Near Source Acoustical Particle Velocity Measurements with Ambient Noise

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Abstract

An acoustical measurement very near a structure can be a cheap alternative to other contactless vibration measurement techniques such as laser vibrometry. However, measurements of the acoustical pressure suffer greatly from ambient noise, making these measurements unsuitable for many industrial applications. De Bree and Druyvesteyn suggested that a measurement of the acoustical particle velocity does not have this drawback and provided theory and qualitative measurement results [1].

We present quantitative measurement results of the relative noise contribution in pressure and particle velocity measurements. The ratio of these quantities receives special attention. The model used in previous research is a lumped model, in which some important aspects are neglected. We present results of a numerical model of the vibrating structure and the air. The numerical model and the measurements indicate the same trends but the lumped model does not describe the trends well. Nevertheless, this study also suggests that the sensitivity to background noise is generally considerably greater in pressure measurement than in a particle velocity measurement.

1 Introduction

We aim to make a comparison between the sensitivity to background noise of pressure and particle velocity measurements near the surface of a structure. An illustration for a simple 1D example is given in figure 1. The signal is defined as the pressure or particle velocity in the absence of ambient noise. In figure 1(a), the signal level is constant. The noise on the other hand is defined as the pressure and particle velocity caused by the background noise in the absence of structural vibration. As can be seen in figure 1(b), the noise level of the particle velocity tends to zero near the structure surface in this simple case but the pressure attains a maximum. By the superposition principle, a measurement of acoustical particle velocity in the presence of noise is equal to the sum of signal and noise. In this simple example, a particle velocity measurement is clearly superior to a pressure measurement.

The structural response to the ambient noise is neglected in figure 1 but in the rest of this paper, we take into account a two way structural-acoustic coupling. Due to the structural response to the ambient noise, the acoustical domain is excited which is measured with acoustical sensors. Since this component of the measurement is not present in the absence of ambient noise, it is classified as noise. Hence, even measurements of a laser vibrometer are classified to have a finite signal to noise (S/N) ratio according to definitions. Finally, we assume that sensor noise is negligible compared to the effects of ambient (acoustical) noise.

![Figure 1: Acoustical response to a vibrating structure and an incoming acoustical wave.](image-url)
A mathematical description of the trends described above can be made in the frequency domain. First, we denote the S/N ratios of the two measurements as follows:

$$\gamma_p = \frac{p_S}{p_N} \quad \text{and} \quad \gamma_v = \frac{v_S}{v_N}$$

Where $p$ and $v$ denote pressure and velocity and the indices $S$ and $N$ stand for signal and noise respectively. $\gamma_p$ and $\gamma_v$ are the S/N ratios of pressure and particle velocity respectively. In order to compare these S/N ratios, the ratio of $\gamma_v$ and $\gamma_p$ is used. It is a measure for the quality of a particle velocity measurement relative to that of a pressure measurement. Rewriting this ratio:

$$R_Z = \frac{\gamma_v}{\gamma_p} = \frac{v_S}{v_N} \cdot \frac{p_N}{p_S} = \frac{Z_N}{Z_S} \quad \text{with} \quad Z_N = \frac{p_N}{v_N} \quad ; \quad Z_S = \frac{p_S}{v_S}$$

Hence, $R_Z$ is named the impedance ratio. Since $Z_N$ and $Z_S$ are both independent of the amplitude of structural vibration and the level of background noise, so is $R_Z$. This means that a comparison can be made independent of these two properties.

All of the above is presented implicitly or explicitly in the work of de Bree and Druyvesteyn [1]. Their physical model is based on a lumped (1 degree of freedom) approach for both structural vibration and for the acoustical response. Two important aspects are not taken into account. First, the lumped mechanical model only represents the lowest eigenfrequency accurately whereas the frequency band of interest includes many eigenfrequencies. Second, the distance between the location of measurement and the surface is set to zero in their acoustical model but the freedom of positioning the sensor at any distance from the surface is exactly the difference between an acoustical particle velocity measurement and a laser vibrometer measurement.

Our main aim is to perform a study with respect to the sensitivity to background noise of pressure and particle velocity sensors in a case which is representative of technical products. A physical model will be presented that describes several aspects of this problem. Since this model is, inevitably, a simplification of reality, it will be validated with experiments. Also, some specific aspects are discussed in detail: attention will be paid to the impact of complex dynamical behavior of the structure on the sensitivity to background noise and the influence of the distance between the sensor and the surface.

In section 2 a numerical model is presented and in section 3 the experimental setup for validation is discussed. In section 4, a comparison between model and measurements is given. The model is validated and both numerical and measurement results are studied. Finally, conclusions and recommendations are presented in section 5.

## 2 Physical model

In this section, a physical model for calculation of the impedance ratio is presented. The following requirements are set for this model.

- The structure has complex modal behavior
- The acoustical model is a 3D model in an infinite domain.
- There exists a two-way coupling between structural and acoustic behavior.
- The location of the virtual sensor can be varied.

