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Published in:
Journal of the Acoustical Society of America

Link to article, DOI:
10.1121/1.5049708

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Tang, X., Jeong, C-H., & Yan, X. (2018). Prediction of sound absorption based on specific airflow resistance and air permeability of textiles. *Journal of the Acoustical Society of America*, *144*(2), EL100-EL104. https://doi.org/10.1121/1.5049708

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Citation: The Journal of the Acoustical Society of America **144**, EL100 (2018); doi: 10.1121/1.5049708
View online: https://doi.org/10.1121/1.5049708
View Table of Contents: http://asa.scitation.org/toc/jas/144/2
Published by the Acoustical Society of America

Prediction of sound absorption based on specific airflow resistance and air permeability of textiles

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Abstract: Both specific airflow resistance and air permeability can be used as a parameter to estimate the sound absorption of textiles. The measurement of specific airflow resistance is specified in ISO 9053 (Int. Standards Org., 1991), but it is known to be inaccurate for low specific airflow resistance. This paper compares the measured specific airflow resistance according to ISO 9053 and those calculated from air permeability according to ISO 9237 (Int. Standards Org., 1995). The sound absorption coefficients predicted by Pieren's model [R. Pieren, Textile Res. J. **82**(9), 864–874 (2012)] are compared with measurements by the impedance tube method, which concludes that those predicted from the air permeability are more accurate than those from the measured specific airflow resistance for textiles.

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Date Received: June 11, 2018 **Date Accepted:** July 24, 2018

1. Introduction

In noise control engineering, airflow resistance is the most important input parameter for estimating sound absorption for porous type absorbers. It is defined as the ratio of the pressure drop to the airflow velocity through a test sample.[1,2] The airflow resistance could effectively describe the resistance effects of air passed through a fibrous material. As described in ISO 9053,[1] the standardized measurement procedure is based on the unidirectional and controlled airflow or the alternative airflow, and it is necessary to determine the alternating component of the pressure in the test volume. The recommended airflow velocity should be as low as 0.5 mm/s or 5 mm/s; the test procedure usually requires complicated equipment.[3] Moreover, it is known to be imprecise to measure specific airflow resistance when it is lower than 50 Pa s/m due to low signal-to-noise ratios.[4,5]

Similar to the airflow resistance, the test principle of the air permeability is also based on the air pressure drop and airflow velocity. The air permeability is easily measured through the widely used fabric air permeability instrument in textiles industry.[6] In this work, the specific airflow resistance of woven fabric was calculated from air permeability according to ISO 9237 (Ref. 7) and measured according to ISO 9053.[1] To validate the reliability of measured and calculated specific airflow resistance, Pieren's absorption model[5] was used to predict the sound absorption coefficients of woven fabrics. The purpose of this work is to investigate which input parameter could predict sound absorption via Pieren's model more accurately, and further study the effects of the air pressure drop. For textile materials, air permeability data are more available, so it is advantageous to obtain the airflow resistance from the air permeability.

2. Methodology

The air permeability is the amount of air passing through a specific area in the given time. According to Darcy's law, air permeability could be intrinsically determined by the following equation:

$$Q_m = k\frac{\Delta p}{\mu d}, \qquad (1)$$

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where Q_m is the rate of flow (m/s), k is the flow permeability coefficient (non-dimensional), Δp is the pressure drop (Pa), μ is the dynamic viscosity of the air (Pa s), and d is the thickness of the fabric (m). The flow permeability coefficient k is determined by the intrinsic characteristics of fibrous materials, such as porosity and tortuosity. According to ISO 9237,[7] the air permeability Q (mm/s), is the velocity of airflow passing perpendicularly through a specimen,

$$Q = \frac{q_v}{A_p} \times 167, \tag{2}$$

where q_v has the volumetric airflow rate (Liter/min), A_p is the cross-sectional area of the fabric (cm^2), and 167 is the unit conversion factor.

