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Influence of background noise on non-contact vibration measurements using particle velocity sensors

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ABSTRACT

Structural vibrations are usually measured using accelerometers or laser Doppler vibrometers. However, the weight of the accelerometers can influence vibration patterns and lasers can have problems with non-reflective or fibrous materials. Alternatively, vibration can also be measured acoustically using particle velocity sensors positioned near the structure. Although the capabilities of this approach have been demonstrated in several studies, the influence of background noise on the results has been considered insufficiently thus far. This paper explores how non-contact vibration measurements using particle velocity sensors are affected by external sound sources; results from both simulations and measurements are presented and analysed.

Keywords: particle velocity, non-contact vibrations, background noise.
I-INCE Classification of Subjects Number(s): 72.2.2

1. INTRODUCTION

Accelerometers and laser vibrometers are common transducers used in most vibro-acoustic problems. Both sensors give reliable results under favourable conditions. However, attaching sensors to a vibrating structure is not always possible and accelerometers add a mass load that may significantly influence the panel surface vibration. On the other hand, a non intrusive approach using laser vibrometers may seem more attractive. Optical non-contact solutions, such as Laser Doppler Vibrometry (LDV) (1), enable the fast acquisition of a large number of measurements with good spatial resolution. On the other hand, the high price, setup complexity and the fact that non-reflecting or fibrous materials may cause difficulties during the measurement process, limit the use of LDV in many applications. Alternatively, acoustic particle velocity sensors have also been proven suitable for performing non-contact vibration measurements (2, 3). Under specific conditions, surface velocity is proportional to particle velocity allowing for the acquisition of vibrational information with an acoustic transducer. Several studies have revealed the potential of particle velocity sensors for characterising structural vibrations (4, 5, 6, 7, 8, 9), but thus far the presence of noise has not been assessed in detail. This paper studies the impact of noise during the data acquisition process upon spectral estimations of structural vibrations from a theoretical and experimental point of view.

2. THE VERY-NEAR FIELD THEORY

The following derivation for relating the velocity of a vibrating surface and the particle velocity above it follows the work of de Bree et. al. introduced in (4, 5). It begins by studying the definition of the Helmholtz wave equation in terms of velocity potential $\Psi(x)$, i.e.

$$\bigtriangledown^2 \Psi + k^2 \Psi = 0 \tag{1}$$

where $\bigtriangledown^2$ is equivalent to the Laplace operator and k is the wave number $(2\pi f/c_0)$. A description of the sound field near a vibrating surface can be obtained by evaluating Equation (1) with the following boundary conditions:

$$\begin{cases} u_n = \partial\Psi/\partial_n & \text{if } x = 0 \\ \Psi \propto e^{jkx}/x & \text{if } x \to \infty \end{cases} \tag{2}$$

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where x is the distance to the vibrating surface; ∂/∂_n is the normal derivative and u_n is the normal component of the particle velocity. The observable acoustic values, sound pressure p and particle velocity $\mathbf{u}$, are linked to the potential as follows:

$$\mathbf{u} = \bigtriangledown\Psi \ \ , \ \ p = -j\omega\rho\Psi \tag{3}$$

where $\bigtriangledown$ represents the gradient operator and ρ is the density of the medium (air).

According to (4), a region can be defined between the vibrating surface and the start of the space conventionally called the "near-field", where Equation 1 is reduced to the Laplace equation for incompressible fluids. In order to derive this expression it is necessary to perform a Taylor series expansion of the velocity potential term $\Psi(x)$ in the vicinity of the surface and then only consider sound waves of wavelength (λ) much larger than the spatial wavelength which defines the vibrating surface (L_{eff}). In summary, it can be shown that the sound field at a distance r from a vibrating surface can be considered to be in the "very near-field" if the two following conditions are met:

$$\begin{cases} r << L_{eff}/2\pi & \text{condition (I)} \\ \\ \lambda >> L_{eff} & \text{condition (II)} \end{cases} \tag{4}$$

In the very near-field, the normal component of the particle velocity equals the structural velocity of the vibrating surface with negligible error. These considerations are the basis of non-contact vibration measurements using particle velocity sensors.

