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Infrasonic Measurement of Building Air Leakage: A Progress Report

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ABSTRACT: This research compares a new infrasonic method with the conventional blower method for determining the composite effective size of all the air-leakage passages in a house or apartment. In the frequency range used (0.1 to 7 Hz) small buildings are characterized mainly by one acoustic capacitance and one nonlinear leakage resistance. Infrasonic apparatus comprising a motor-driven source having known output, a sensitive pressure pickup, and an electronic signal processor has been constructed and used to measure leakage from several apartments and a house. Under field conditions the results of the infrasonic and blower measurements agree within a factor of two or three. Since the infrasonic system requires no through-the-wall blower vent or pressure taps, it is easier to set up than a blower system.

KEY WORDS: air infiltration, air leakage, building energy use, energy conservation, infrasonics, low-frequency acoustics, measurements

One property of a building that is of great importance in determining the infiltration performance [*1*][4] is the size of the leakage passages (cracks) through the building envelope. The composite effective size of the leakage passages can be determined by using a blower to pressurize (or evacuate) the building while at the same time measuring both flow (cubic metre per second or cubic foot per minute) and inside-outside pressure difference. As an alternative to the blower method, we have been experimenting with an

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[4] The italic numbers in brackets refer to the list of references appended to this paper.

infrasonic method whereby a very low frequency (about one cycle per second) alternating air flow of known magnitude is applied to the interior of the building, and the alternating component of inside pressure that results is measured [*2*]. The pressure response is a function of the type and size of leakage paths. Thus, the object of the research is to compare the efficacy of the new infrasonic method with that of the blower method. It is hoped that a portable easy-to-use measuring instrument for testing small buildings, mainly houses and apartments, will eventually be developed as a consequence of our research.

Apparatus Used

Figure 1 shows a simplified schematic diagram of the apparatus used [*2*]. The infrasonic system comprises a portable source and a pressure sensor that are set up inside the building to be tested. During a test all the inside doors are opened and all the outside doors and windows are closed. There is no through-the-wall vent on the source, and no through-the-wall pressure tap for the pressure sensor.

As can be seen from Fig. 1, the source alternately compresses and rarefies the air above the piston. But it is really the bottom of the piston that performs the useful function since it applies an alternating volumetric air flow to the enclosure (house) under test.

Of course, the space above the piston may be vented to the outside, and

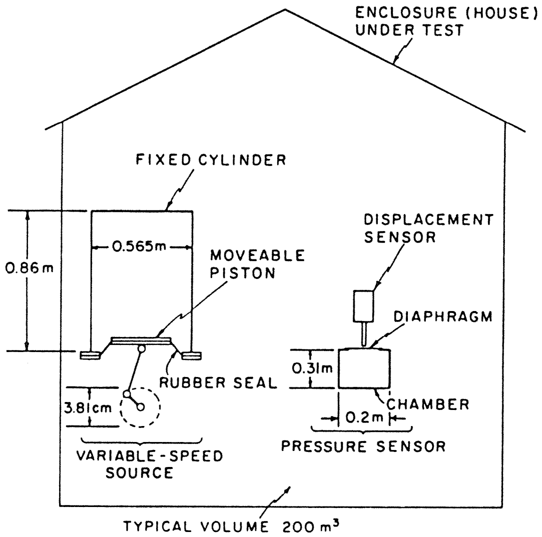


FIG. 1—*Simplified schematic diagram of a system for measuring the infrasonic impedance of a building.*

this would decrease the peak power required to drive the source. But providing a through-the-wall vent on the source would negate one of the important advantages of the infrasonic method, because normally no such connection to the source is required.

Our present apparatus employs a fixed-displacement variable-speed source, since such a source is easier to build than one having variable displacement. As indicated in Fig. 1, the piston has a thin gum-rubber sheet to seal the piston to the cylinder. The 0.457-m-diameter piston has a peak-to-peak displacement of 3.81 cm so that the total piston displacement is approximately 0.00626 m^3. Thus, the source is more like a bellows or diaphragm pump than a conventional piston pump.

Turning now to the pressure sensor, it consists of a rigid chamber 0.203-m diameter by 0.31-m high having a very thin plastic membrane across the 10-cm-diameter opening. As the pressure in the enclosure (house) under test varies because of the source, the plastic membrane is deflected in and out. This deflection is measured using an optical instrument.