The structure that is used is a clamped rectangular aluminium plate with dimensions 160×210×1.1 mm. The plate is modeled inside an infinite baffle: a rigid planar surface that does not vibrate (see figure 2). The plate is modeled to radiate sound freely in an infinite domain limited only by the baffle. The noise source is modeled as a monopole placed 0.6m from the structure surface.

### 2.1 Structural model

The structure is excited by an internal excitation (signal) and ambient noise. The structural model is only used to calculate the structural response to ambient noise. The response to the internal excitation is not modeled because it will be excited by an acoustical load on the rear side of the plate in the experiments. Instead of modeling this
complex load case, a laser vibrometer is used to measure the structural velocity on the surface on a grid of points. These structural vibrations are then used as input for the acoustical model.

The structural model is a finite element (FE) model of 20 × 20 linear quadrilateral shell elements (see figure 3(a)). In order to reduce the computational time, modal reduction is applied using 22 structural mode shapes and no residual modes. The model has been found to be accurate within 1% in a frequency range of 0–2000Hz.

2.2 Acoustical model

The following acoustical phenomena are modeled (see figure 3(b)):

1. 'signal', generated by the structural vibration due to internal excitation
2. ambient noise in free space
3. noise generated by the structural vibration due to ambient noise
4. the reflection of ambient noise on a uniformly reflecting surface (baffle)

These phenomena do not constitute a full structural-acoustic coupling model because the structural excitation due to item 3 is not taken into account. Some preliminary tests indicate that the error is negligible with respect to other (numerical) errors.

The acoustical models for items 2 and 4 result in simple analytical equations. They are the acoustical response to a monopole source in free space and its mirror source respectively. The acoustical model for items 1 and 3 include the response to structural vibration. In this case, the structural vibrations serve as input for an acoustical model based on a discretization of the Rayleigh integral: an integral equation which describes the acoustical response due to a vibrating structure in an infinite baffle. The equation is given in equation 3 and the discretization we use is given
in equation 4.

\[ p(\vec{x}) = \int_{A} K(\|\vec{x} - \vec{y}\|) \, v_n(\vec{y}) \, d\vec{y} \quad (3) \]

\[ \approx \sum_{i=1}^{N} S_i \, K(\|\vec{x} - \vec{y}_i\|) \, v_n(\vec{y}_i) \quad (4) \]

Where \( \vec{x} \), \( \vec{y} \) and \( A \) denote the source point, the location of the measurement and the surface area respectively. \( K \) is a kernel function that is known analytically [3]. In equation 4 \( N \), \( S_i \) and \( \vec{y}_i \) are the number of elements, the area of element \( i \) and the center point of element \( i \) respectively. Finally, equations 3 and 4 also hold for the measured particle velocity in some direction, but with a different kernel function [2].

In order to make the transfer from the structural mesh to the acoustical mesh simpler, the acoustical elements are chosen to coincide with the structural elements (see figure 3(c)). This means that normal velocity on an acoustical integration point – located on the center of an element – is the mean of the responses of the structural nodes – located at the four corners of the element.

The acoustical model has been found to be accurate within 1% in a frequency range of 0–2000Hz for both pressure and particle velocity if the distance of the virtual sensor to the structure surface is at least 10 mm.

### 2.3 Summary

Finally, the steps involved in calculating the impedance ratio are summarized. The following steps are performed to calculate the signal and noise components of pressure and particle velocity measurements.

- **Signal**
  - Measure the structural vibration caused by the internal excitation
  - Calculate the acoustical response based on the structural vibration (item 1)

- **Noise**
  - Calculate the acoustical response of the noise source in free space (item 2)
  - Calculate the structural vibration caused by the noise source
  - Calculate the acoustical response based on the structural vibration (item 3)
  - Calculate the acoustical response of the mirror source in free space (item 4)

This leads to the quantities \( p_S, p_N, v_S \) and \( v_N \). Equation 2 is then used to calculate the impedance ratio. Note that a unit excitation can be used for both the internal excitation and the ambient noise because the magnitudes have no impact on the impedance ratio.

### 3 Experiments

#### 3.1 Measurement strategy

The impedance ratio can not be measured directly. Instead, the four physical quantities \( p_S, p_N, v_S \) and \( v_N \) are determined in separate experiments and the impedance ratio is calculated using equation 2. Two important aspects in our research are (first) the impact of complex dynamical behavior on the sensitivity to background noise and (second) the impact of the sensor location on this sensitivity.

The impact of complex dynamical behavior will influence the four quantities \( p_S, p_N, v_S \) and \( v_N \). This impact will receive attention in section 4. In order to study the second aspect, measurements are performed at a number of distances between 1 and 30 mm from the surface.
3.2 Experimental setup

An overview of the experimental setup is given in figure 4. The following elements are present.

- An ambient noise source, represented by a loudspeaker in a wooden box with a nozzle of 10 mm (see figure 5(a)). It is placed directly above the noise source, 1m from the structure surface.

