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LOW-FREQUENCY MEASUREMENT OF LEAKAGE IN ENCLOSURES

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ABSTRACT

A wide variety of enclosed structures either require or cannot entirely prevent leakage from their interior space to the outside. Existing methods for measuring such leakage have important disadvantages. We have developed a device and technique that permits leakage areas to be measured from within or without the enclosure without causing unacceptable disturbance. The apparatus uses low-frequency (1 Hz) acoustic monopoles to generate an internal pressure signal which is then analyzed syncronously to provide a measurement of leakage area. We have successfully applied this technique to measuring air tightness in residential houses, and believe it can be easily adapted for use in field, laboratory, or classroom applications. We are currently evaluating why the values we obtained were, on average, 14% lower than those obtained through conventional methods and we are investigating the apparent inability of the device, as presently designed, to measure large leaks.

Physics and Astronomy Classification Scheme indexing codes: 06, 44, 47, 66

INTRODUCTION

Whether leakage pathways from the interior to the exterior of a structure or enclosure are an intentional or unavoidable design feature, it is quite often of critical importance that leakage be detected and/or accurately measured. Leakage *detection* is particularly important in UHV systems or gas pipelines where it is somewhat complicated by the presence of separate regions of substantially different pressures, and the demand that all leakage sites above a specified threshold be localized. Many leakage detection methods exist[1] and will not be addressed further. Leakage *measurement*, on the other hand, is important when the pressure differences are relatively low and the leaks are either unavoidable (e.g. the shell of a house), or desirable (e.g., an acoustic enclosure). In these cases, localizing leakage sites is less critical than quantifying the total leakage.

Among the many methods that exist for measuring leakage, the most straightforward is to pressurize the structure (e.g. a house) by forcing more of the surrounding air into it, and then analyze the resultant pressure vs. flow data. In many circumstances, however, this technique has serious disadvantages: 1) it requires a net fluid flow into (or out of) the enclosure, 2) results may not be seriously degraded by noise, and 3) fluid compressibility may lead to systematic errors. Our purpose here is to describe a method and a device designed to minimize these problems by using an oscillatory forcing function to perturb the system and synchronous demodulation to determine the total leakage. A prototype device was constructed in our laboratory and used to determine the air tightness of houses. Preliminary results suggest that the instrument described here can be used as a sensitive probe for studying the physics of air flow through building envelopes.

INSTRUMENTATION

There are three essential components to the instrument: the drive module, the pressure module, and the analysis/control module. The *drive module* is responsible for generating an oscillatory change in the volume of the enclosure.[a] The *pressure module* is responsible for measuring the instantaneous internal pressure change. (Depending on the pressure ranges involved, this measurement can be done with either an absolute pressure transducer or a differential transducer that uses a physical filter to provide the average internal pressure as a reference.) The *analysis/control module* is responsible for controlling the drive mechanism and calculating the leakage area from the drive and pressure signals.

Figure 1 is a sketch of a typical setup in which the apparatus is mounted within of the envelope of the enclosure and all analysis and control elements are external to the enclosure. This configuration, especially useful for test chambers and classroom applications, does require mounting the drive component in the envelope.

Figure 2 is a sketch of a typical setup in which *all* components are inside the envelope of the enclosure. A sealed back-volume is used for the drive mechanism. Depending upon the relative size of the enclosure, the pressure range of interest, and power requirements, use of this technique may be limited.

The analysis/control module either controls or measures the instantaneous displacement of the drive and measures the pressure response in the enclosure. In the analysis section, continuity of compressible fluids is combined with phase sensitive detection (which is used to extract the signal at a specific frequency) to reduce the data.

