

# COMPARISON OF THE RECEPTION PLATE METHOD AND THE INVERSE FORCE METHOD FOR ASSESSING THE POWER OF A DUMMY VIBRATORY SOURCE

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Multiple vibratory sources are integrated in the aircraft. The vibrational power of these sources is injected to the receiving structure through their connections points resulting in annoying acoustic levels in the cabin. This noise, referred to as structure borne noise, could be mitigated if vibrating systems, receiving structures and interfaces between them are well designed. Methods, such as Reception Plate Method (RPM), Inverse Force Method (IFM) or Component-Based Transfer Path Analysis (CB-TPA) have been developed to specify proper design guidelines related to noise mitigation during the design phase. This work focuses on the RPM and IFM, which allow for measuring the power from a vibratory source into a reception plate. Previous works, based on a round-robin evaluation, have shown that the RPM is very sensitive to the experimental test setup. The main errors come from the plate loss factor measurement and spatially-averaged plate velocity, which contribute directly into the power computation. In this work, a similar experimental setup has been developed. The experimental loss factor is obtained with the impulse response decay method and several automatic dB-decays are considered. The number of accelerometers and their positions are also investigated for assessing the spatially-averaged plate velocity. Both analyses allow for determining the RPM power with minimum-maximum deviation curves. The RPM results are compared with the IFM considering one and three translational degrees of freedom using a custom-made dummy source with a controlled tonal behavior varying from low (100 Hz) to high (1200 Hz) frequencies.

Keywords: structure borne noise, reception plate method, inverse force method, dummy vibratory source

## 1. Introduction

Multiple vibratory sources are integrated in the aircraft. The vibrational power of these sources is injected to the receiving structure through their connections points resulting in annoying acoustic levels in the cabin. This noise, referred to as structure borne noise, could be mitigated if vibrating systems, receiving structures and interfaces between them are well designed. Methods, such as Reception Plate Method (RPM) [1], Inverse Force Method (IFM) [2] or Component-Based Transfer Path Analysis (CB-TPA) [3] have been developed to specify proper design guidelines related to noise mitigation during the design phase. These methods are investigated in two distinct papers [4] and the present work focuses on the RPM and IFM, which allow for assessing the power from a vibratory source into a reception plate.

A recent study has focused on a round-robin evaluation of the vibration power estimation based on the RPM [1]. Four industrial partners were invited to measure the vibration power of an air pump. The vibration powers provided by the RPM and IFM, along the perpendicular direction to the plate, were compared. Although the experimental set-up and sources were similar, large variations in the vibration power were found. As the RPM relies on the product of the loss factor and the spatially-averaged plate velocity, these two quantities were pointed out as the source of the discrepancies.

In this work, a similar experimental set-up has been considered. A custom-made dummy source, allowing the generation of low or high frequency vibration, has been designed. The loss factor is measured with the impulse response decay method [5]. The influence of the automatic dB-decay and the number of accelerometers and their positions are investigated. The vibration powers provided by the RPM, along the perpendicular direction to the plate, are compared with the IFM accounting for one and three translational degrees of freedom.

Section 2 presents a quick overview of the theoretical background of the RPM and the IFM. The experimental set-up is detailed in Section 3. The loss factor, spatially-averaged plate velocity and the source power provided by the RPM are shown in Section 4. Finally, the RPM and IFM results are compared in Section 5.

