approaches. One approach determines the loss factor from the measured structural reverberation time (black solid line with 95 % confidence interval) and the other determines the loss factor from the driving-point mobility using the half-power bandwidth method from five randomly distributed positions (blue asterisk makers). FEM and measurements are generally in close agreement indicating that the damping from the resilient material has been successfully incorporated into the FEM Sylomer model.

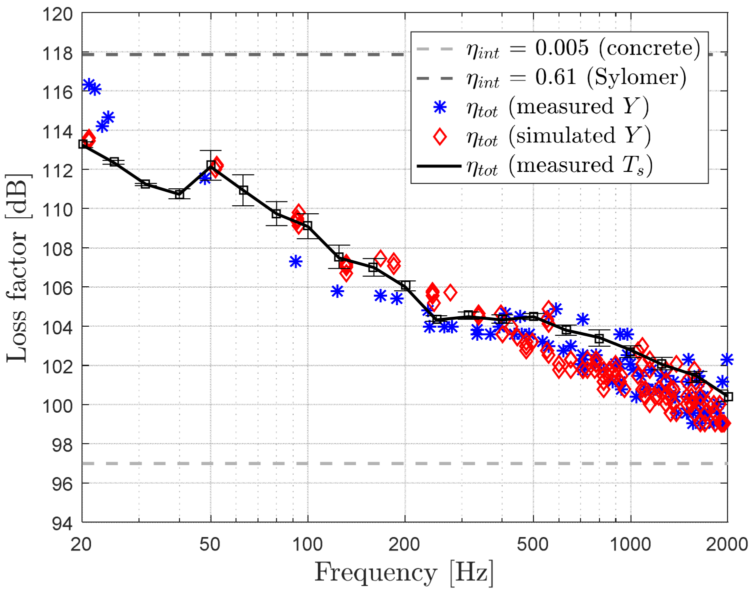

Figure 5 – FEM Sylomer model: simulated and measured loss factors

4.2 Experimental mode shapes from EMA

For the horizontal reception plate in the laboratory, Figure 6 shows the experimentally determined mode shapes from EMA.

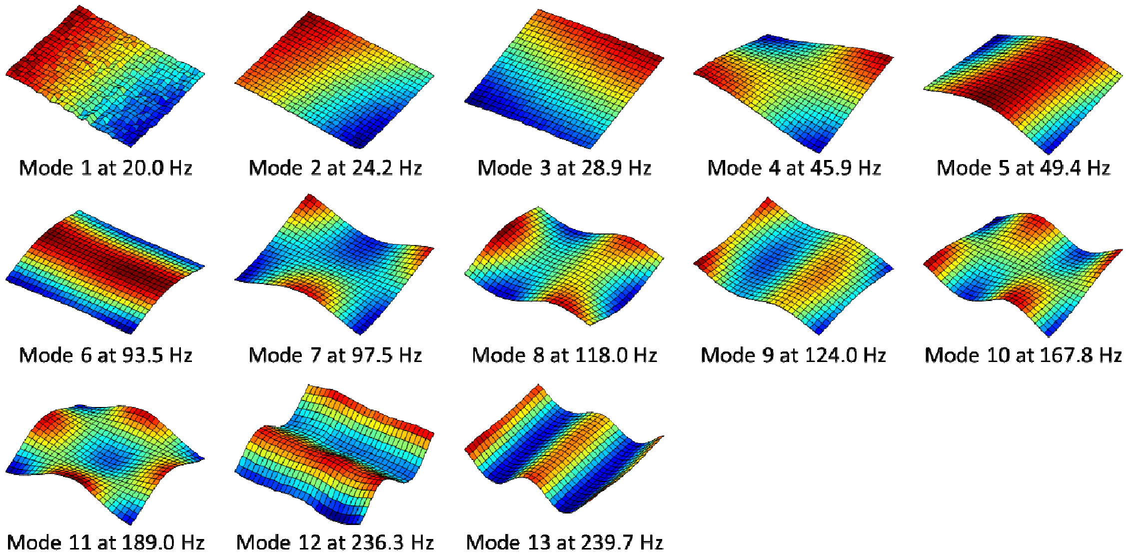

Figure 6 – Lowest 13 mode shapes and eigenfrequencies from EMA measurements on the horizontal reception plate

4.3 Validation of FEM models with EMA

Both FEM models are validated against EMA in terms of the percentage error between two sets of natural frequencies, the Natural Frequency Deviation (NFD) as well as the Modal Assurance Criterion (MAC) for out-of-plane motion.