There is an important issue concerning the estimation of the very near-field size. To measure in this region, x should be at least two orders of magnitude smaller than $L_{eff}/2\pi$. Nevertheless, it should be noted that the effective wavelength relative to the vibrating surface L_{eff} may change with frequency. In practice, this means that the measurement distance range allowing for the direct acquisition of structural vibrations using a particle velocity sensor is determined by the mechanical properties of the vibrating surface, as well as the presence of noise in the measurement environment.

3. PARTICLE VELOCITY, SURFACE VELOCITY AND ACCELERATION

Before studying the impact of background noise upon non-contact vibration measurements, it is worth clarifying the relationship between particle velocity, surface velocity and surface acceleration. For an excited body that vibrates in a stationary harmonic regime with normal velocity v_n, it can be established that

$$a_n = \frac{\partial v_n}{\partial t} = \frac{\partial\left(v_0 e^{j(\omega t-\phi)}\right)}{\partial t} = j\omega v_0 e^{j(\omega t-\phi)} = j\omega v_n \tag{5}$$

where a_n is the normal surface acceleration, v_0 is the vibration speed and ϕ is an arbitrary phase value. Hence, there is a linear relationship between surface velocity and acceleration that allows for the direct computation of both quantities by simply measuring one of them. In contrast, the particle velocity in front of a vibrating body depends upon a term describing how efficiently vibrational energy is converted into acoustic excitation in the form of normal velocity along with the noise generated by any external source perceived at the sensor position x, hence

$$u_n(x) = v_n Z_{\mathrm{r}}(x) + \sigma_n \tag{6}$$

where $Z_r(x)$ is a term which relates the surface displacement and the particle velocity at the position x; whereas σ_n is the variance of the noise signal perceived at x. In the particular case of a baffled circular piston in the absence of noise, the particle velocity u_n measured on the axis of a rigid circular piston of radius a is related to its surface velocity v_n as such (10)

$$u_n(x) = v_n(1-\beta e^{-2j\gamma})e^{j(\omega t-kx)} \tag{7}$$

where

$$\beta = x/\sqrt{a^2+x^2} \ \text{and} \ \gamma = k\left(\sqrt{a^2+x^2}-x\right)/2 \tag{8}$$

The terms $Z_r(x)$ and σ_n are usually unknown for most practical applications since both depend upon the characteristics of the radiating source and the measurement environment. However, as it has been proven in (4, 5), the measurement distance plays a key role, since the effect of those terms is minimised near the vibrating surface. Therefore, non-contact vibration measurements using particle velocity sensors should be performed as close as possible to the vibrating body in order to meet the very near field conditions (Equation 4).

4. EXPERIMENTAL EVALUATION

This section presents a series of experiments focused on studying the vibro-acoustic behaviour of a rigid circular piston. Firstly, the on-axis sound radiation is evaluated whilst driving the piston with a random excitation. Next, two more tests are introduced in order to assess the noise reduction achieved with a particle velocity sensor in the vicinity of a rigid body, i.e. the sound field perceived in front of the piston while it is static and a set of arbitrary distributed loudspeakers generate high sound pressure levels in the testing room.

All tests were undertaken using a 1.5 mm thick aluminium plate of diameter 80 mm which was coupled to a shaker. A conic structure of ABS plastic was glued to the back of the plate in order to increase the stiffness of the vibrating element. Figure 1 shows a detailed picture of the component (left) and the measurement setup (right).

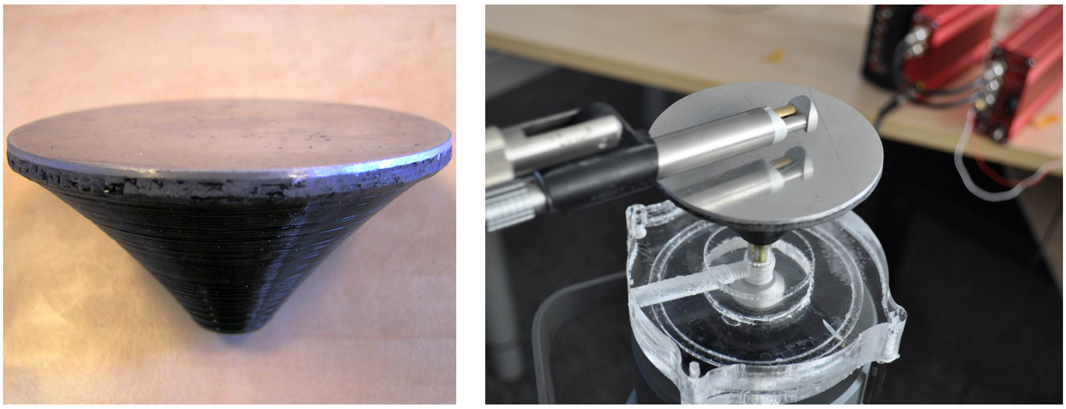

Figure 1 – Piston with aluminium surface (left) and measurement setup (right).