ANALYSIS

For a compressible medium, the flow (leakage) through the envelope must be determined from the continuity equation:

$$Q + \dot{V} + c\,\dot{P} = 0 \tag{1}$$

As it stands, this expression poses difficulties for estimating the instantaneous flow, Q, because of (1) the uncertainties in the capacity of the enclosure, c, and (2) the noise associated with taking the time-derivative of pressure. To increase the signal-to-noise ratio and eliminate the term involving the capacity, we employ an oscillatory drive and ***phase-sensitive detection***[2] (i.e. synchronous demodulation) in a quasi-stationary regime (i.e., well below any leak or enclosure resonances). We then multiply the continuity equation [Equation (1)] through by the pressure and average over a whole number of cycles:

$$\left\{ Q \;\; \Delta P \right\}_{ave} + \left\{ \dot{V} \;\; \Delta P \right\}_{ave} + \left\{ c \; \dot{P} \;\; \Delta P \right\}_{ave} = 0 \tag{2}$$

The assumption of a quasi-stationary regime allows us to simplify Equation (2). Because we are below any resonances, the capacity can be assumed to be a (real) slowly-varying function and taken out of the expression:

$$\left\{ c \; \dot{P} \; \Delta P \right\}_{ave} = c \left\{ \dot{P} \;\; \Delta P \right\}_{ave} \tag{3.1}$$

Because the cycle average of any periodic quantity and its time-derivative is zero, this term drops out of the expression.

$$\left\{ \dot{P} \;\; \Delta P \right\}_{ave} \rightarrow \left\{ \dot{P} \;\; P \right\}_{ave} \rightarrow 0 \tag{3.2}$$

If the enclosure were assumed to be rigid, the change in enclosure volume would be equal to the applied drive volume and we could replace the $\dot{V}$ term by $\dot{V}_d$ in Equation (1); but real enclosures cannot be assumed to be perfectly rigid. Because of the quasi-stationary assumption, however, any flexing of the enclosure must be in phase with the pressure change[b] — and, therefore, out of phase with the pressure. Thus, the volume of the enclosure can be replaced with the drive volume *in the demodulated term*:

$$\left\{ \dot{V} \;\; \Delta P \right\}_{ave} = \left\{ \dot{V}_d \;\; \Delta P \right\}_{ave} \tag{4}$$

Combining the two previous equations leads to the following expression:

$$\left\{ Q \ \Delta P \right\}_{ave} + \left\{ \dot{V}_d \ \Delta P \right\}_{ave} = 0 \tag{5}$$

By normalizing the first term by the pressure we could, in principle, determine the fluid leakage. This represents the standard kind of *lock-in* technique[3] with the pressure serving as the reference signal. However, we are more interested in finding an invariant characteristic of the leakage than the actual flow. We will therefore redefine the flow as a function of invariant leakage characteristics and of applied pressure. (We assume we are working in a regime in which the fluid flow is quasi-stationary, and thus the flow will always be in phase with the pressure and, no leakage information will be lost by this phase-sensitive analysis.)

From general fluid dynamics[4,5] one can show that a power law equation is adequate to describe the flow function in the quasi-stationary regime:

$$Q = K \ | \ \Delta P \ |^{\,n} \ sign\,(\ \Delta P\ ) \tag{6}$$

The two familiar limits are laminar flow (n=1) and turbulent (orifice) flow (n=1/2). In general the flow exponent will lie between these two physical limits. For convenience we will rewrite the equation using the physical parameter corresponding to the turbulent limit (i.e., the *effective leakage area*):

$$Q = L \sqrt{\frac{2P_r}{\rho}} \left| \frac{\Delta P}{P_r} \right|^{n} sign\,(\ \Delta P\ ) \tag{7}$$

Because we want the equation to be true regardless of the exponent, we are forced to introduce a reference pressure into the definition. The pressure chosen should be characteristic of the pressure range appropriate to the leakage of interest.

If we now combine our expression for the leakage with the demodulated continuity equation, we get the following:

$$L = -\sqrt{\frac{\rho}{2P_r}} \ \frac{\left\{ \dot{V}_d \dfrac{\Delta P}{P_r} \right\}_{ave}}{\left\{ \left| \dfrac{\Delta P}{P_r} \right|^{n+1} \right\}_{ave}} \tag{8}$$

The equation defines a leakage characteristic (L) in terms of the measured data, the reference pressure, and the fluid properties.

SIZING

In designing an instrument for a specific application, one has control over two parameters: the size of the drive volume and the frequency of operation. Several constraints the designer needs to consider, however, are the size of the device, measurement time, magnitude of induced pressure, and accuracy. The practical considerations of physical size and length of time necessary to make a measurement suggest that the device shall be as small as possible, and operate at as high a frequency as possible—subject to the other constraints.

