# VOLUME AND FREQUENCY SCALING FOR INTERNAL PRESSURES IN WIND-TUNNEL TESTS

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## Introduction

The correct scaling rules for internal pressure fluctuations were described as early as 1979 [1]. However, many wind-tunnel tests involving internal pressures are carried out with incorrect scaling. In this paper, the correct scaling rule for internal volume is derived using a different approach to that in [1], but the same result is obtained : the internal volume should be distorted by the square of the velocity ratio. If this is not done, the frequencies of internal pressure fluctuations will be scaled incorrectly with respect to those for the external pressures and unpredictable results will be obtained.

## Frequency scaling for Helmholtz resonance frequency

The Helmholtz resonance phenomenon in fluctuating internal pressures is a well-known one, and has been verified experimentally in both full-scale and model tests, [1], [2], [3].

The resonant frequency can be derived by assuming that a defined 'slug'of air moves in and out of a single dominant opening in a building wall in response to external pressure changes, as shown in Figure 1.

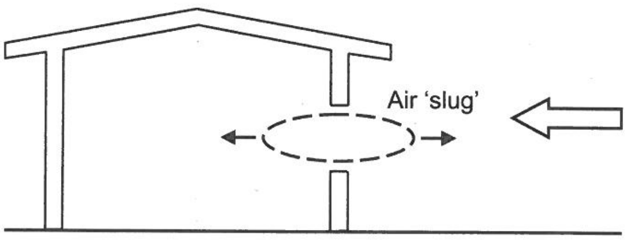


Figure 1. Helmholtz resonator concept of fluctuating internal pressures

For a single dominant opening (area A), the Helmholtz resonance frequency is given by [1], [4]:

$$n_H = \frac{1}{2\pi}\sqrt{\frac{\gamma A p_0}{\rho_0 \ell_e V_0}} \qquad (1)$$

where $p_0$ is atmospheric pressure, $\rho_a$ is the air density, $\ell_e$ is the effective length of the air 'slug', and $V_0$ is the internal volume.

Thus, $n_H \propto \sqrt{\dfrac{\sqrt{A} p_0}{\rho_0 V_0}}$

$$n_H^{\,2} \propto \frac{\sqrt{A}.p_0}{\rho_0 V_0}$$

Then, the ratio of model to full-scale frequency is given by:

$$[n_H]_r^2 = \frac{[L]_r [p_0]_r}{[\rho_a]_r [V_0]_r} = \frac{[L]_r}{[V_0]_r}$$

since $[p_0]_r = [\rho_a] = 1.0$, for testing in air at normal atmospheric pressures.

However, for scaling with frequencies in the external flow:

$$[n_H]_r = \frac{[U]_r}{[L]_r} \qquad (2)$$

Hence, for correct frequency scaling, $[n_H]_r^2 = \frac{[L]_r}{[V_0]_r} = \frac{[U]_r^2}{[L]_r^2}$

$$\text{i.e. } [V_0]_r = \frac{[L]_r^3}{[U]_r^2} \qquad (3)$$

Thus, if the velocity ratio, $[U]_r$, is equal to 1.0, i.e. when the wind-tunnel speed is the same as full scale design speeds, then the internal volume should be scaled according to the geometrical scaling ratio,

$$[V_0]_r = [L]_r^3 \times 1.0$$

However, if $[U]_r$ is less than 1.0, which is usually the case in wind-tunnel tests, then the internal volume should be distorted by a factor of $1/[U]_r^2$. For example, if the velocity ratio is 0.5, then the internal volume, $V_0$, should be increased by a factor of 4.

Frequency scaling for 'characteristic' frequency

Vickery [5], [6], and Harris [7], derived a 'characteristic response time' of internal pressures for the buildings with openings, or distributed permeability, on both windward and leeward walls. By neglecting inertial terms and linearizing, a first-order differential equation is obtained for the internal pressure fluctuations, and the characteristic response time is the time constant for the system. The 'characteristic frequency' is the response time divided by $2\pi$.

External pressure fluctuations above the characteristic frequency will be low-pass 'filtered' by the system, and not be felt as internal pressures.