Figure 7 shows the NFD for both FEM models. The FEM FFFF model shows poor agreement for the first three natural frequencies because these are rigid body modes with zero frequency and a stiffness matrix which is zero. In contrast, for the FEM Sylomer model, the plate is restrained at the edges by the resilient material; hence the stiffness matrix is non-zero. This gives three rigid body modes with non-zero eigenfrequencies. Close agreement is achieved in terms of eigenfrequencies for (a) the six corresponding mode pairs in the frequency range from 100 to 250 Hz for the FEM FFFF model and (b) for the 13 eigenfrequencies in the frequency range from 20 to 250 Hz for the FEM Sylomer model.

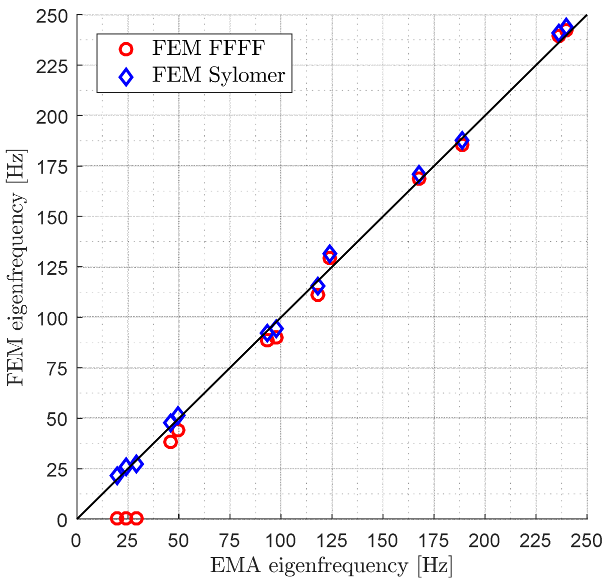

Figure 7 – Comparison of natural frequencies for corresponding mode pairs below 250Hz

Figures 8 and 9 show the MAC results comparing EMA with FEM for the FFFF and Sylomer models respectively. With the FEM FFFF model, strong correlation is only achieved at and above the fourth mode; the first three rigid body mode shapes that are determined through EMA are weakly correlated with FEM. In contrast, the FEM Sylomer model shows high correlation for all 13 modes. Hence, the close agreement between experimental eigenfrequencies and mode shapes for the FEM Sylomer model show that (a) simplistic assumptions about the actual reception plate having free boundaries are inappropriate at low frequencies and (b) the resilient material has been correctly incorporated in the FEM model.

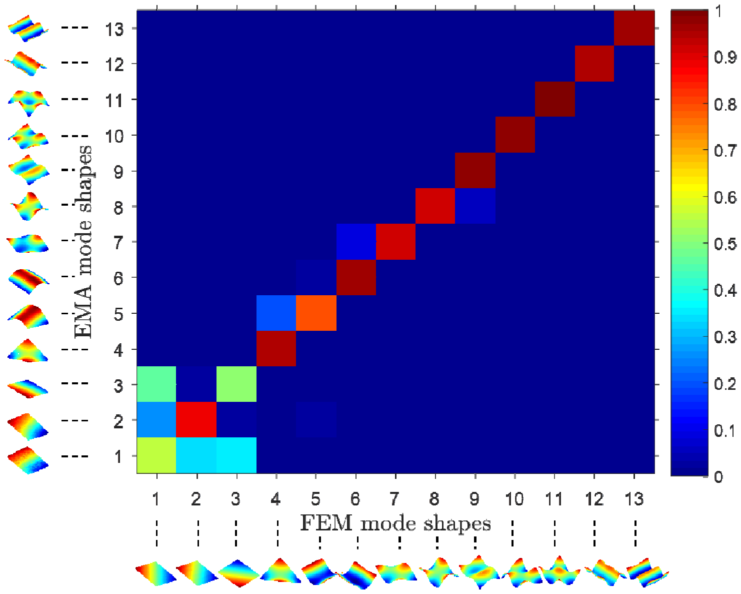

Figure 8 – MAC values (mode shapes from FEM FFFF model and EMA)