The pressure variations that must be detected are very small so that, for example, the pressure sensor must be several hundred times more sensitive than an ordinary household barometer. In fact a resolution of 0.1 to 0.01 Pa is desirable. In order to prevent normal barometric pressure fluctuations from interfering with the measurements, the pressure sensor chamber is provided with a very small slow leak. The slow leak is designed so as not to decrease the sensitivity of the pressure sensor to signals in the frequency range of interest (above 0.01 Hz).

Of course, the pressure sensor chamber could also have been connected to the outside of the enclosure under test so as to eliminate the problems due to barometric pressure fluctuations. But providing a through-the-wall connection for the pressure sensor would negate one of the advantages of the infrasonic system that normally no such pressure taps are required.

The signal from the pressure sensor is processed electronically and fed to a strip chart recorder and indicating voltmeters [*3*]. One of the functions of the electronic system is to attenuate ordinary acoustic noise. To do this the system employs a sharp-cut-off filter that blocks signals above 7.0 Hz.

Figures 2 and 3 show photographs of the apparatus. At the present time part of the pressure sensor electronics is still in breadboard style so as to facilitate further modification.

Theoretical Analysis

Neglecting Compressibility

Ideally the variable-speed reciprocating-piston source provides a sinusoidal volumetric drive on the enclosure (building) under test given by

$$v_s(t) = V_s \sin \omega t \qquad (1)$$

where

V_s = one half of the total piston displacement (cubic metre),
ω = the angular speed of the shaft (radian per second), and
t = the time (seconds).

For a fixed-displacement source V_s is constant. There are, of course, no valves associated with the piston so that the net average volumetric flow is zero. The source is more like a loudspeaker than an ordinary pump or blower.