At sufficiently high drive frequencies, the physical process will be dominated by the compression of the fluid; at lower frequencies the process will be dominated by (the desired process of) flow through the envelope. The break-point frequency, which is the dividing line between these two regimes, is a standard concept in electrical engineering analysis of AC circuits.[6] When applied to volume changes in an enclosure, the break-point frequency is the frequency at which the pressure-response asymptotes of the leakage-dominated (low-frequency) regime and the compression-dominated (high-frequency) regime intersect:

$$f_{bp} = \frac{L\sqrt{\frac{2P_r}{\rho}}}{c^n \; V_d^{1-n} \; P_r^n} \tag{9}$$

Because the signal-to-noise ratio decreases as the applied frequency increases from below the break-point frequency, the designer should consider reasonable ranges for the leakage area, capacity[c], and drive volume to ensure that the apparatus will operate below the break-point frequency.

The reference pressure, P_r, is presumably representative of the range of interest of the leakage. To increase the accuracy of the leakage area in the vicinity of the reference pressure by decreasing the sensitivity of the calculation to the leakage exponent, the designer should select the instrument parameters in such a way that the root-mean-square pressure is near the reference pressure (i.e. $Prms \approx P_r$).

PRELIMINARY APPLICATION

Our first application of this device was to measure the air tightness of buildings[7] by a process and device we have called *AC pressurization*. Initial field results[8] have demonstrated the approach and compared it to other methods. Independent work that attempted to use alternating pressures to measure air tightness was done at Syracuse University in 1978.[9] In their efforts, electrical engineering circuit analysis was employed to extract the air tightness, but no accurate field measurement tool was developed.

In our AC pressurization application, the drive-component displacement of 50 liters allowed the device to operate in the 0.1-4.0 Hz frequency range (sufficiently below the 2-10 Hz breakpoint frequency of most houses) and to be small enough for easy installation in a doorway. The device consisted of a 60-cm diameter piston-bellows drive component, a low-frequency microphone, signal-conditioning filters, and a computer for calculating the leakage area as well as compiling intermediate experimental data. The piston-bellows assembly, along with the DC motor and scotch yoke mechanism that drives it, is mounted in a doorway. The stroke of the scotch yoke mechanism could be varied between 4 and 18 cm, allowing the volume drive to be varied between 10 and 50 liters. The frequency of the device could be varied between 0.1 and 4 Hz and was controlled by adjusting the speed of the DC motor. The speed of the piston was monitored with a wire-cable velocity transducer, and the pressure response was monitored with a low-frequency microphone sensitive to 0.01 Pa.

The comparisons in Table 1 show that measurements obtained with our synchronous technique (i.e., AC pressurization) and the conventional technique[10] (taken to be the reference case) agree reasonably well, but that the AC pressurization values are consistently lower (average = 14%) than reference values. Because neither measurement technique is a primary (or secondary) standard, however, which technique is correct cannot be determined without taking independent measurements.

One possible explanation for this discrepancy is that our quasi-stationary assumption breaks down for a certain class of leaks—specifically, those leaks involving large movement of fluids. Because the size distribution of leaks in actual houses is unknown, we devised two additional sets of experiments to test this hypothesis in different houses: one set involved opening fireplace dampers and the second involved opening windows. In the first experiment the leakage area measured by AC pressurization did not change when the damper was opened. In the second test we measured the leakage area of a (62 cm tall) window as it was opened further and further. The result of this test was that the leakage area increased with window opening up to a certain point (6 cm) after which the size of the opening no longer affected the measured leakage area. Although not conclusive, these experiments indicate that the AC pressurization technique as currently implemented cannot accurately measure large leakage areas. Future work will concentrate on refining the accuracy, precision, and operational limits of the instrument.