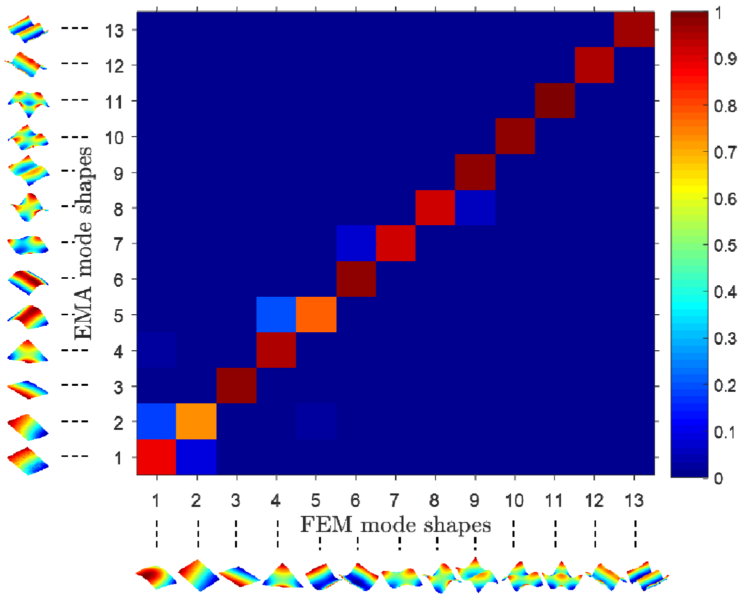

Figure 9 – MAC values (mode shapes from FEM Sylomer model and EMA)

4.4 Numerical experiments using FEM to assess the validity of reception plate power

The difference between direct injected power and reception plate power for five randomly distributed, point excitation positions is shown on Figures 10 and 11 for the FEM FFFF and Sylomer models respectively.

For the FEM FFFF model at and above the 80 Hz one-third octave band there is close agreement (±1 dB) between the direct injected and reception plate power where there is at least one mode in each one-third octave band (even though the modal overlap factor, $M << 1$ below 200 Hz). Large deviations (>3 dB) occur below 31.5 Hz due to low damping and low mode counts in the one-third octave bands. In fact, the lowest bending mode falls in the 31.5Hz one-third octave band and there are only rigid body modes at lower frequencies for which the definition of reception plate power in eq (4) is not valid. At 63 Hz there is one excitation point (shown in black) located near a corner where a mode is not excited which leads to large differences between the powers.

For the FEM Sylomer model there is close agreement (±1 dB) over the whole frequency range because there are bending modes at and above 20 Hz. Whilst there are no modes predicted in the 63 and 80 Hz bands, high damping from the viscoelastic material in adjacent bands is also beneficial as it increases the modal overlap.