## 2. Reception plate method and inverse force method formulations

The RPM is based on the power balance principle stating that the power injected  $\Pi_{injected}$  by a vibratory source into a plate is equal to the power dissipated by the plate  $\Pi_{dissipated}$ . This method makes the assumption of high modal density and overlap (reverberant field) which means that theoretically RPM is a high frequency method. In this case, considering only the perpendicular direction to the plate ( $z$  direction in this work),  $\Pi_{dissipated}$  is given by

$$\Pi_{dissipated} = \omega \eta m \langle v_b^2 \rangle, \quad (1)$$

where  $\omega$  is the pulsation,  $\eta$  is the plate loss factor,  $m$  is the plate mass,  $v_b$  is the plate velocity at point  $b$  along the  $z$  direction when the source is on and  $\langle \cdot \rangle$  means spatial average,

$$\langle v_b^2 \rangle = \frac{1}{M} \sum_{i=1}^M |v_{bi}^2|, \quad (2)$$

where  $M$  is the number of accelerometers on the plate. In the following,  $\langle v_b^2 \rangle$  is called spatially-averaged plate velocity. It is worth mentioning that Eq. 1 is also valid at the plate resonance, in this case the loss factor is equal to the modal damping and the pulsation is equal to the mode.

The power injected  $\Pi_{injected}$  in a plate is given by

$$\Pi_{injected} = F_c v_c, \quad (3)$$

where  $v_c$  is the contact point velocity and  $F_c$  is the contact point force which can be assessed by the Inverse Force Method (IFM) [2] with

$$F_c = [\mathbf{Y}_{B,bc}]^{-1} v_b, \quad (4)$$

where  $\mathbf{Y}_{B,bc}$  is the transfer plate mobility when the excitation is at point  $c$  and the measure of the plate vibration velocity at point  $b$ . In theory, the  $\mathbf{Y}_{B,bc}$  matrix has to be fully characterized which means applying forces and moments at the contact points and measuring the three translational and three rotational degrees of freedom onto the plate. If matrix elements cannot be measured, the method accuracy decreases due to the incompleteness of the matrix. The one degrees of freedom case is the poorest case in term of matrix completeness. Moreover, the method accuracy is improved when the matrix is over-determined (measure point  $b$  larger than contact point  $c$ ). In reference [1], the IFM taking into account the perpendicular direction to the plate is used as a self-check quality. In this work, the IFM based on the three translational degrees of freedom is considered as the reference. In the following, both methods are denoted IFM<sub>z</sub> and IFM<sub>xyz</sub>, respectively. The rotational degrees of freedom are not taken into account due to experimental limitations. This method is also denoted as classical TPA matrix-inverse method in reference [3].

### 3. Experimental set-up and test procedures

The plate used was a stainless steel plate with dimensions 38 in by 54 in by 3/16 in (965.2 mm by 1371.6 mm by 4.8 mm) and weighed 47.7 kg. A dedicated test bench, with wood beams of (3.5 × 3.5) in<sup>2</sup>, was designed (Figure 1.b). The plate was supported by the test bench with a damping material (Bary-mat BM-1C) in between. This material was added to avoid flatness default between the plate and the test bench. The plate velocity at points  $b$  was measured with 8 triaxial accelerometers (PCB 356A45) and the velocity contact points  $c$  was measured with 4 triaxial accelerometers (PCB 356A03). The accelerometer weights are 4.2 g and 1 g respectively and are considered negligible compared to the plate mass. The impact excitation was generated with a hammer (PCB 086C03). The signals were recorded with a National Instruments PXIe 1073 chassis and two acquisition cards 2 PXIe 4497 providing a 51,200 Hz frequency sampling. Figure 1 shows a picture of the experimental set-up and a sketch of the impact and measurement point locations. The blue crosses are the plate accelerometer locations, the green squares are the contact accelerometer locations and the red dot are the impact excitation points for loss factor measurement. Figure 2 provides the test procedure to obtain the power dissipated (RPM) and the power injected (IFM). With the RPM, the first step is to measure the plate loss factor which is obtained by the impulse response decay method [5] without the source installed. Five impact positions have been tested (red dots in Figure 1.a) and the decay signal was recorded by eight accelerometers (blue crosses in Figure 1.a). Ten trials per impact were performed for averaging purposes. Each accelerometer signal was filtered by a bandpass Butterworth filter for each 12<sup>th</sup> octave band in the frequency range [50-2000] Hz. Then, inverse Schroeder integration was used to assess the decay curve. The slope of the decay curve was determined with different automatic dB-decays (in dB). Finally, the loss factor was given by