TABLE 1:
COMPARISON OF LEAKAGE AREAS MEASURED BY AC PRESSURIZATION AND CONVENTIONAL METHODS

House ID	*LEAKAGE AREA (cm^2)* *Conventional*	*AC Press*	*Difference (%)*	*FREQUENCY (Hz)* *Drive*	*Breakpoint*
A	1300	990	24	1.11	2.6
B	1100	930	15	1.03	2.4
C	940	910	3	1.04	3.4
D	700	600	14	0.69	1.4
E	1200	1000	17	1.21	1.9
F	580	520	10	0.62	1.0

NOMENCLATURE

c = *(Effective) capacity of internal volume [m^3/Pa]*

f_{bp} = *Breakpoint frequency [Hz]*

K = *Leakage coefficient [$m^3/s\ Pa^n$]*

L = *Leakage area [m^2]*

n = *Leakage flow exponent [-]*

P = *Internal pressure [Pa]*

ΔP = *Inside-outside pressure difference [Pa]*

P_r = *Reference pressure [Pa]*

$\dot{P}$ = *Time derivative in internal pressure [Pa/s]*

P_{rms} = *The cycle-averaged root mean square pressure [Pa]*

ρ = *Fluid density [kg/m^3]*

Q = *Air Leakage [m^3/s]*

V = *Volume of enclosure [m^3]*

$\dot{V}$ = *Time derivative of enclosure volume [m^3/s]*

V_d = *Displacement of Drive [m^3]*

$\dot{V}_d$ = *Time derivative of drive displacement [m^3/s]*

$\left\{ \cdots \right\}_{ave}$ *Indicates a cycle average of the enclosed quantity*

FOOTNOTES

[a] A sinusoidal drive, although not strictly required for the analysis, somewhat improves the signal-to-noise ratio and may be more instructive in a classroom environment.

[b] In a more general analysis any such quasi-stationary flexing appears as an increase in the capacity term.

[c] The capacity here refers to the total capacity, which may include a component due to the (below resonant) flexing of the enclosure.

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FIGURE 1: Sketch of leakage-measuring apparatus with externally mounted drive component and external analysis and control.

