NON-CONTACTING ACOUSTIC DISPLACEMENT SENSOR

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ABSTRACT

Most vibration transducers are sufficiently massive to induce significant changes in the system response of lightweight structures. This is not the case for non-contacting transducers. The system described herein offers a potential low cost solution for measurements of large amplitude, low frequency vibrations.

SOMMAIRE

La plupart de transmitteurs de vibration sont suffisament massive q'ils induisent des changements signifatives dans la réponse des structures poids-lègeres. Ceci n'est pas le cas pour les transmitteurs non-contactant. La système décrit ici offert une solution avec potentiel de coût raisonable pour des mesures de vibrations de grande amplitude et frequence bas.

NOMENCLATURE

k	wavenumber (m^{-1})	$\overline{\mathbf{Y}}^*$	time averaged image source position (m)
m_o	mass of vibrating object (kg)	α	reflection co-efficient
m_{ex}	mass of accelerometer (kg)	K	spring constant (kg/sec^2)
$\mathbf{X}$	observer position (m)	μ	damping constant (kg/sec)
$\mathbf{Y}$	source position (m)	ω	radian frequency (sec^{-1})
$\mathbf{Y}^*$	image source position (m)		

INTRODUCTION

In certain applications measurements of vibrating systems are complicated by the additional mass of accelerometers. In some instances, lightweight devices can be used; however, as figure 1 suggests, there appears to be a direct correlation between accelerometer weight and sensitivity [1]. Thus there is little hope of sensing small accelerations of lightweight structures with conventional accelerometers.

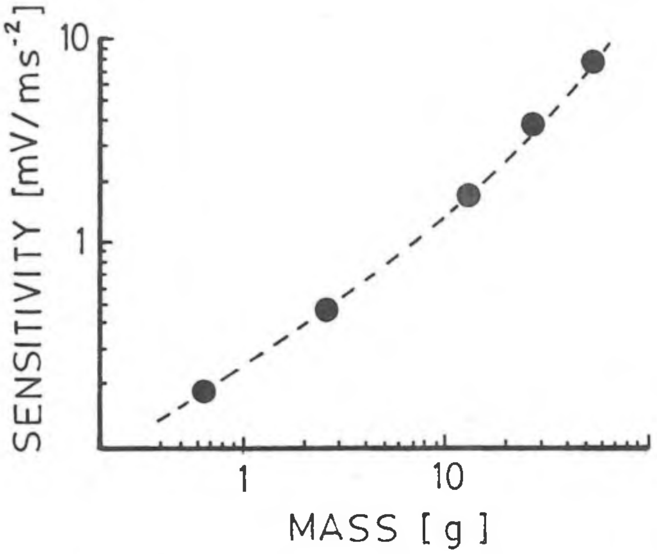

Figure 1. Voltage Sensitivity vs Weight for a Family of Accelerometers.

One can estimate the influence of the added mass by considering a lightly damped spring mass system. Addition of an external mass m_{ex} in the form of an accelerometer results in a change of the resonant frequency (ω_R) as well as the damping co-efficient (ξ):

$$\omega_R \approx \sqrt{\frac{K}{m_e + m_{ex}}} = \sqrt{\frac{K}{m_0}}\,\frac{1}{\sqrt{1 + m_{ex}/m_0}} = \frac{\omega_o}{(1+m_{ex}/m_0)^{.5}} \qquad [1]$$

$$\xi = \xi_o \sqrt{1+m_{ex}/m_0} \quad ; \quad \xi_o = \mu \sqrt{m_0/K}$$

In multi-degree of freedom and distributed systems there is also a change in the modal structure.

To avoid the possibility of "transducer loading" a non-contacting transducer ought to be employed. There are several types available, capacitive, inductive and optical. The first two require that the transducer be in close proximity to the vibrating object (typically a few millimeters). In addition a portion of the surface of the object must be metallic. Optical methods either track a reflected beam via a servo mechanism, or use coherent radiation (laser) and decode the doppler shifted reflection. The optical systems possess a wide dynamic range and can be used at considerable distance from the "target"; however they are rather expensive.

The system described herein is a low-cost noncontacting displacement sensor. It was designed to meet a requirement of the Aircushion Technology group at the University of Toronto Institute for Aerospace Studies (UTIAS). The prototype was built while the author was at UTIAS and all the test data reported here were taken in the aeroacoustic laboratory there [2]. The principal objective was to devise a low-cost transducer capable of measuring large amplitude (50 mm), low frequency (10Hz) motions of a scale model aircushion vehicle skirt. The theoretical background and initial testing are described below.

Theoretical Considerations

It is well known that the frequency of sound heard by an observer is governed by the frequency emitted by the sound source and the relative motion of the source and observer. Consider for example an observer at **X** and a source at **Y** (Fig. 2). An infinite, hard boundary reflects some of the sound back to the observer. The reflection is modelled by placing an image source behind the boundary which now is completely transparent.