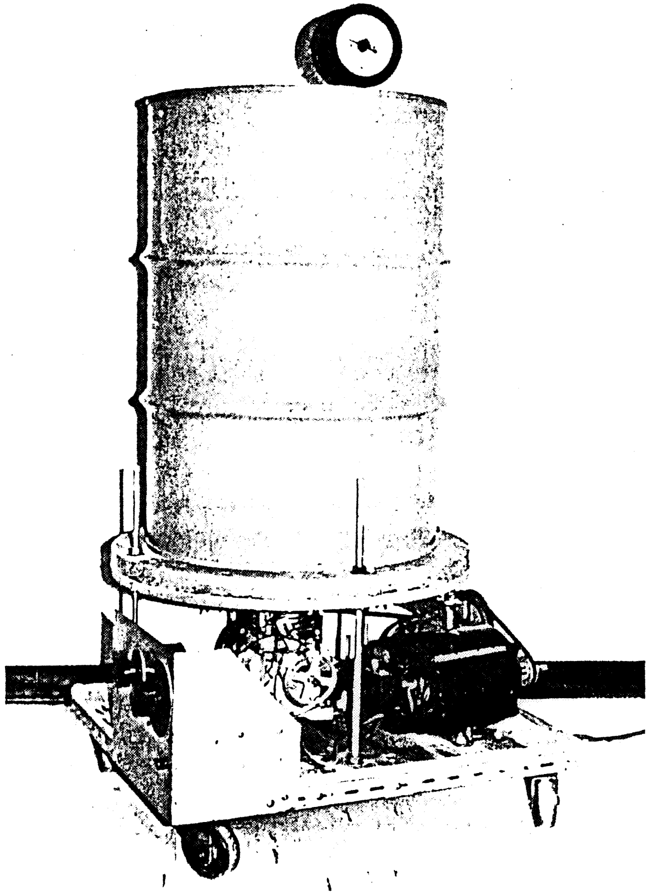


FIG. 2—*Photograph of infrasonic source.*

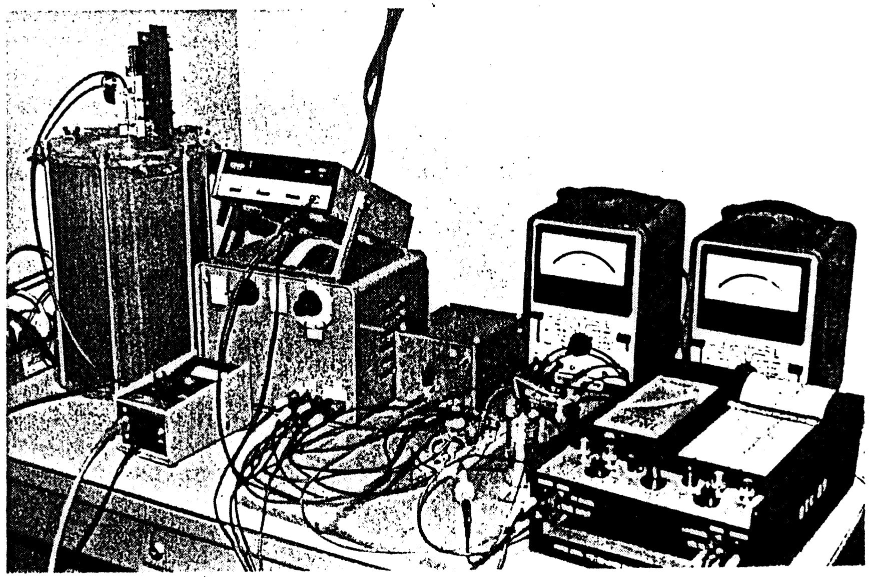


FIG. 3—*Photograph of pressure sensor. The cylindrical sensor chamber is at the left.*

Differentiating Eq 1 with respect to time yields the volumetric flow rate of the source

$$q_s(t) = \frac{d\, v_s(t)}{dt}$$

$$= V_s \omega \cos \omega t$$

$$= Q_s \cos \omega t \qquad (2)$$

where

$$Q_s = V_s \omega \qquad (3)$$

Here $q_s(t)$ is the volumetric flow rate (cubic metre per second) which varies sinusoidally with time and has an amplitude given by Eq 3. We see that in order to vary Q_s, the peak value of the volumetric flow applied to the enclosure (house) under test using a fixed-displacement source, we need to vary the source angular speed, ω.

Now, consider the infrasonic test of an enclosure (building) where we can neglect the compressibility of the air within the enclosure. (The conditions where this assumption can be made are discussed below.) Then all the volumetric flow from the source, $q_s(t)$, goes in and out through the leakage passages and gives rise to a cyclically-varying inside-outside pressure difference $\Delta p(t)$ having a peak-to-peak magnitude $2\Delta p_{\max}$. Although $q_s(t)$ is sinusoidal, $\Delta p(t)$ is generally not sinusoidal since the relation of flow to pressure difference for typical leakage passages is not linear.

The results of blower tests on enclosures such as buildings generally conform to the empirical equation

$$Q = K(\Delta p)^n \tag{4}$$

where

Q = the steady flow (cubic metre per second),
K = a constant that depends on the total effective size of all the leakage passages, and
n = an exponent generally between 0.5 and 0.7

Inverting Eq 4 yields

$$\Delta p = K^{-1/n} Q^{1/n} \tag{5}$$

Therefore, a log-log plot of Δp versus Q should yield a straight line having slope $1/n$.

If the same dependence of pressure difference on flow holds for an infrasonic test as for a blower test, then Eqs 4 and 5 can also be used to relate instantaneous values of pressure and flow. (That is, we neglect possible inertial effects of the flow.) In particular we can relate the peak pressure and peak flow by

$$\Delta p_{\max} = K^{-1/n} Q_s^{1/n} \tag{6}$$

Thus, under the assumed conditions (negligible compressibility of the air in the enclosure and negligible inertia effects of the flow through the leakage passages), a plot of $\Delta p_{\max}$ versus Q_s for an infrasonic test would be identical to the usual pressure difference-versus-flow curve obtained from a blower test. The results of an infrasonic test should, therefore, appear as shown in Fig. 4 as a straight line having slope $1/n$ when $\Delta p_{\max}$ is plotted against Q_s on log-log paper. To obtain a wide range of flows requires a wide range of source speeds. Experimentally, results agree with these predictions at low frequencies, but at high frequencies, above 1 to 5 Hz, deviations from the straight line on log-log plots are observed.