As specified in ISO 9053,[1] specific airflow resistance R_s (Pa s/m or Rayls) could be defined by the following formula:

$$R_s = \frac{\Delta p \cdot A_f}{q'_v}, \tag{3}$$

where Δp is the differential air pressure in pascals (Pa), q'_v is volumetric airflow rate (m^3/s), and A_f is the test area of sample (m^2). It could be seen that the calculation process is closely related to the volumetric airflow rate. Assuming that these two volumetric airflow parameters are equivalent, so $q_v/q'_v = 1000 \times 60$, the relationship between specific airflow resistance and air permeability is obtained as follows:

$$R_s = \frac{\Delta p \cdot A'_f \times 60 \times 167 \times 10^3}{Q \cdot A_p \times 10^4} = \frac{\Delta p \cdot A'_f \times 1002}{Q \cdot A_p}, \tag{4}$$

where A'_f is the fabric area in the test of specific airflow resistance (cm^2). Obviously, the pressure drop, Δp, plays an important role in the calculation of R_s from Q in Eq. (4).

According to ISO 9053,[1] the air pressure drop sensitivity for measuring airflow resistance should be as low as 0.1 Pa. However, the pressure drop in the test of air permeability is generally higher than 50 Pa according to ISO 9237,[7] for example, 100 Pa for apparel fabric and 200 Pa for industrial fabric. So, is it possible to deduce the specific airflow resistance based on the measured air permeability of pressure drop higher than 50 Pa? What is the effect of pressure drop on the reliability of calculated specific airflow resistance? Sections 3–5 discuss measured results of the specific airflow resistance and air permeability of fabrics according to ISO 9053 and ISO 9237, respectively,[1,7] and then the effects of the air pressure drop.

3. Measurements

The photos of 24 fabrics used in this work are shown in Fig. 1. The air permeability was tested by a fabric air permeability instrument (YG461E, Ningbo Textile Equipment Co., Ltd., China) in accordance with ISO 9237.[7] It can be seen from Eq. (4) that the measured air permeability was affected by the air pressure drop, Δp. As stipulated in ISO 9237,[7] the pressure drop that ranged from 50 to 500 Pa could be applied according to different kinds of fabrics. In this study, the pressure drop is 50, 100, 150, and 200 Pa, while the test fabric area A_p is 50 cm^2. Specific airflow resistance was measured by the Nor1517A equipment (Airflow Resistance Measurement System, Norsonic Co., Ltd., Norway) according to ISO 9053.[1] The sound absorption coefficients of the 24 fabrics are measured by the impedance tube method according to ISO 10534-2.[8]

4. Air permeability and airflow resistance

The measured air permeability under different pressure drops and specific airflow resistance of 24 fabrics are listed in Table 1, where the air permeability is ranging from 200 to 1400 mm/s. In addition, it could be known from Eq. (4) that the specific airflow resistance is inversely proportional to the air permeability under the given pressure drop. Figure 2 shows the measured and calculated airflow resistance with the vertical bars as standard errors. In Fig. 2, most of the measured specific airflow resistance (18 out of 24 fabrics) are lower than the calculated values by Eq. (4) from air permeability with a pressure drop of 50 Pa. In addition, the difference between measured and calculated values is gradually decreased with the increase of specific airflow resistance. For the fabrics with measured specific airflow resistance higher than 80 Pa s/m, the measured values agree better with the calculated values. This result concurs with the previous study that the test accuracy of low specific airflow resistance is poor due to low signal-to-noise ratios.[4,5,9] Therefore, the Pearson

