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SINGLE-FIGURE RATING OF POROUS WOVEN HOSES USING A NON-LINEAR FLOW RESISTANCE MODEL

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1. INTRODUCTION

The reduction of intake noise is a very important factor in controlling the interior noise levels of cars, particularly at low and major engine operating speeds. Porous hoses [1] made of wire-reinforced, woven fabric, coated with an acrylic resin are currently used in many automotive intake systems for reducing noise radiated from the snorkel opening. Several of the side-branch or Helmholtz resonators in an intake system can be replaced by one porous hose section, thus suppressing the intake resonances. In addition, owing to the flexibility of the porous woven hose, the system layout, installation, and vibration isolation become considerably easier. The porous woven hose is now considered to be a very promising and efficient silencing component.

For predicting the silencing performance of an intake system with a porous woven hose, information on the acoustic wall impedance is essential [2]. The acoustic impedance of a porous woven hose depends on acoustical, structural, and geometrical characteristics: flow resistance, thickness variation due to small corrugations, local inhomogeneities in material composition, local stiffness variation, interlacing roughness, coating uniformity, diameter, and length.

For the major automotive companies and hose manufacturers, all the aforementioned physical characteristics of the porous woven hose have been rated by the following single-figure parameter that can be measured as illustrated in Figure 1:

$$f_p = \frac{\gamma P_0}{2\pi}\frac{1}{VZ} = \frac{\gamma P_0}{2\pi}\frac{1}{\pi r_i^2 L}\frac{1}{\Delta P/Q}, \tag{1}$$

where γ represents the ratio of specific heats, P_0 the ambient pressure, V the internal volume of hose, L the length of hose, r_i the inner radius of hose, ΔP the effective pressure drop at the hose inlet relative to the ambient pressure, Q the volume flow rate through the hose wall, and $Z = \Delta P/Q$. This parameter is typically determined at a given specific volume flow rate,

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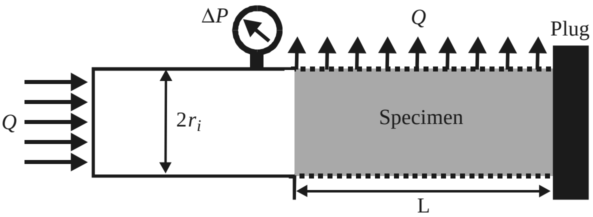

Figure 1. Schematic showing the measurement set-up and related parameters.

$Q = 0{\cdot}026\ \mathrm{m}^3/\mathrm{s}$. This volume flow rate corresponds to 25–40% of the maximum flow rate of the actual intake systems of 1·5–2·5 liter engines.

As mentioned above, this parameter is equivalent to a single-figure rating of the overall physical characteristics of a porous woven hose, which is mainly affected by the length, radius, weaving quality, and coating conditions. The dimension of the right-hand side of equation (1) corresponds to the inverse of time. For this reason, it is referred to as the "porous frequency", "cut-off frequency" or "porosity" in Hz by the manufacturers, as well as NVH engineers in major automotive companies in the world. However, this somewhat strange in situ terminology of "porous frequency" has neither an important physical meaning nor a direct relation to the porosity or the ordinary frequency. It should be noted that geometrical factors such as diameter and length are involved in equation (1) as well as the surface condition such as the interlacing or texture openness of the wall and the coating quality. Note that a quick change of equation (1) leads to

$$f_p = -\frac{1}{2\pi}\frac{Q}{\Delta V}, \tag{2}$$

where ΔV is the change in internal air volume due to suction through the entire wall surface.

Notwithstanding the fact that the acoustical properties of porous woven hoses are bound to be inhomogeneous due to structural and fabricating conditions as mentioned earlier, the physical and acoustical properties of the weaving condition is usually measured for a hose section of predetermined length and diameter, e.g., 1 m in length and 0·055 m in diameter. However, it should be noted that the measured acoustic impedance for a porous frequency, which is determined for such a specified length and diameter, is different from those for other hoses of different lengths and diameters, but with the same weaving and coating characteristics. This phenomenon is caused partly from the inhomogeneity of the fabrication conditions, but is mainly the result of the non-linearity of the involved physical parameters. The purpose of this paper is to investigate the non-linearity of a porous woven hose by examining its similarity with typical fibrous porous materials. After obtaining the porous frequency from the empirical non-linear characteristics of a porous woven hose, it is easily possible to determine the porous frequency of the same woven hose by comparing it with others in terms of length and/or diameter from such non-linear parameters.