Including Compressibility

Most enclosures such as apartments or houses for which measured air-leakage properties are of interest have sufficiently large volumes and suffi-

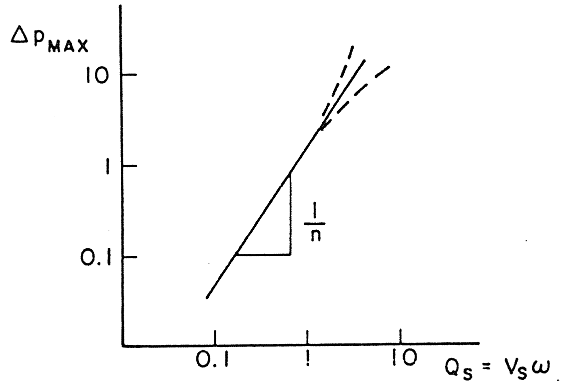


FIG. 4—*Predicted plot of $\Delta p_{\max}$ versus Q_s for a fixed-displacement pump, neglecting compressibility and inertia effects. The broken lines show possible deviations at high frequencies due to compressibility or inertia effects.*

ciently small leakages so that compressibility effects can not be neglected at frequencies above a few cycles per second. This section analyzes the compressibility effect in some detail. Two main assumptions are required: (1) the dimensions of the building are relatively small compared to an acoustic wavelength for all the test frequencies so that the whole enclosure undergoes pressure variations that are of the same magnitude and time phase, and (2) inertia effects can be neglected.

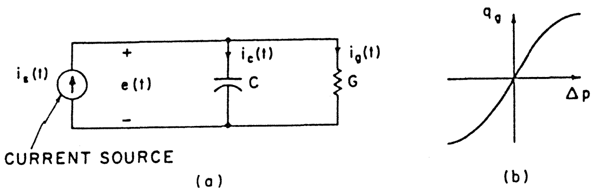
One way to help to understand the effect of the compressibility of the air within the enclosure (house) under test is to consider an electrical analog for the system, as shown in Fig. 5. The current source, $i_s(t)$, represents the infrasonic volumetric flow source. As we found earlier, in Eqs 2 and 3, the amplitude of the source, $V_s\omega$, varies linearly with the angular frequency (source speed), ω. The potential difference, $e(t)$, in the electrical analog represents the inside-outside pressure difference, $\Delta p(t)$. The current $i_g(t)$ through the electrical conductance G represents the leakage flow, $q_g(t)$, through the leaks of the enclosure. The current $i_c(t)$ into the electrical capacitance C represents the flow, $q_c(t)$, required to compress the air within the enclosure represented by the acoustic capacitance, C.

For isentropic conditions

$$PV^\gamma = \text{constant}$$

where

P = the total pressure,
V = the total volume, and
γ = 1.401.



ANALOGOUS QUANTITIES

ELECTRICAL		MECHANICAL	
$i_s(t)$	A	$q_s(t)$	m^3/s
$e(t)$	V	$\Delta p(t)$	Pa
$i_g(t)$	A	$q_g(t)$	m^3/s
G	S	K	m^3/s Pa
$i_c(t)$	A	$q_c(t)$	m^3/s
C	F	C	m^2/Pa

FIG. 5—*Analogous electric circuit for an enclosure having capacitance and leakage.*

Analysis shows that the acoustic capacitance is given by

$$C = -\frac{\Delta V}{\Delta P} = \frac{V}{\gamma P} \tag{7}$$

where, for our purposes, P is atmospheric pressure, which is almost constant. Thus C depends directly on V, the volume of the enclosure.

Unfortunately, as evidenced by Eq 4, the air leakage of a building does not vary linearly with pressure; consequently, in the electrical analog shown in Fig. 5, G is not a constant. Nevertheless, the electrical analog does help to interpret the results of the infrasonic measurement of buildings.

Figure 6 shows the frequency response curve for the electrical analog of Fig. 5. (Since in this analog network the source amplitude increases linearly with frequency, the frequency response differs from that of typical electrical circuits.) At low frequencies we can neglect the capacitance and obtain exactly the same curve as predicted before, plotted in Fig. 4, except that the horizontal axis is now labeled in terms of frequency ω instead of Q_s ($Q_s = V_s\omega$). That is, the pressure given by

$$\Delta p_{\max} = K^{-1/n} (V_s\omega)^{1/n} \tag{8}$$

in the low-frequency range when compressibility effects are neglected.