$$\eta = \frac{2.2}{f \cdot RT}, \quad (5)$$

where  $f$  is the central frequency of the 12<sup>th</sup> octave band and  $RT$  is the reverberation time. The spatially-averaged plate velocity was provided by a maximum of 8 accelerometers at points  $b$  (Figure 1.a). Classical Fast Fourier transform in 12<sup>th</sup> octave band was used with Hanning window and 90% overlap. With the IFM<sub>xyz</sub>, the transfer plate mobility was obtained by measuring the frequency response function (H1 estimator) between hammer and accelerometer signals. The impact excitations, along the three translational degrees of freedom, were performed at contact point (green squares in Figure 1.a) and the triaxial

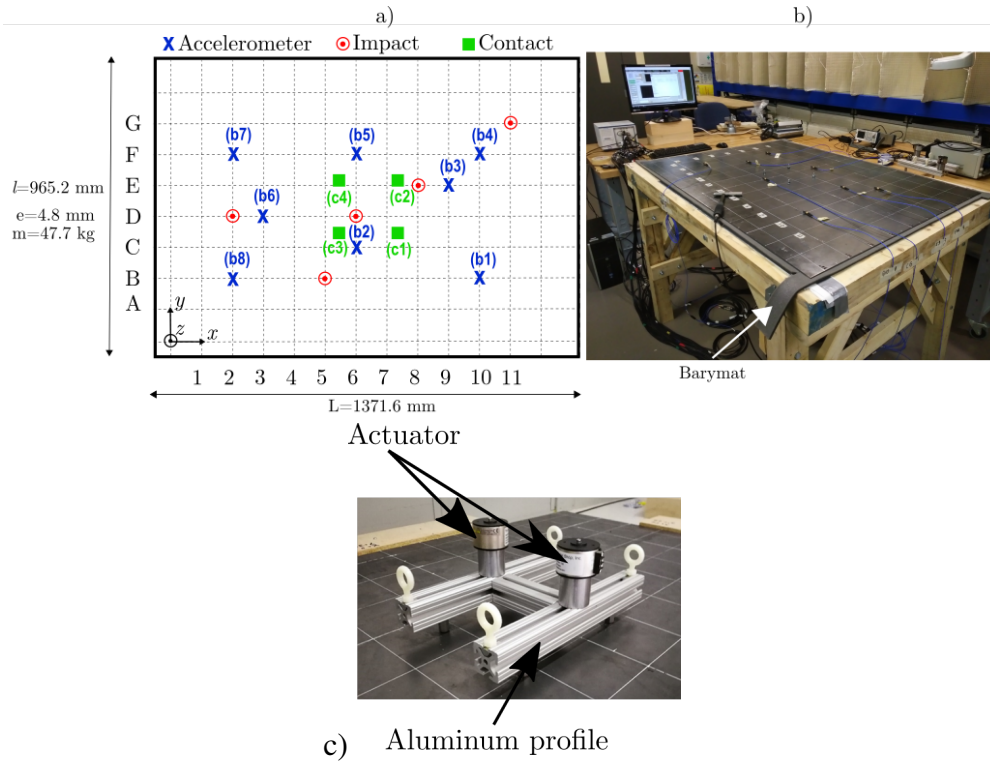


Figure 1: a) Sketch and b) picture of the experimental set-up. c) Picture of the custom-made dummy source.

accelerometer signals were recorded on the plate (blue crosses in Figure 1.a). With the IFM<sub>z</sub> only the z direction (perpendicular to the plate) is considered. Ten trials per impact were performed for averaging purpose. The plate and contact point velocities were provided by classical Fast Fourier transform in 12<sup>th</sup> octave band (Hanning window and 90% overlap). The vibratory source to be characterized was a custom-made dummy source composed of three aluminum beams (H-shape) and two miniature inertial electrodynamic actuators (Modal Shop model 2002E) (as shown in Figure 1.c). The actuator source signals was sine waves (in phase) generated by a BK precision 4052 signal generator. In this work, the source was rigidly attached to the plate.