2. ALTERNATE EXPRESSION OF SURFACE POROSITY

Figure 2 shows a photo of the actual measurement apparatus for porous frequency, of which the basic measurement layout is shown in Figure 1. One end of the porous woven hose sample is sealed with an impermeable plug and compressed air is supplied to the other end of the apparatus. The volume flow rate of air is measured by a flow meter (Flowmetrics,

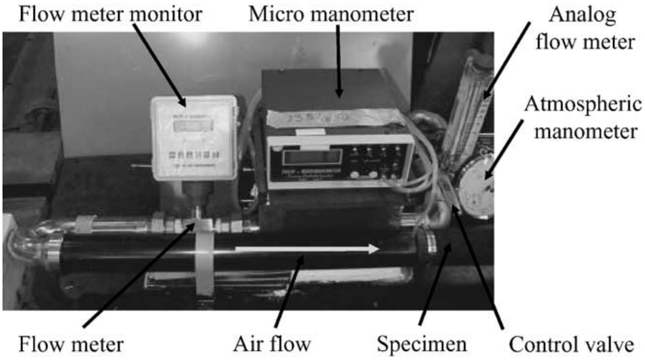

Figure 2. Apparatus used for measuring the relation between effective pressure drop and volume flow rate.

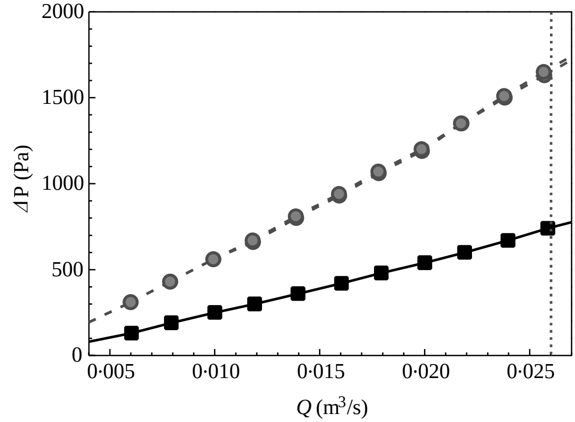

Figure 3. Measured relation between effective pressure drop and volume flow rate: —■—, $L = 1$ m; —●— —, $L = 0{\cdot}5$ m; -----, condition of $Q = 0{\cdot}026$ m^3/s.

FM20) and the effective pressure drop at each volume flow rate is measured by a micro-manometer (Furness Controls, FCO12-4). Figure 3 shows a typical measured relation between effective pressure drop and volume flow rate. First, a sample, nearly 1 m in length, was measured and then, after halving the same 1 m long sample into two, i.e., giving two 0·5 m long samples, the two tubes were measured. Therefore, on average, it is assumed that the three samples possess the same weaving and coating conditions. The measurements were performed using a volume flow rate range of 0·004–0·040 m^3/s for the 1 m long sample, and with 0·004–0·027 m^3/s for the two 0·5 m long samples. As can be seen in Figure 3, the measured curves for the two different lengths do not show any consistency in spite of the fact that the samples possess exactly the same wall properties. Furthermore, the measured curves show a slight tendency toward non-linearity. The result suggests that other methods or parameters are needed for specifying the overall characteristics of the hose.

In order to represent the overall wall characteristics of a porous woven hose by only one curve, the experimental results are rearranged using the effective pressure drop ΔP and the averaged normal velocity through the wall, $u_n = Q/(2\pi r_i L)$, instead of the volume flow rate. Figure 4 shows such rearranged experimental results. In this figure, the two vertical lines indicate a volume flow rate of $Q = 0{\cdot}026\,\mathrm{m}^3/s$. The ratio between the averaged normal

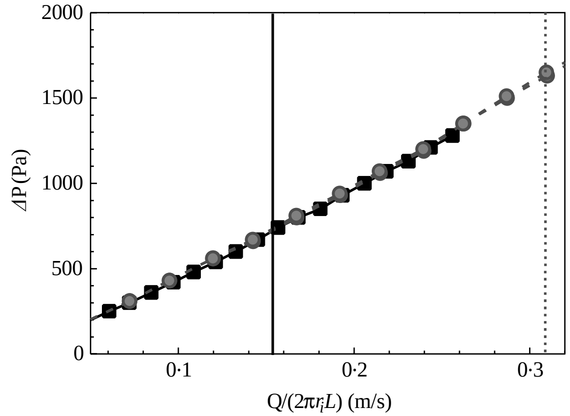

Figure 4. Measured relation between effective pressure drop and averaged normal velocity: —■—, $L = 1$ m; —●— —, $L = 0{\cdot}5$ m; ———, conditions of $Q = 0{\cdot}026\ \mathrm{m^3/s}$ for $L = 1$ m; -----, conditions of $Q = 0{\cdot}026\ \mathrm{m^3/s}$ for $L = 0{\cdot}5$ m.