At high frequency essentially all the source volumetric flow is used to compress the air in the enclosure so that the response amplitude is constant. That is

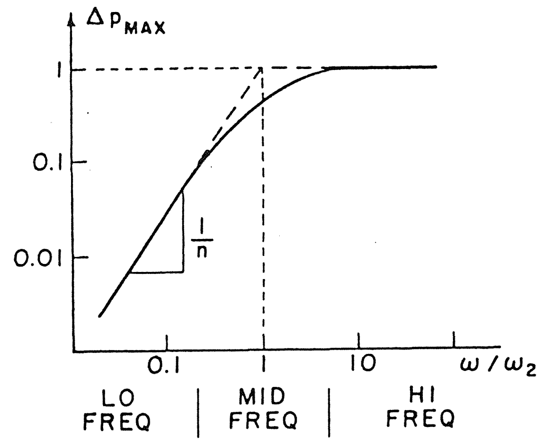


FIG. 6—*Frequency-response curve including capacitance effect. Scales are normalized.*

$$\Delta p_{\max} = \frac{1}{C} V_s = \frac{\gamma P}{V} V_s \tag{9}$$

in the high-frequency range. Because of the nonlinear characteristics of the leak, the response in the intermediate range of frequencies is not given by a closed-form solution: it must be calculated numerically [3].

It is interesting to find an expression for the angular frequency ω_2 at which the low-frequency asymptote and high-frequency asymptote intersect. Thus, equating the expression for Δp_m given by Eqs 8 and 9 yields

$$\omega_2 = K \frac{1}{C^n V_s^{1-n}} \tag{10}$$

For typical apartments and houses we have found using our apparatus that ω_2 is of the order of 3 to 12 rad/s (0.5 to 2 Hz). If the purpose of an experiment is to determine air leakage, then clearly the test must be conducted at frequencies which are low compared to ω_2, because the response at higher frequencies depends mainly on the capacitance and not on the leakage.

Experimental Results

Enclosures Tested

Air leakage measurements were made on three interior rooms in the main engineering building (Link Hall) at Syracuse University, on several electrically-heated apartments in a married-student housing project, and on one single-family house.

For the tests on two of the interior rooms, considerable effort was devoted to sealing all the cracks and openings. All the other enclosures were tested as found. For the one-story single-family house, however, the basement door was sealed with masking tape so that only the main floor comprised the enclosure under test.

Experimental Procedure

Both an infrasonic test and a blower test were run under the same conditions for most of the enclosures measured. For the infrasonic test the infrasonic source shown in Fig. 2 was placed near the center of the enclosure being tested, and the infrasonic sensor shown in Fig. 3 was located nearby. (Tests showed that the relative location was not important in the frequency range used.)

The blower tests were carried out using the apparatus shown in Figs. 7 and 8. The apparatus consisted of a one-horsepower direct-connected 3450-rpm blower in a box having a nozzle on the inlet. Five different nozzles were employed to cover all the flow ranges used. Pressure drop across the nozzle and enclosure inside-outside pressure difference were measured with conventional inclined manometers.

Sample Results

Figure 9 shows the results of a blower test on an interior laboratory room showing that under favorable conditions fairly good results conforming to Eq 4 are obtained.