4.1 Non-contact vibration and sound radiation

As shown by de Bree et al. (4, 5), particle velocity sensors can be used to measure surface vibrations if the acoustic and vibrational wavelengths are much larger than the measurement distance. This section provides a quantitative assessment of the estimation accuracy for a simple case such as a rigid moving piston. Following the derivations of Beissner on the sound radiation of a piston source (10) together with the theory given in Section 3, the surface acceleration S_{aa}, surface velocity S_{vv} and on-axis particle velocity $S_{uu}(x)$ power spectra of a baffled circular piston can be related as follows:

$$S_{aa} = \omega^2 S_{vv} = \omega^2 S_{uu}(x) \left(\frac{1}{\beta^2 - 2\beta cos(2\gamma) + 1} \right) \tag{9}$$

Several particle velocity measurements were performed along the central axis of the vibrating piston whilst an accelerometer was attached to the device in order to characterise its surface velocity. The test was undertaken in a controlled environment in the presence of a relatively low level of background noise. Surface velocity and particle velocity measurements are compared in Figure 2 along with the estimation error of the non-contact vibration measurements computed by applying Equation 9.

As shown in Figure 2, the measured particle velocity matches the calculated values using the accelerometer data. The right hand side of Figure 2 shows that the estimation error increases at high frequencies, even more so as the probe is positioned farther from the surface. The upper frequency limit mainly depends upon the measurement distance, as expected from the theory given in Section 2. Furthermore, the level differences in the low frequency region are probably caused by the absence of an infinite baffle around the circular piston in the current experimental setup. Notably, a linear decay of 4 dB per centimetre is found below 1 kHz in the first 5 centimetres for this particular piston source.

4.2 Sound visualisation around a rigid structure

The normal particle velocity perceived around a static rigid piston is evaluated in this section to provide an impression of the influence of background noise on particle velocity measurements. The device shown in Figure 1 was fixed whilst a set of loudspeakers randomly distributed across the testing room were driven with uncorrelated white noise signals. Point-by-point measurements were taken at 90 different positions in the vicinity of the piston, with a spatial resolution of 0.01 m, keeping the orientation of the particle velocity sensor parallel to the piston axis. Figure 3 presents the results found for different frequency bands.

As shown, the particle velocity level generally decreases when the sensor is positioned close to the aluminium plate. It should be noted that the noise level is generally reduced by more than 10 dB when the

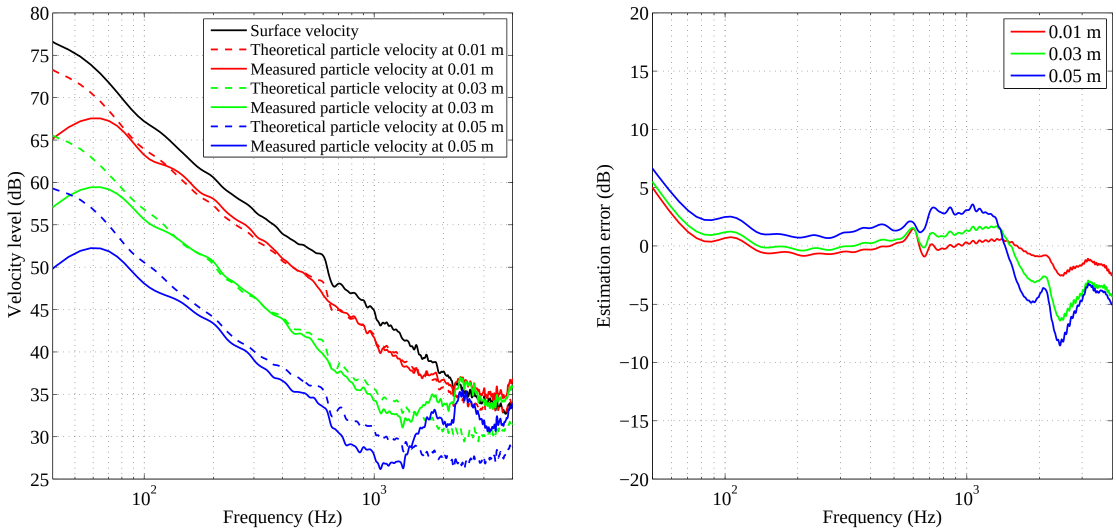

Figure 2 – Comparison of calculated and measured velocity levels using an accelerometer and a particle velocity sensor (left); level difference between calculated and measured surface velocity(right).