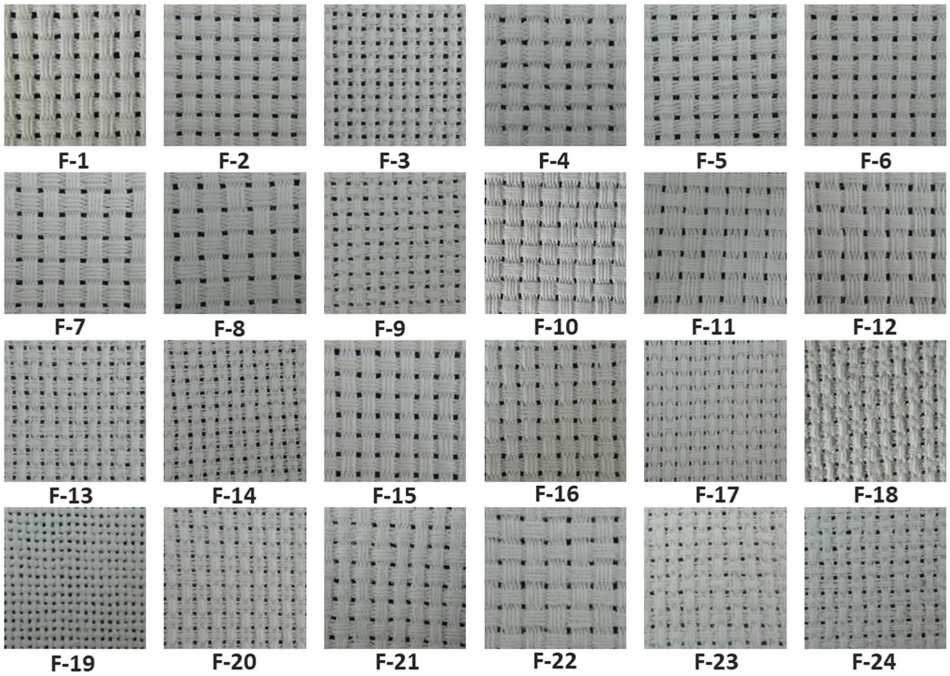

Fig. 1. (Color online) Photographs of 24 kinds of cross-stitching woven fabrics used in this study.

correlation[10] was used to investigate the reliability of specific airflow resistance tested by Nor1517A equipment. The Pearson correlation coefficients between measured specific airflow resistance and calculated ones from air permeability are shown in Table 2. The Pearson correlation coefficient becomes higher than 0.720 for 50, 100, and 150 Pa air pressure drop, and r is 0.692 when the air pressure drop is 200 Pa. For all used pressure drops, measured values are significantly related to the calculated values at 1% significance level.

Table 1. Measured air permeability and specific airflow resistance of 24 fabrics.

Fabrics	Surface density (kg/m^2)	Air permeability (mm/s) $\Delta p = 50$ Pa	Air permeability (mm/s) $\Delta p = 100$ Pa	Air permeability (mm/s) $\Delta p = 150$ Pa	Air permeability (mm/s) $\Delta p = 200$ Pa	Specific airflow resistance (Pa s/m)
F-1	0.292	486.4	753.2	951.7	1113.3	28.6
F-2	0.319	504.0	799.2	1010.9	1222.9	32.4
F-3	0.253	568.8	887.8	1124.6	1349.1	34.8
F-4	0.366	391.5	598.4	771.8	915.9	37.7
F-5	0.324	410.7	670.4	864.5	1015.5	38.8
F-6	0.371	422.7	679.6	871.5	1019.3	39.0
F-7	0.373	385.3	611.2	806.2	968.7	45.0
F-8	0.367	384.2	602.8	791.7	947.8	48.1
F-9	0.288	387.3	628.8	825.6	982.8	49.0
F-10	0.301	342.5	547.1	732.4	888.4	49.4
F-11	0.326	338.4	522.3	689.2	827.9	49.5
F-12	0.306	349.7	534.7	699.3	836.8	52.0
F-13	0.232	420.5	704.0	918.9	1093.6	52.6
F-14	0.229	461.5	748.6	969.1	1151.7	55.0
F-15	0.368	416.7	655.3	845.3	995.4	64.5
F-16	0.345	287.2	456.7	585.0	706.9	67.2
F-17	0.228	248.6	421.1	565.9	707.6	68.6
F-18	0.276	326.9	519.9	695.2	842.9	72.6
F-19	0.247	481.7	805.4	1034.9	1262.2	79.0
F-20	0.248	342.0	555.3	744.3	903.3	114.0
F-21	0.356	303.9	482.1	623.1	752.6	116.0
F-22	0.315	255.5	411.9	544.7	664.7	129.0
F-23	0.273	261.6	436.4	578.2	718	135.0
F-24	0.245	236.5	401.5	540.9	681.2	172.0