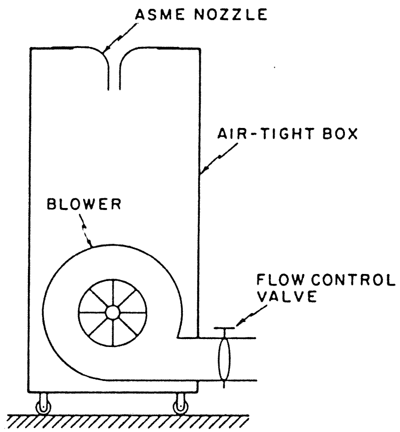


FIG. 7—*Blower test apparatus.*

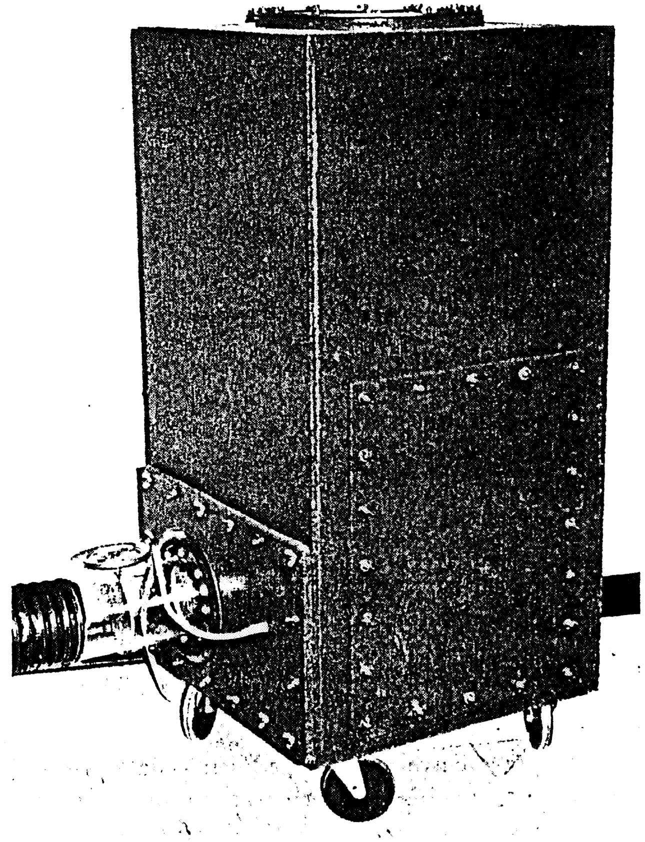


FIG. 8—*Blower test apparatus.*

Figure 10 shows the results of a blower test on the single-family house. Here the manometer fluctuations caused by outside wind gusts lead to considerable scatter in the flow-versus-pressure data.

Figure 11 shows the data from an infrasonic test and also from a blower test on the same enclosure. Notice that because of the small size of the infrasonic source, the ranges of the two tests do not overlap. Figure 12 shows a frequency response curve obtained by the infrasonic method under favorable conditions for an inside room. Clearly the behavior follows the theoretical predictions quite closely. Figure 13 shows more typical frequency response mesurements under less favorable conditions on the single-family house.

In order to process the measurements a least-squared-error computer

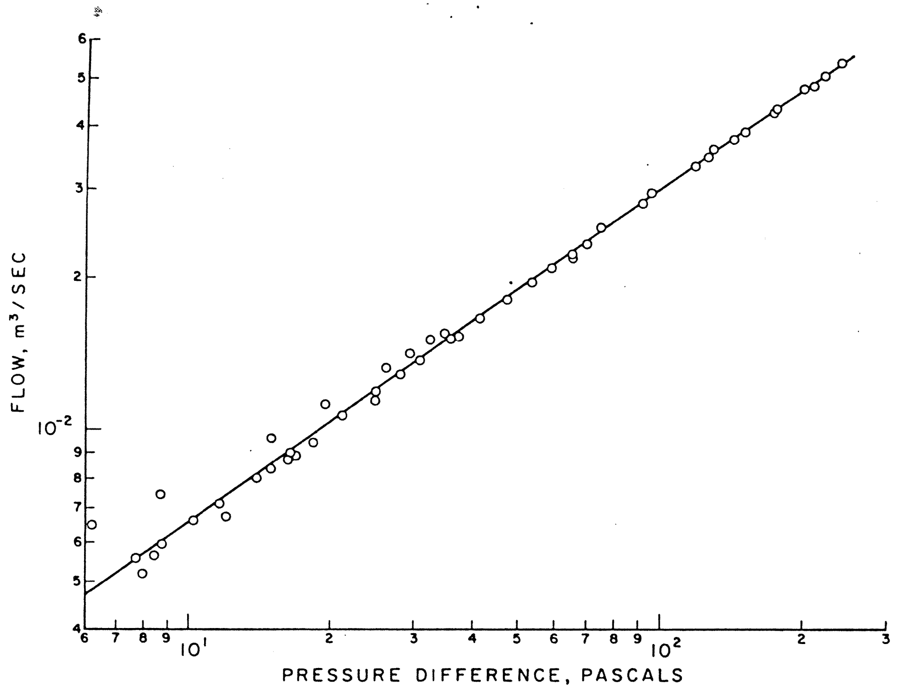


FIG. 9—*Results of blower test on an interior room. Most cracks have been sealed.*

program was used to fit a curve to the experimental data [*4*]. The computer plotted results of the least-squared-error curve fitting process are shown in the figures. The computer program also yielded the parameters of the curve from which, in effect, K and n were determined.