#### 4. Influence of the loss factor computation and spatially-averaged plate velocity on the RPM results

First, the influence of the plate loss factor is investigated. The slope of a decay curve can be determined by an operator or by automatic dB-decay. In this work, five automatic dB-decays are considered: 3, 6, 10, 20 and 30 dB. An automatic dB-decay of 3 dB means that the slope of the decay curve is determined when the energy has decreased by 3 dB. The results are presented in Figure 3. Below 100 Hz, the loss factor is strongly influenced by the automatic dB-decay, the highest loss factor is provided by the lowest automatic dB-decay (3 dB). Increasing the automatic dB-decay decreases the loss factor. The lowest loss factor is provided by the highest automatic dB-decay. In mid frequencies (between 100 and 500 Hz), the loss factor varies independently of the automatic dB-decay. Finally, above 500 Hz the loss factor is independent of the automatic dB-decay. For low frequency, the loss factor obtained is compared with modal damping derived from half-power bandwidth method (3 dB method). Both methods

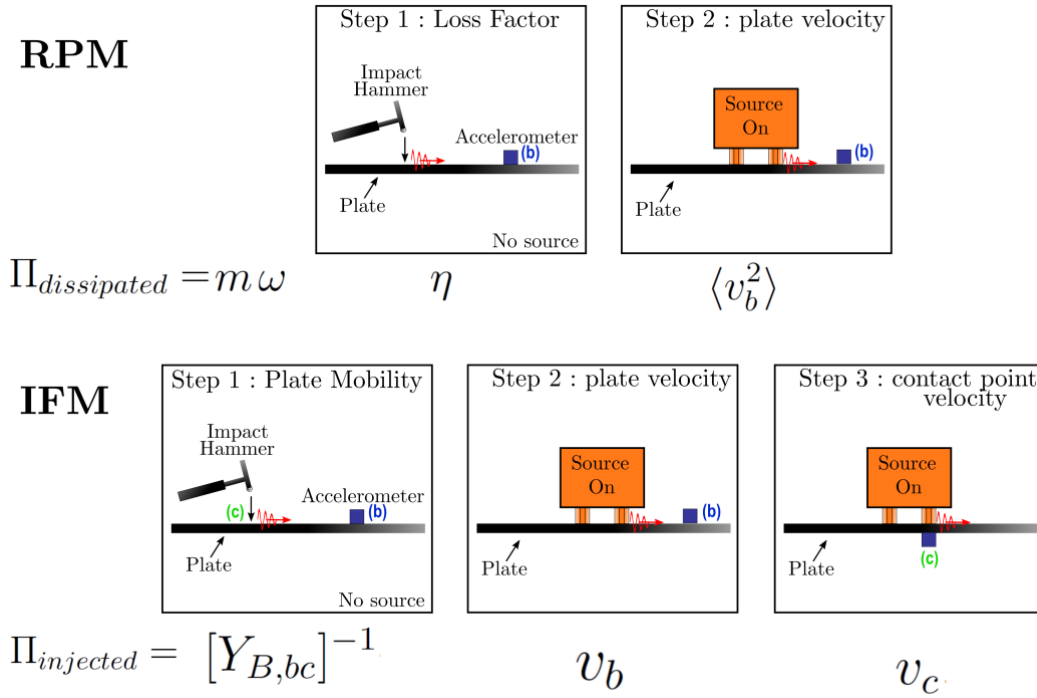


Figure 2: Test procedures to obtain the power dissipated (RPM) and the power injected (IFM).

are in good agreement. The damping once the source is installed has not been considered here, it will be measured in a future work.