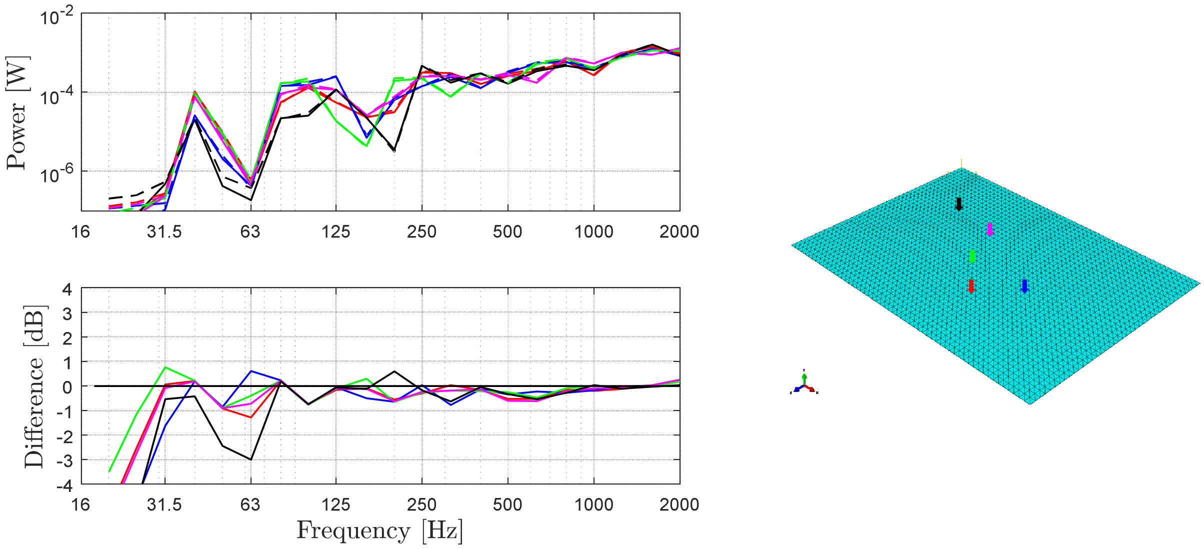

Figure 10 – FEM FFFF model: Direct injected power – solid lines, reception plate power – dashed lines (Upper graph), Direct injected power minus reception plate power (Lower graph)

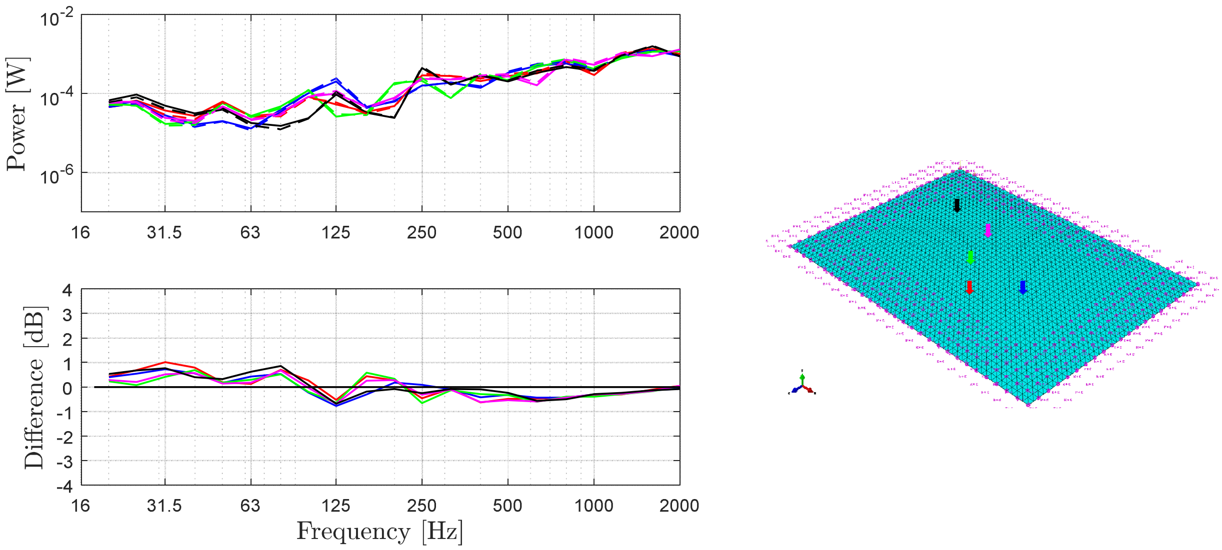

Figure 11 – FEM Sylomer model: Direct injected power – solid lines, reception plate power – dashed lines (Upper graph), Direct injected power minus reception plate power (Lower graph)

5. CONCLUSIONS AND FUTURE RESEARCH

Reception plates are used to measure the structure-borne sound power from machinery in the laboratory. In this paper, FEM models have been developed to simulate an idealised reception plate (free boundaries) and a realistic implementation of a laboratory reception plate which is supported around its edges by viscoelastic material to increase its damping. The idealised reception plate model only shows good agreement in terms of natural frequencies and mode shapes at and above 100 Hz whereas the realistic reception plate model gives close agreement in all bands up to 250 Hz.

Numerical experiments also confirm that the FEM model which incorporates the resilient material gives better agreement in terms of the comparison of the direct injected power against the reception plate power. The next stage of the research is to use the validated FEM model of the laboratory reception plate to assess sampling strategies for vibration measurements that are needed to determine the reception plate power and to investigate the effect of multi-contact and framed sources installed at different points on the reception plate.

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