Table 1 compares the air leakage to be expected at 25 Pa inside-outside pressure difference based on the blower and infrasonic measurements. Except for Apartment 1, where insufficient low-frequency data were obtained, the results agree within a factor or three. The large discrepancy is attributed to difficulties in calibrating the equipment and to interference from wind gusts.

Evaluation and Conclusions

The purpose of the research reported on here was to evaluate the proposed infrasonic measuring system, and compare it with the conventional blower system for measuring the air leakage of buildings. On the basis of the work to date the following conclusions can be drawn:

1. The accuracy of the present infrasonic measuring system is rather low. In most cases the infrasonic results compare with the blower results within

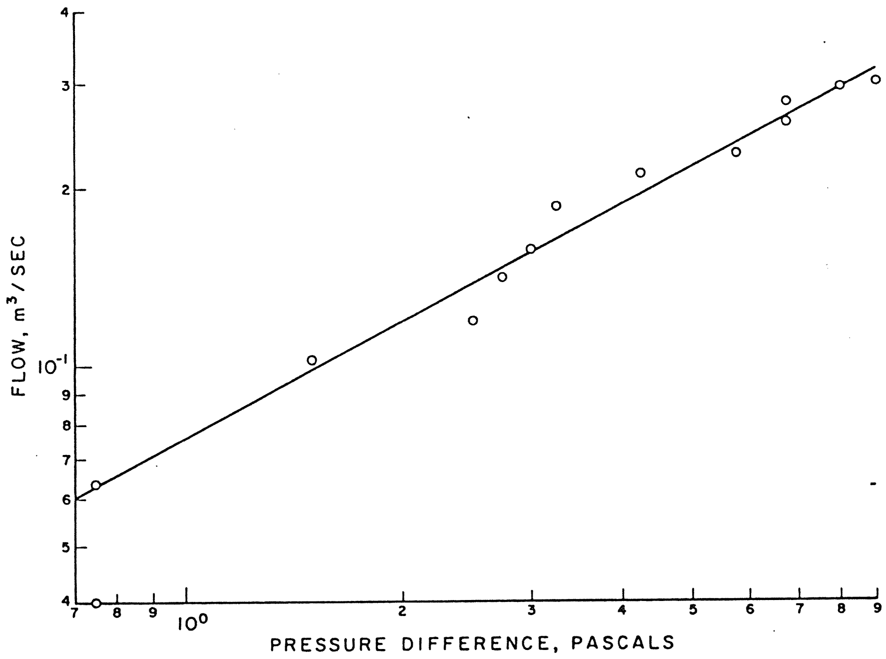


FIG. 10—*Results of a blower test on a single-family house.*

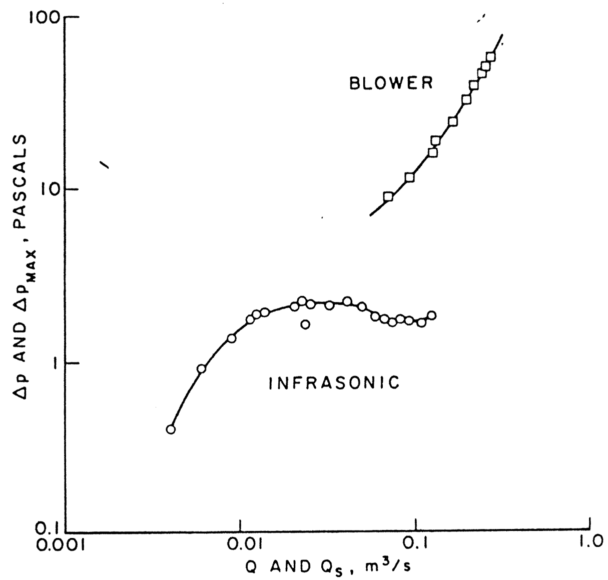


FIG. 11—*Results of a blower test and infrasonic test on Apartment 3.*

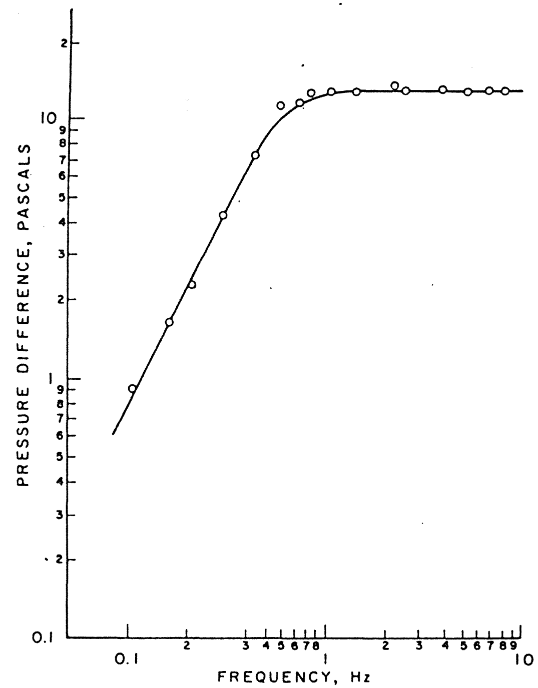


FIG. 12—*Results of an infrasonic test on an interior room.*

a factor of three. The poor agreement is attributed to errors due to wind-gusts and instrument calibration.