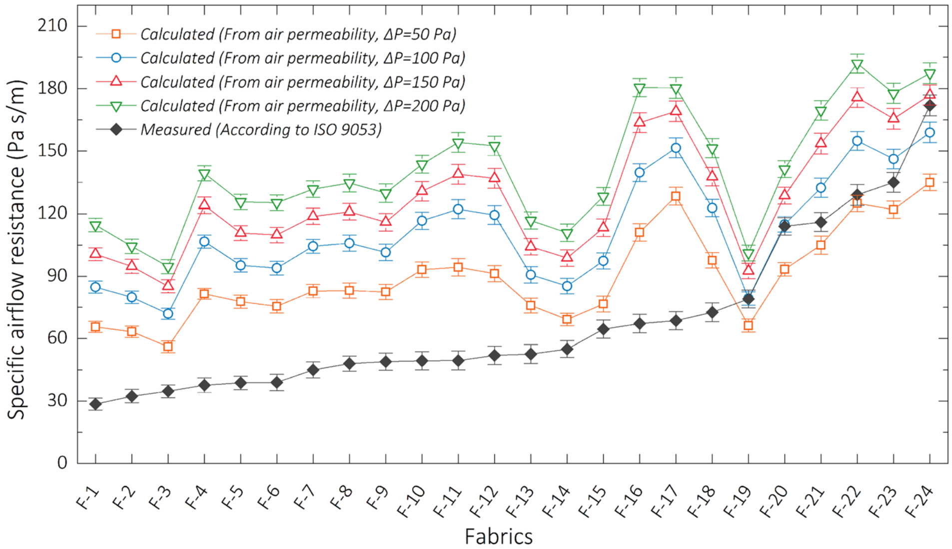

Fig. 2. (Color online) Measured and calculated specific airflow resistance of 24 fabrics.

In this study, the air permeability ranges from 200 to 1400 mm/s, which is far higher than the limit value of 0.5 mm/s reported by Beranek and Vér.[11] It has been found that the specific airflow resistance depends on the airflow velocity higher than 0.5 mm/s due to the pressure drop effects. In Sec. 5, Pieren's model was used to predict the sound absorption properties of fabrics based on both measured and calculated specific airflow resistance.

5. Prediction of sound absorption

Pieren has established a model to predict the sound absorption properties of thin fabrics.[5] In his model, specific airflow resistance R_s is used to characterize the sound energy loss inside the fabric, which is mainly attributed to the viscous friction. The expression of surface impedance is formulated as follows:

$$Z_T = Z_s + Z_c = \frac{R_s(\omega m)^2}{R_s^2 + (\omega m)^2} + j\frac{R_s^2(\omega m)}{R_s^2 + (\omega m)^2} - jZ_0 \cot(k_0 D), \tag{5}$$

where Z_s is the impedance of fabric and Z_c is the impedance of backing air gap, and D is the air gap depth, which is 0.03 m. k_0 denotes the wave number in air, and ω is the angular frequency, m is the surface mass density (kg/m^2), Z_0 is the air characteristic impedance, $Z_0 = \rho c$, ρ is the air density (kg/m^3), and c is the speed of sound in air (m/s). The normal incidence sound absorption coefficients are calculated as $1 - |(Z_T - \rho c)/((Z_T + \rho c)|^2$.[5]