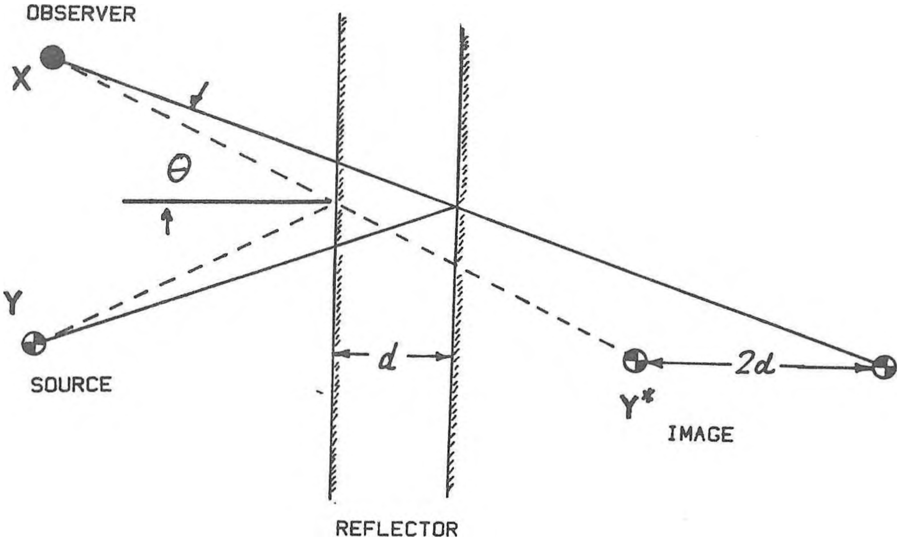

Figure 2. Idealized Configuration for Non-contacting Displacement Transducer.

A change in position of the barrier induces a change in the location of the image source. Let the source radiate a single pure tone, then the observer detects two signals, the direct wave (P_D) and the reflected wave (P_R).

$$
\begin{aligned}
P(X,t) &= P_D(X,t) + P_R(X,t) \qquad [2] \\
&= P_D \cos\omega t \left\{ \frac{\cos k|X-Y|}{|X-Y|} + \alpha \frac{\cos k|X-Y^*|}{|X-Y^*|} \right\} \\
&\quad + P_D \sin\omega t \left\{ \frac{\sin k|X-Y|}{|X-Y|} + \alpha \frac{\sin k|X-Y^*|}{|X-Y^*|} \right\}
\end{aligned}
$$

If the amplitude of vibration of the boundary (target) is small with respect to the average distances and the wavelength,

$$p \approx P_D \cos\omega t \left\{ \frac{\cos k|X-Y|}{|X-Y|} + \alpha \frac{\cos k|X-\overline{Y^*}|}{|X-\overline{Y^*}|} - \alpha\, d(t)\, \frac{k\cos\theta}{|X-\overline{Y^*}|} \sin k|X-\overline{Y^*}| \right\} + P_D \sin\omega t \left\{ \frac{\sin k|X-Y|}{|X-Y|} + \alpha \frac{\sin k|X-\overline{Y^*}|}{|X-\overline{Y^*}|} + \alpha\, d(t)\, \frac{k\cos\theta}{|X-\overline{Y^*}|} \cos k|X-\overline{Y^*}| \right\} \qquad [3]$$

follows. The detected signal contains both in-phase (cos ωt) and quadrature (sin ωt) components with a mean and time-varying amplitude. The variations (to first order) are linear with respect to the displacement of the target with respect to its average position.

The displacement sensitivities are

$\alpha \dfrac{k\cos\theta}{|X-\overline{Y^*}|} \sin k|X-\overline{Y^*}|$ [in phase] and $\alpha \dfrac{k\cos\theta}{|X-\overline{Y^*}|} \cos k|X-\overline{Y^*}|$ [quadrature]

respectively. All quantities are known are easily measured providing one with all the necessary information. A lock-in amplifier can be used to detect the in-phase and quadrature components. The DC or average component can be removed electronically resulting in a time-varying signal directly proportional to displacement.

Prototype Testing

A prototype system was assembled from stock components. The sound source, a tweeter, and the receiver, a Bruel and Kjaer 4135 ¼" microphone - 2618 preamplifier combination, were mounted side by side and aimed at a 20 cm x 10 cm aluminum target, instrumented with a Bruel and Kjaer 4381 accelerometer. The target was driven by a Goodmann's vibration generator. A PAR 126 lock-in amplifier served as a phasedetector and two independent oscillators provided signals to the vibration generator and the loudspeaker (Fig. 3). Although the capital cost of the equipment used is considerable, low priced alternatives may be used.