velocity and the effective pressure drop can be called the "effective flow resistance" from the analogy of typical porous sound-absorbing materials [3, 4]. The "effective flow resistivity" can also be defined as

$$2\pi r_i L\,\frac{\Delta P}{Qt} = \frac{\Delta P}{t u_n} \equiv R_1(u_n) \tag{3}$$

where t is the average wall thickness. The word "effective" is used for the flow resistivity because $R_1(u_n)$ does not have precisely the same meaning as the term ordinary "flow resistivity", which is usually used for general porous materials. The measured ΔP is actually the effective pressure drop, which indicates the pressure difference between the outside and one end of the test specimen inside. In addition, the measured flow velocity does not represent an actual flow velocity through the porous wall, which is not constant in the axial direction, but is related to the averaged flow velocity through the porous wall. Consequently, the porous frequency is somehow related to the average flow resistance through the wall of the porous woven hose. The effective flow resistivity is a more useful term than the porous frequency defined in equation (1) for quality control and manufacturing of porous woven hoses having specified weaving and coating characteristics. Thus, the porous frequency defined in equation (1) can be redefined as

$$f_p = \frac{\gamma P_0}{\pi r_i}\,\frac{1}{2\pi r_i L}\,\frac{1}{\Delta P/Q} = \frac{\gamma P_0}{\pi r_i L}\,\frac{1}{t R_1(u_n)}. \tag{4}$$

With this new expression of porous frequency, one can easily specify the wall properties of a porous woven hose.

3. NON-LINEAR CHARACTERISTICS

Because the flow resistivity R_1 is non-linearly dependent on the averaged normal velocity, the porous frequencies measured at different lengths will be different, although the hoses possess the same wall properties. For example, the measured porous frequency is $f_{p1} = 310{\cdot}1$ for a sample with $2r_{i1} = 0{\cdot}055$ m and $L_1 = 0{\cdot}5$ m, but the measured porous

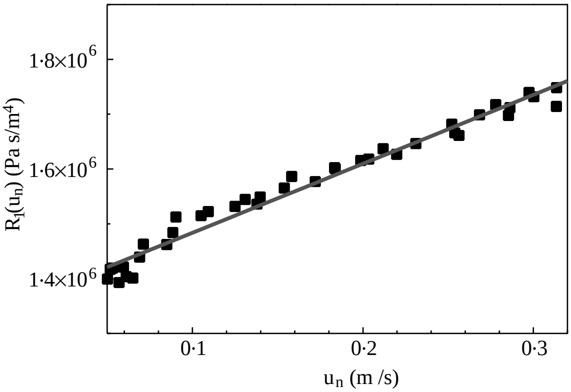

Figure 5. Measured effective flow resistivity of a porous woven hose: ■, measured data; ——— , regression line ($R_1 = R_1^0 + Fu_n$, $R_1^0 = 1{\cdot}358 \times 10^6$, $F = 1{\cdot}259 \times 10^6$, $R^2 = 0{\cdot}973$).

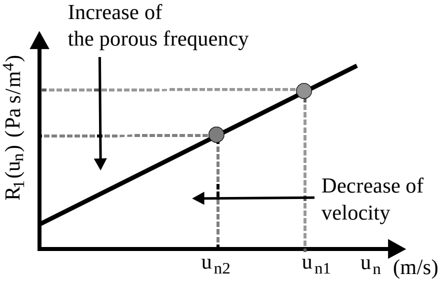

Figure 6. Variation of porous frequency due to change in sample length. Note that the length of the porous woven hose that results in the average surface normal velocity u_{n1} is longer than that having u_{n2}.

frequency of a sample with $2r_{i2} = 0{\cdot}055$ m and $L_2 = 1$ m, still having the same wall properties, is $f_{p2} = 350{\cdot}2$. Note that the unit Hz, which is usually used for a porous frequency f_p, is omitted here on purpose to emphasize the fact that it has no relation with an ordinary frequency. Figure 5 shows a measured result of effective flow resistivity as a function of averaged normal velocity. This non-linear characteristic of the porous woven hose is very similar to those of typical porous materials. The main reason for the non-linearity in this flow range is that, in addition to the viscous drag force on the material, there is also a turbulent contribution. Figure 6 shows a conceptual diagram of the variation in porous frequency with change in the length of the sample tube. Because the surface area changes with a change in sample length, the averaged normal velocity, which causes the specified volume flow rate also changes. Therefore, the effective flow resistivity is changed due to its dependence on the averaged normal velocity. Consequently, the porous frequency values measured for two arbitrary different lengths are different even if the two hoses possess the same wall characteristics.