The characteristic response time for internal pressures in a building with distributed openings on the windward side $A_W$, and on the leeward side, $A_L$, is given by (neglecting inertial effects) [5], [7]:

$$\tau = \frac{\rho_a V_o \overline{U} A_W A_L}{\gamma k p_o (A_W^2 + A_L^2)^{3/2}} \sqrt{C_{pW} - C_{pL}} \qquad (4)$$

where $\gamma$ is the ratio of specific heats for air, k is the orifice constant, and $C_{pW}$ and $C_{pL}$ are the average external pressure coefficients on the windward and leeward wall, respectively.

For $A_W$=$A_L$=A and fixed $C_{Pw}$ and $C_{PL}$ ,

$$\tau \propto \frac{\rho_a V_0 \overline{U}}{p_0 A}$$

and the characteristic frequency,

$$n_C \propto \frac{p_0 A}{\rho_a V_0 \overline{U}}$$

Then, the ratio of model to full-scale frequency is given by:

$$[n_C]_r = \frac{[p_0]_r [L]_r^2}{[\rho_a]_r [V_0]_r [U]_r} = \frac{[L]_r^2}{[V_0]_r [U]_r}$$

For correct scaling with frequencies in the external flow,

$$[n_C]_r = \frac{[U]_r}{[L]_r} = \frac{[L]_r^2}{[V_0]_r [U]_r}$$

Hence, $[V_0]_r = \dfrac{[L]_r^3}{[U]_r^2}$ (3)

Thus the same the scaling criterion applies, as for Helmholtz resonance frequency – i.e. the internal volume needs to be distorted if velocity ratio is not equal to 1.0.

Consequences of not distorting the internal volume

It is instructive to consider what the effect of the incorrect scaling has on the results when a velocity ratio significantly less than 1.0 is used in wind-tunnel testing for the single opening case, and no volume distortion is applied. If the volume is too small, from Equation (1) the Helmholtz resonant frequency in the experiments is clearly too high (by a factor equal to the reciprocal of the velocity ratio). Also the damping of the resonance is too low [1]. Thus frequencies above the Helmholtz frequency, that would have been low-pass filtered if the correct volume scaling had been used, will have not been in the tests, and in fact would have been significantly amplified. Thus, in general, the fluctuating internal pressures will be over-predicted.

For the distributed permeability case, Equation (4) shows that too low a volume will give a characteristic response time that is too small. External fluctuations will therefore not be low-pass filtered that should have been – again the internal pressures will be over-predicted by the tests.

If net external-internal pressures are being measured, the correlation between the external and internal pressures is also significant, and this will also be changed by the incorrect volume scaling in a way that is hard to predict.

Discussion and Conclusions

The derivation given in this paper is an alternative one to that given in [1] (in which it was expressed as a form of Mach Number scaling), but gives the same result. It shows that the correct volume scaling is required for frequency matching, whether or not significant Helmholtz resonance is present. It can be also be shown that the damping of the Helmholtz resonance is incorrectly scaled if the correct volume scaling is not adopted [1].

Equation (3) shows that, in order to correctly simulate internal pressure fluctuations in wind-tunnel models, the required scaling ratio for internal volume is equal to the cube of the length ratio, divided by the velocity ratio squared. This rule applies for correct scaling of both the Helmholtz resonance frequency [1], [2], and the 'characteristic frequency' defined by Vickery [5], [6], for buildings with distributed leakage. Thus, for correct scaling of the frequencies of internal pressure fluctuations in wind-tunnel tests, the internal volume should be increased above that obtained from simple geometric scaling, if the ratio of model to full-scale wind velocity is less than 1.0.

The additional volume required when the velocity ratio is less than 1.0 (as is usually the case when wind-tunnel results are applied to full-scale design wind speeds), can be provided beneath a wind-tunnel floor and connected to the interior of the model.

Failing to provide a sufficiently large volume will generally over-predict the fluctuating internal pressures, but it is difficult to quantify the error involved. Thus it is advisable to correctly scale the internal volume unless it is particularly difficult or inconvenient to do this.

References

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