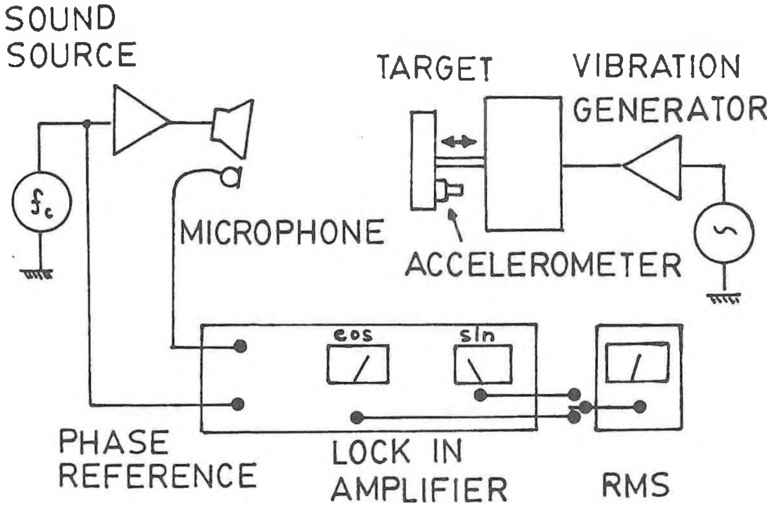

Figure 3. Prototype and Test Arrangement.

There is no need for a high performance microphone, as only relative measurements are made. An inexpensive phase-locked loop can be configured into a lock-in amplifier [3], the oscillator required to drive the loud-speaker being part of the phase-locked loop. Signal conditioning of the lock-in output is achieved via operational amplifiers driving suitable outputs. Surprisingly the prototype system worked quite well. This is illustrated by the comparison of several vibration spectra measured with the accelerometer and the remote displacement transducer, (Fig. 4). The agreement is good.

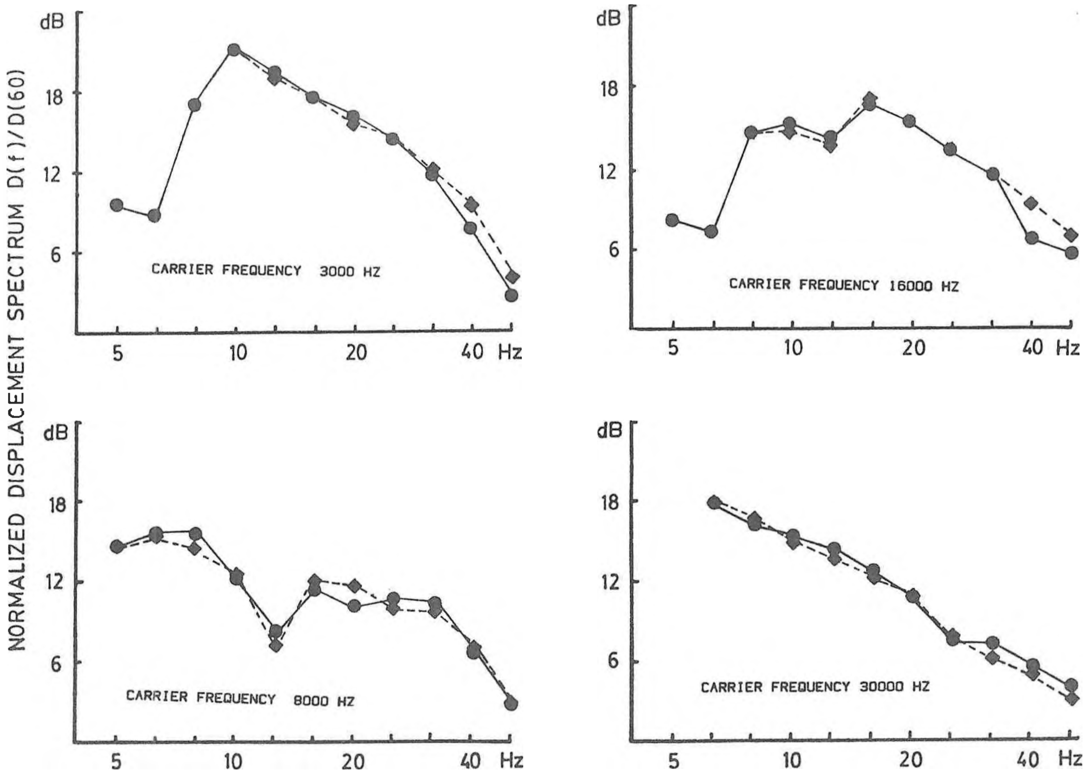

Figure 4. Comparison of Displacement Spectra Measured with i) noncontacting System ● ii) derived from accelerometer data ◆ .

One feauture of the system is the ability to cater to different measurement requirements. Small displacements can be examined by illuminating the target with a high frequency beam. Large amplitudes can be measured if low frequencies are used. In this instance the relative large wavelength of sound is an advantage.

CONCLUDING REMARKS

At the present time, precise calibration requires a number of subtle tests that may prove cumbersome to the novice. However, once the user is aware of the operating principle, the instrument can be used confidently as a remote displacement transducer.

ACKNOWLEDGEMENT

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