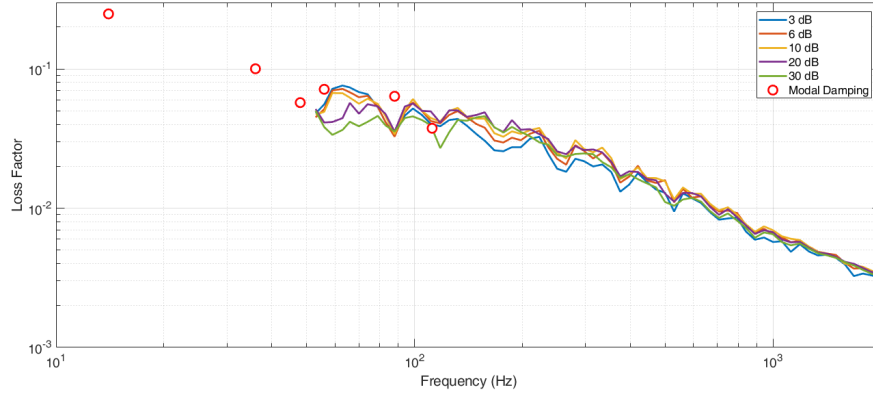


Figure 3: Comparison of the loss factor for different automatic dB-decays.

Then, the spatially-averaged plate velocity, along  $z$  direction (only degree of freedom accounted for in the RPM), is investigated in relation to the number of accelerometers and their positions. Three different configurations are considered: the 4 accelerometers closer to the contact points (b2, b3, b5 and b6), the 4 accelerometers further to the contact points (b1, b4, b7 and b8), and the whole set of 8 accelerometers. The custom-made dummy source is driven by a sine wave at 100 Hz. Figure 4.a shows the obtained results. The largest difference between the peak levels is 3.5 dB (closer accelerometers versus further accelerometers) with the maximum peak value provided by the closer accelerometers. This fact illustrates

that the sensor position is very important when measuring the plate velocity. When the 8 accelerometers are considered the peak value is obviously in between.

Now, the power dissipated provided by the RPM is computed for the five automatic dB-decays and the three spatially-averaged plate velocities which leads to fifteen different dissipated powers. The minimum, average and maximum values of the power for each frequency band are presented in Figure 4.b in order to provide the deviation due to the different estimation of the loss factor and spatially-averaged plate velocity. For 100 Hz, the peak level difference between the minimum and maximum is 6 dB which confirms the sensitivity of the RPM to the plate loss factor and spatially-averaged plate velocity.

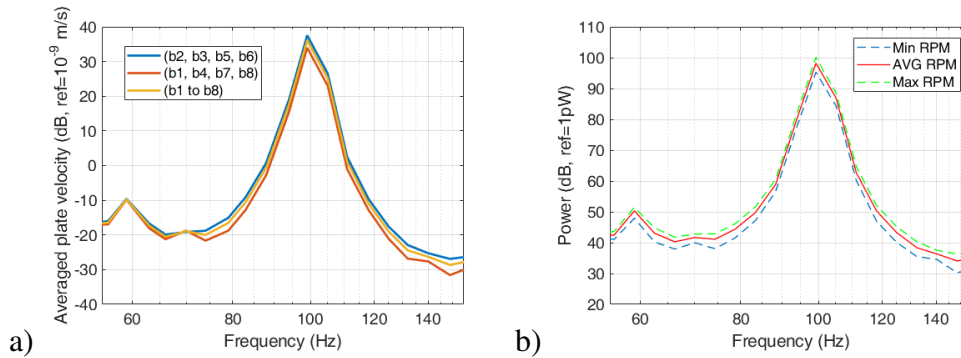


Figure 4: a) Comparison of the spatially-averaged plate velocity (along  $z$  direction) in relation to the number of accelerometers and their positions. b) Power dissipated provided by RPM.