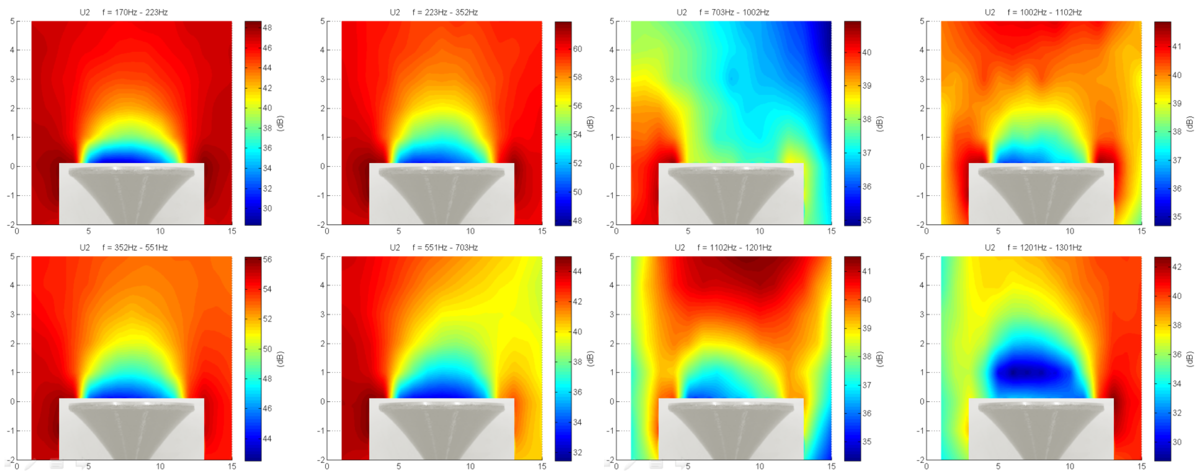

Figure 3 – Acoustic particle velocity perceived around a rigid piston in the presence of background noise.

measurements are performed close to the rigid surface. In the frequency range evaluated, only the sound map of 700 Hz to 1 kHz displays a different behaviour, probably caused by the non-anechoic testing room and the limited amount of loudspeakers used in the test to simulate diffuse field conditions.

4.3 Background noise reduction

Industrial machinery is often surrounded by other devices which cannot be removed or silenced during the acoustic test. In such conditions, the signal-to-noise ratio is greatly reduced, as is the quality of the experimental data. It is then desirable to minimise the influence of background noise in order to avoid errors in non-contact vibration measurements.

Background noise is normally quantified by the amount of sound pressure, and it is therefore convenient to compare its level to the particle velocity acquired at the same location. The level difference between both quantities describes how noise is perceived by the two different sensors. The term “noise reduction” is introduced to denote that level difference, i.e.

$$NR = 20\log_{10}\left(\frac{|p|}{p_{\text{ref}}}\right) - 20\log_{10}\left(\frac{|u_n|}{u_{\text{ref}}}\right) \tag{10}$$

where $p_{\text{ref}} = 20\,\mu\text{Pa}$ and $u_{\text{ref}} = 50\,\text{nm/s}$. The above expression has been evaluated experimentally using not only the piston shown in Figure1, but also a rigid object of larger dimensions, such as a 0.3 m x 0.3 m wooden plate of with a thickness of 20 mm. Ten sound pressure and normal particle velocity measurements were taken along the central axis of each structure at distances between 5mm and 50mm. The results of this test are shown in Figure 4. The figure shows the noise reduction level for both cases, plotting the third octave noise reduction spectra for each measurement case with a solid line. As can be seen, the noise reduction achieved with particle velocity sensors progressively increases as the sensor is positioned closer to the rigid element. Notably, a stronger frequency dependency is shown in the case of the rigid wooden plate due to the larger dimensions of the studied object, which introduces an additional noise reduction at low frequencies.