Similar to the typical fibrous sound-absorbing material [5], the dependence of R_1 on u_n can be described by an empirical relation as

$$\frac{\Delta P}{tu_n} = R_1(u_n) = R_1^0 + Fu_n, \tag{5}$$

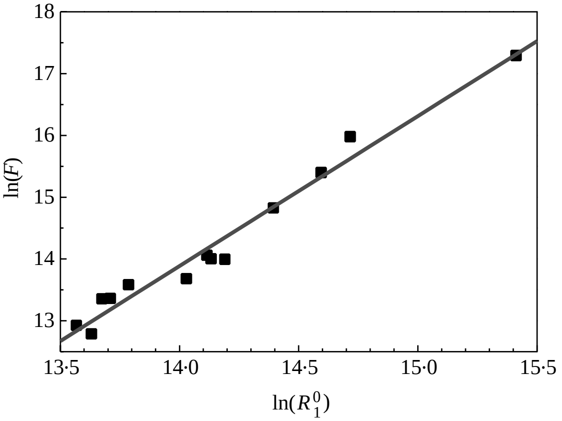

Figure 7. Measured F versus R_1^0 and the regression line ($R_1 = R_1^0 + Fu_n$, $F = a(R_1^0)^b$, $\ln a = -20{\cdot}09$, $b = 2{\cdot}427$, $R^2 = 0{\cdot}972$): ■, measured data; ——, regression line.

where R_1^0 denotes the flow resistivity in the very low-velocity region and F is the non-linearity factor that describes the dependence of R_1 on u_n. An approximate empirical relationship between R_1^0 and F is assumed as the following power law equation:

$$F = a(R_1^0)^b, \tag{6}$$

where a and b are the regression coefficients, to be experimentally determined. Also, R_1^0 can be determined from a regression analysis of the experimental data.

An example of the regression line for measured F versus R_1^0 is shown in Figure 7 and are, $\ln a = -20{\cdot}09$, $b = 2{\cdot}427$, of which the correlation coefficient was $R^2 = 0{\cdot}972$. Using these regression coefficients a and b, the difference in the porous frequencies f_p for samples having different lengths can be explained. For example, consider a sample with $2r_{i1} = 0{\cdot}055$ m and $L_1 = 0{\cdot}5$ m, the measured porous frequency of which is given as $f_{p1} = 310{\cdot}1$. From these measured data, $R_1^0 = 1{\cdot}3437 \times 10^6$ N s/m^4 can be found by regression analysis using equations (5) and (6). The porous frequency for a sample with other dimensions, e.g., $2r_{i2} = 0{\cdot}055$ m and $L_2 = 1$ m, having the same wall properties, can then be obtained as $\hat{f}_{p2} = 351{\cdot}9$. The estimated porous frequency obtained in this manner is in good agreement with the actual measured porous frequency value of $f_{p2} = 350{\cdot}2$ for a sample with a size of $2r_{i2} = 0{\cdot}055$ m and $L_2 = 1$ m. Consequently, the difference in porous frequencies for samples having different lengths can be explained in this manner.

As can be seen in equations (3) and (4), the same discussion can be extended to two arbitrary hose samples having different diameters, but the actual discussion is reserved because very similar conclusions can be reached when the length parameter is replaced by the inner diameter.

4. CONCLUSIONS

The physics underlying the porous frequency that specifies the overall wall characteristics of a porous woven hose are explained and it was verified that both the wall properties and dimensions of the hose affect the porous frequency. A similarity was found in the concept of flow resistivity for such hoses, compared with many fibrous materials. In order to specify the wall properties of a porous woven hose, the effective flow resistivity is defined by incorporating the averaged normal velocity through the wall, so as to resemble those of typical porous sound absorbing materials. In addition, an approximate empirical formulae for modelling the non-linear characteristics of effective flow resistivity were obtained in a manner analogous to that for fibrous sound-absorbing materials. The reason for why different porous frequencies are obtained when the dimensions are different, even if the wall properties are the same, can be explained by the effective flow resistivity, which is demonstrated by an example. The obtained empirical formulae for the non-linear parameters can relate the effective flow resistivity to the practical parameter, viz., the porous frequency. It is concluded that the effective flow resistivity should be used, instead of the conventional "porous frequency", in defining flow-acoustic characteristics, i.e., the "openness" or "porosity" of the texture, or, in other words, in expressing how minutely the texture was woven and also how it was coated by resin, of the porous woven hose.

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REFERENCES

1. A. Cummings and R. Kirby 1999 *Journal of Sound and Vibration* **226**, 237–251. Low-frequency sound transmission in ducts with permeable walls.
2. C.-M. Park, J.-G. Ih, Y. Nakayama and S. Kitahara 2002 *Applied Acoustics* **63**, 775–794. Measurement of acoustic impedance and prediction of transmission loss of the porous woven hose in engine intake systems.
3. ASTM Standard C 522-87 1987 *Standard Test Method for Airflow Resistance of Acoustical Materials*. Philadelphia: American Society for Testing and Materials.
4. K. U. Ingard 1994 *Notes on Sound Absorption Technology*. New York: Noise Control Foundation.
5. L. L. Beranek and I. L. Ver 1992 *Noise and Vibration Control Engineering*: *Principles and Applications*. New York: John Wiley and Sons.