- A vibrating plate: an aluminium plate with dimensions $160 \times 210 \times 1.1$ mm. An aluminium frame thickness 5mm is used to bolt this plate thoroughly to a very stiff aluminum box (see figure 5(b)). The plate is excited by an acoustic field inside the box, generated by a loudspeaker. The box has outer dimensions of $300 \times 220 \times 170$ mm. One side consists of the thin plate and the other sides have a thickness of 30 mm.

- A sensor that measures particle velocity and pressure. The sensor used is of type ultimate sound probe produced by Microflown technologies (see figure 5(c)). It consists of three Microflown sensors to measure the acoustical particle velocity in three directions and a microphone to measure the acoustical pressure. One of the three Microflown sensors is used to measure the particle velocity normal to the surface, and the microphone is used to measure the acoustical pressure.

- A semi-anechoic chamber with dimensions $3.5 \times 3.5 \times 2$ m.

- A reference microphone, which is a Pressure-field 1/2” Microphone type 4192 produced by Brueil&Kjaer.

4 Comparison

In this section, a comparison between measurements and experiments is given. The acoustical response to the internal excitation is studied first (see figure 6). From a physical point of view, it can be seen in the frequency
response function (frf) that the pressure and particle velocity show maxima on the same frequencies. This is analogous to the 1D case where the pressure and particle velocity due to structural vibration are both proportional to the level of structural vibration. The frequency and amplitude of the resonance peaks are captured very accurately in the numerical model, which indicates that the acoustical model is accurate. Please note that laser vibrometer results are used for the structural vibration in this load case.

In figure 7, the pressure and particle velocity are plotted as a function of the distance to the source. Although the exact slope decrease is determined by the shape of vibration of the surface, it can be seen clearly that both the pressure and the particle velocity can decrease as much as 10 dB in a few centimeters. The numerical model and the measurements are in good agreement.

Next, the ‘noise’ component of the measurement is studied (see figure 8). The numerical model and the experimental results indicate similar trends: off resonance, both the model and the experiment indicate a dramatic decrease in the particle velocity near the structure surface. Please note that this also means that by increasing the distance to the structure surface, the sensitivity to background noise in particle velocity measurements increases strongly. A minimum for the pressure is found near a quarter wavelength. On the first resonance frequency of the structure (see figure 9), both the model and the experiments indicate that the particle velocity achieves a maximum near the structure surface. This is caused by a strong vibration of the structure surface due to ambient noise. The second and third modes do not demonstrate this behavior. This is presumably caused by two phenomena. Firstly, the excitation by the noise source is very small because these modes have zero volumetric displacements. Secondly, a vibration in this mode will have a very small impact on the particle velocity sensors because the measurement location is also on a nodal line for these modes.

Finally, the impedance ratios are compared. In general, the exact value of the impedance ratio is very sensitive to sensor noise. Over the entire frequency range, the model and the experiment have the same trends, but the values tend to correspond only in order of magnitude. A few results are given in figure 10. The impedance ratio
close to the surface tends to a value above 10 for most off-resonance frequencies: also those not shown here. On the eigenfrequency of 308.75 Hz, impedance ratios of 1 and 2 are found for the model and the experiment respectively. Presumably, the vibration of the structure surface itself is almost as sensitive to background noise as
a pressure measurement. The prediction by de Bree and Druyvesteyn is also plotted in the figures. Please note that their prediction was derived for the structure surface only. It is plotted as a constant for reasons of readability. The experimental and calculated impedance ratios vary strongly with the frequency due to the complex dynamical behavior. The impedance prediction by de Bree and Druyvesteyn is a very smooth function. Hence, it is concluded that the trends are not predicted well.

5 Conclusions and Recommendations

5.1 Conclusions

- The impact of background noise on contactless vibration measurements very close to the structure surface is found to be considerably smaller for particle velocity measurements than for pressure measurements, unless the frequency is very close to certain structural eigenfrequencies.
- The value of the impedance ratio depends strongly on the dynamical behavior of the system. On eigenfrequencies of the system, the vibration of the structure itself can be very sensitive to background noise. Hence, so are techniques to measure this vibration.
- Off resonance, the impedance ratio decreases rapidly as the distance to the structure surface increases. In the 1D model, particle velocity measurements and pressure measurements are equally sensitive to background noise at a distance of an eighth wavelength.
- Due to the strong impact of complex dynamical behavior on the impedance ratio, the analytical model of de Bree and Druyvesteyn does not capture the trends in the impedance ratio accurately.

5.2 Recommendations

- More accurate measurements and models are necessary for a quantitative match between experimental and theoretical results.
- The impact of the dimensions of the structure on the sensitivity to background noise requires further study.
- When a single (stationary) noise source is dominant, it is sometimes possible to obtain sensor information fully correlated to that source. Since the vibration of the structure is uncorrelated to the noise source, a large portion of the noise can be eliminated with simple signal processing strategies. This may even eliminate part of the inaccuracy found very near the eigenfrequencies.

References