In Fig. 3, the measured sound absorption coefficients α_{measured} by the impedance tube method and predicted sound absorption coefficients $\alpha_{\text{predicted}}$ are compared. As shown in Fig. 3(a), $\alpha_{\text{predicted}}$ using the measured specific airflow resistance is generally lower than the measured coefficients. In Figs. 3(b)–3(e), the predicted absorption coefficient is gradually increased with increasing pressure drop. In addition, the calculated specific airflow resistance from the air permeability can better predict the sound absorption coefficients than the measured ones by ISO 9053.[1] The linear regression equations and coefficients of determination R^2 between the measured and predicted sound absorption coefficients are shown in Fig. 3. In Fig. 3(a), R^2 is as low as 0.85, whereas R^2 values are higher than 0.91 using the predicted specific airflow resistance, as shown in Figs. 3(b)–3(e). The slopes of the regression lines are close to 1 for $\Delta p = 100$ and 150 Pa, indicating that these are good prediction models for sound absorption for textiles.

Table 2. Correlation coefficients between measured and calculated specific airflow resistance under different pressure drops, and critical value at 1% significance level.

	$\Delta p = 50$ Pa	$\Delta p = 100$ Pa	$\Delta p = 150$ Pa	$\Delta p = 200$ Pa	1% significance level
Pearson r	0.766	0.730	0.720	0.692	0.496

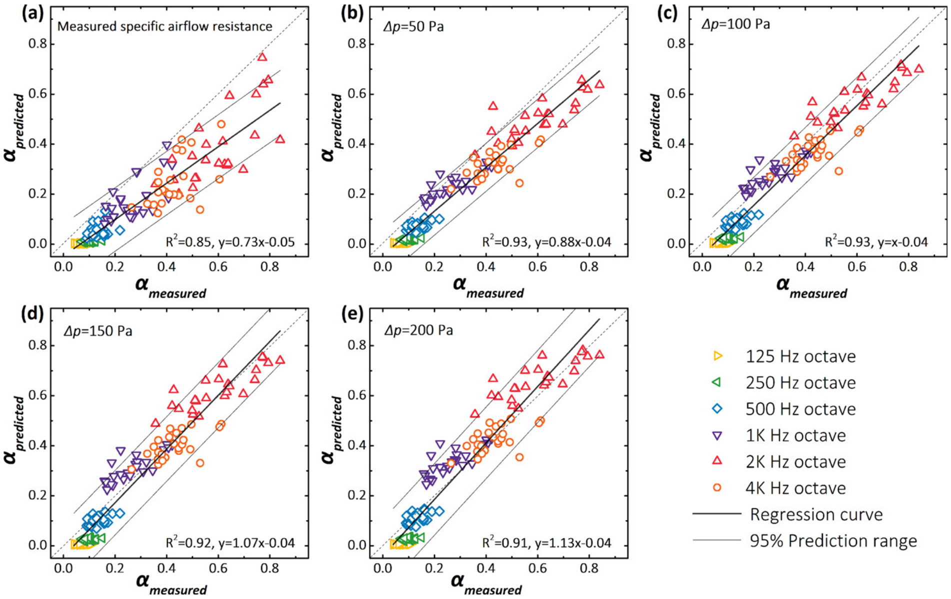

Fig. 3. (Color online) Relationship between the measured and predicted sound absorption coefficients from the specific airflow resistance of 24 fabrics.

6. Conclusions

This work proposes a method to calculate the specific airflow resistance of textiles from air permeability in accordance with ISO 9237 (Ref. 7) and ISO 9053.[1] The results indicated that the measured airflow resistance was generally lower than the calculated specific airflow resistance from air permeability under the given pressure drops. Using Pieren's absorption model, the sound absorption coefficients predicted from the calculated airflow resistance based on air permeability agree better with impedance tube measurements than those predicted from the measured specific airflow resistance.

Acknowledgments

The principal part of this work was finished at the Acoustic Technology Group, DTU. X.T. thanks the scholarship of Special Excellent Doctoral Candidate International Visit Program provided by Donghua University and the Fundamental Research Funds for the Central Universities (No. BCZD2018005). Nadia Larsen is also appreciated for language polishing.

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