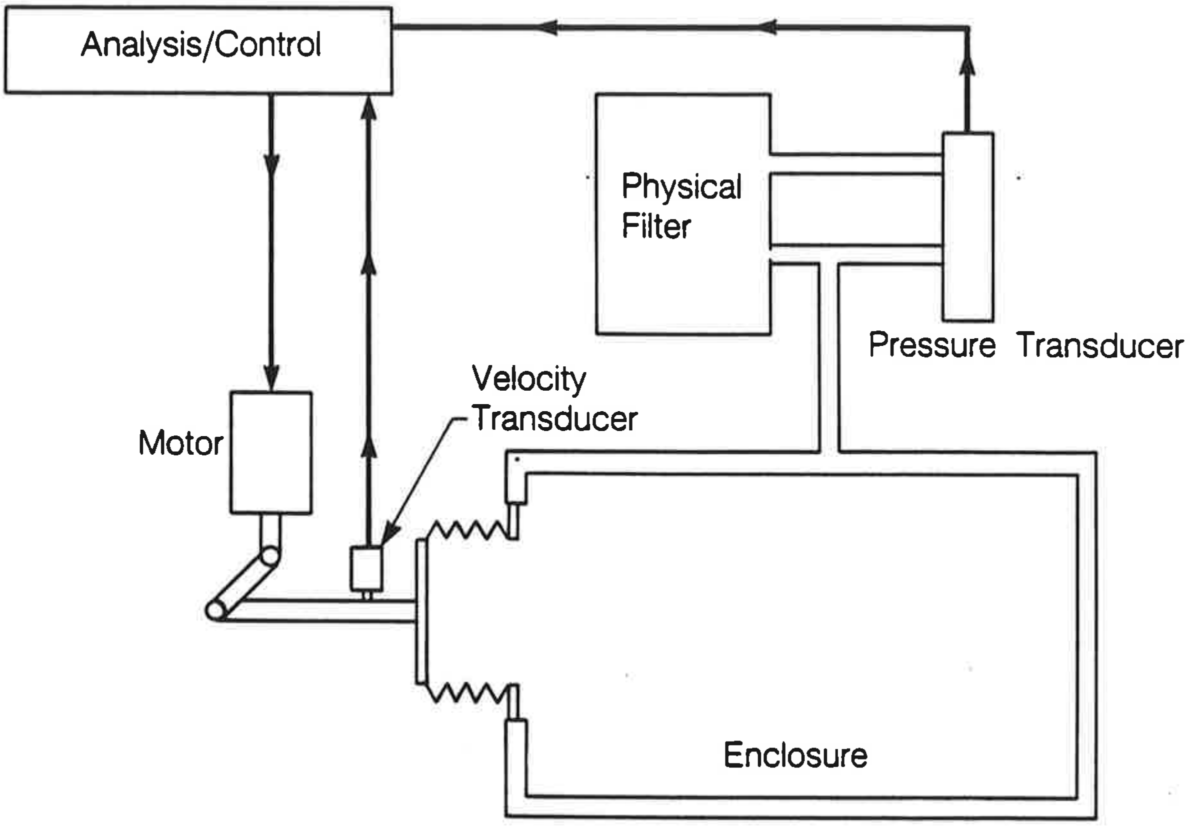

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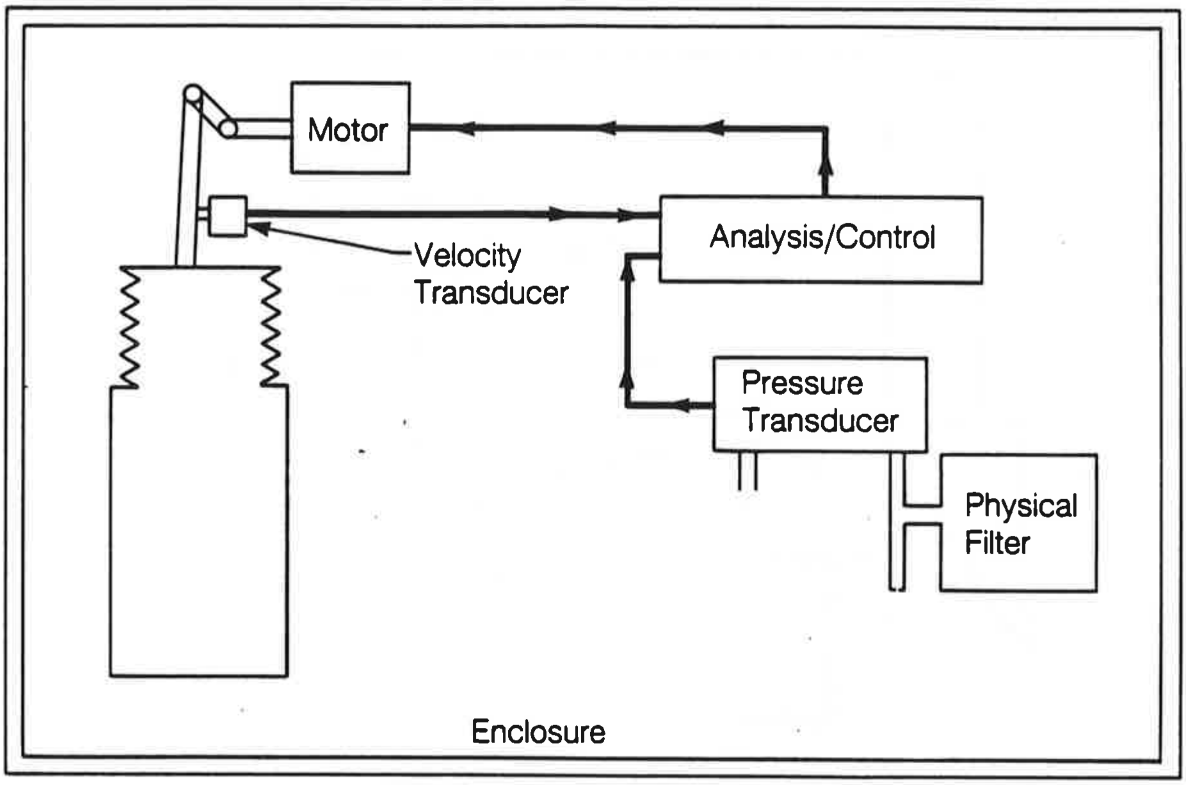
FIGURE 2: Sketch of apparatus with all components internally mounted.



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