## 5. Comparison of RPM and IFM results

In the reference [1], the  $IFM_z$  is used as a self-check quality. In this work, the RPM results are compared with  $IFM_z$  and  $IFM_{xyz}$  with the latter considered as the reference (because the three translational degrees of freedom are taking into account). Figure 5 provides a comparison between RPM and  $IFM_z$  for different vibratory source signal frequencies (100, 150, 500 and 1200 Hz). With the RPM, the minimum, average and maximum values of the power dissipated are depicted. When the source signal is 100 Hz, the maximum RPM value is similar to the  $IFM_z$ . When the source signal is 150 Hz, the  $IFM_z$  fits in between the minimum and maximum RPM curves. When the frequency of the source signal increases (500 Hz and 1200 Hz), the RPM always underestimates the  $IFM_z$  peak values. This fact is visible at 1200 Hz where the difference between RPM and IFM is 7 dB at least.

Finally, the average RPM,  $IFM_z$  and  $IFM_{xyz}$  are compared (i.e. all the translational degrees of freedom are taken into account in the latter). The results are shown in Figure 6. For the high frequency cases (500 and 1200 Hz), the  $IFM_z$  and  $IFM_{xyz}$  provide similar estimation of the of peak value which may mean that the two degrees of freedom ( $x$  and  $y$ ) can be neglected. When the source frequency decreases (100 and 150 Hz), the  $IFM_z$  underestimates the peak value as compared to  $IFM_{xyz}$ , in this case, the ( $x$  and  $y$ ) degrees of freedom have to be taken into account in order to better estimate the source injected power. Therefore, although the RPM is similar to  $IFM_z$  for low frequencies, the power estimated by RPM seems to be always underestimated as compared to  $IFM_{xyz}$ .

## 6. Conclusion

For structural vibration and cabin noise control on aircraft, findings from this work must be considered when determining the appropriate method to study vibrational power of structure borne noise



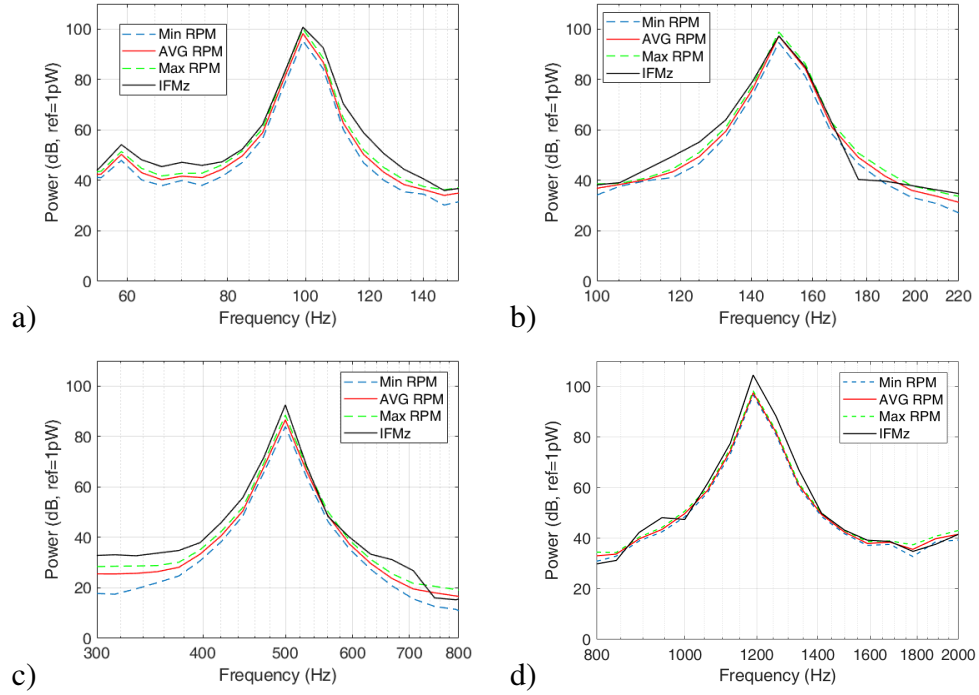


Figure 5: Comparison between RPM and  $IFM_z$  in the case of different vibratory source signal frequency a) 100 Hz, b) 150 Hz, c) 500 Hz and d) 1200 Hz.