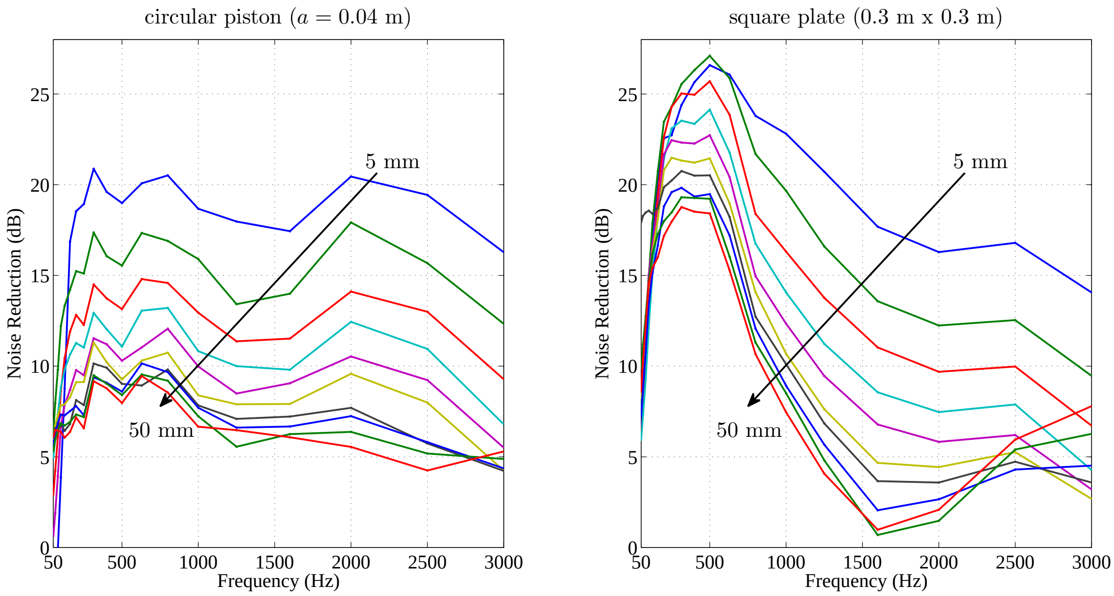

Figure 4 – Noise reduction in front of a rigid circular piston (left) and square wooden plate (right).

In addition, the broadband levels [1] of noise reduction are shown in Table 1 along with the normalised levels of sound pressure and particle velocity . The signals from both transducers have been normalised by the sound pressure acquired at 5 mm from the static rigid piston in order to capture the relative change between different measurement positions.

Table 1 – Normalized sound pressure, normal particle velocity levels and noise reduction level achieved with a particle velocity transducer (dB).

	5 mm	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm	50 mm
NR	19.5	16.3	13.5	12	10.6	9.8	8.8	8.1	7.9	7.5
p	0	- 0.2	-0.1	- 0.1	-0.3	-0.2	-0.3	- 0.4	-0.1	-0.2
u_n	- 19.5	- 16.5	-13.6	-12.1	-10.9	-10	-9.1	-8.5	-8	-7.7

The results presented in the table show that the sound pressure level remains fairly constant, independently of position, whereas the particle velocity level varies strongly. As expected, the noise reduction achieved with particle velocity transducers is more significant when the sensor is placed closer to the rigid surface. In practice, even with a 10 dB noise level above the sound radiated by the machine under assessment, particle velocity measurements performed in the near field can achieve a good signal to noise ratio in such conditions.

5. CONCLUSIONS

Non-contact vibration theory has been reviewed, accounting for background noise during the measurement process and quantifying the noise reduction achieved using particle velocity sensors. The results presented demonstrate that the particle velocity level caused by a set of randomly distributed sound sources significantly decreases in the vicinity of a radiating surface. This key characteristic allows for the characterisation of the vibro-acoustic behaviour of a machine in spite of the presence of high sound pressure levels caused by external sources. Further investigation should be undertaken to assess the noise reduction achieved for complex geometry and non-reflective surface materials.

[1] The frequency range evaluated matches the range of interest, i.e. between 50 Hz and 3 kHz

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