2. The blower test results are easily and directly interpreted whereas, at present, calculations of the air leakage property of a building from an infrasonic test requires using the volume of the building and the measured infrasonic frequency response curve.

3. One very important advantage of the infrasonic apparatus is that it is easier to use than a blower since no through-the-wall blower vent or pressure taps are required. The set up time for the infrasonic system is therefore much less than for the blower system.

4. The next step in the development of the infrasonic air leakage measuring system is to improve the accuracy of measurements.

Acknowledgment

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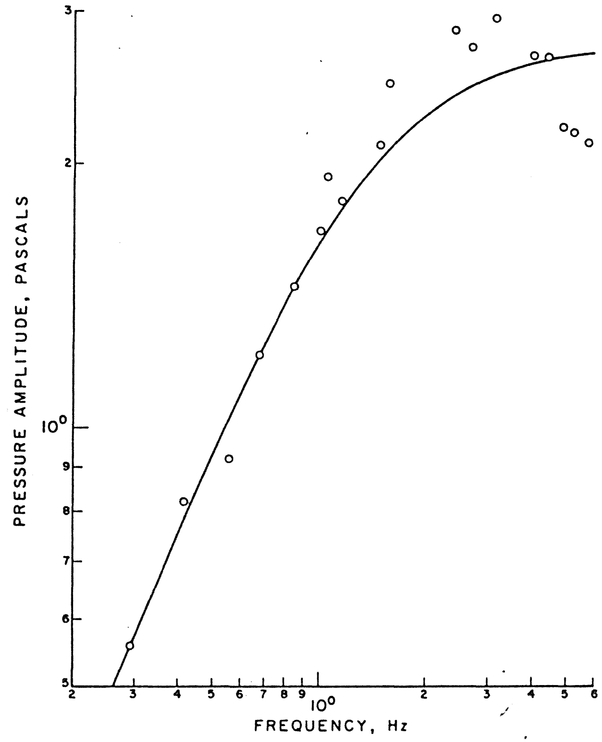

FIG. 13—*Results of an infrasonic test on the single-family house.*

TABLE 1—*Comparison of air leakage at 25 Pa calculated from blower and infrasonic measurements.*

Description	Volume, m^3	Blower, Q_B m^3/s	Infrasonic, Q_I m^3/s	Q_I/Q_B
Room 1	50	0.012	0.024	2.00
Room 2	38.3	0.159	0.227	1.42
Room 3	20	0.026	0.014	0.538
Apt 1	192	0.187	0.0031	0.0165
Apt 2	194	0.146	0.0564	0.386
Apt 3	194	0.164	0.052	0.317
Apt 4	193	0.176	0.118	0.670
House	142	0.611	0.265	0.433

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