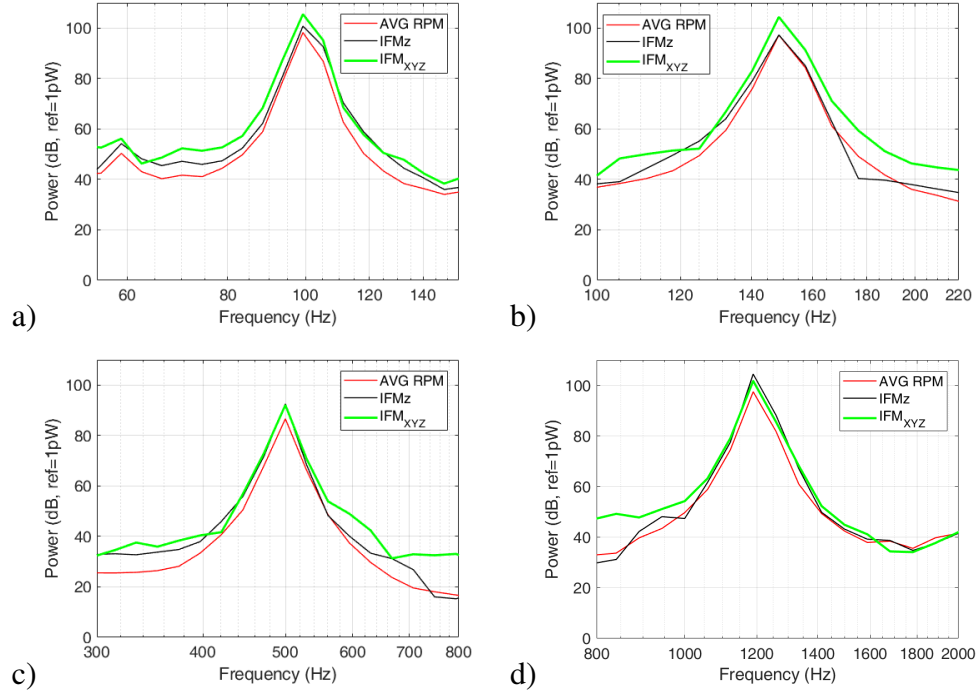


Figure 6: Comparison between RPM,  $IFM_z$  and  $IFM_{xyz}$  in the case of different vibratory source signal frequency a) 100 Hz, b) 150 Hz, c) 500 Hz and d) 1200 Hz.

sources. In this work, the Reception Plate Method (RPM) is compared to the Inverse Force Method considering one and three translational degrees of freedom ( $IFM_z$  and  $IFM_{xyz}$ ) using a custom-made dummy source with a controlled tonal behavior varying from low (100 Hz) to high (1200 Hz) frequencies. First, the influence of the loss factor and the spatially-averaged plate velocity on the RPM results is investigated. Five automatic dB-decays are considered to compute the loss factor and three different sets of accelerometers are considered to compute the spatially-averaged plate velocity. Both studies allows for determining an average RPM power surrounded by minimum-maximum curves. These results are compared with the  $IFM_z$ . It is shown that peak values are similar with the RPM and  $IFM_z$  for low frequency content. However, when the frequency increases the RPM underestimates the power. Finally, the RPM,  $IFM_z$  and  $IFM_{xyz}$  are compared. In high frequencies, the peak values provided by  $IFM_z$  and  $IFM_{xyz}$  are similar which may mean that the two degrees of freedom ( $x$  and  $y$ ) are negligible. Decreasing the source frequency shows that the  $IFM_z$  underestimates the power as compared to  $IFM_{xyz}$ . Therefore, although the RPM provided the same power as the  $IFM_z$  for low frequency content, this one seems to underestimate the power compared to the  $IFM_{xyz}$ .

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