A new high-frequency impedance tube for measuring sound absorption coefficient and sound transmission loss

Masateru KIMURA[1]; Jason KUNIO INCE Bd. Cert.[2]; Andreas SCHUHMACHER[3], Yunseon RYU[4]

[1] Brüel & Kjær Japan, Japan

[2] Brüel & Kjær North America, USA

[3,4] Brüel & Kjær Sound & Vibration Measurement, Denmark

ABSTRACT

A high-frequency Impedance Tube (HF Tube) that can measure acoustic performance (sound absorption coefficient and sound transmission loss) up to 12.8 kHz was developed. This frequency range has become important due to trends in the automotive and cell phone industry. The trend toward more electric and hybrid vehicles has brought about new noise sources and challenges. One in particular is electrical invertor noise in the 10 kHz range, which is one of the dominant noise sources in these vehicles. In cell phone and smart phone applications, the trend is to improve telephone speech quality. High frequency audible noise has a major influence on perceived quality. Previously, conventional impedance tubes (for example the Bruel and Kjaer Type 4206) could not evaluate acoustic performance in the frequency range of 8~10 kHz. The usable frequency range of the standard tube was limited to 6.4 kHz based on the microphone spacing and tube diameter. Therefore, based on ASTM E1050/ISO 10534-2 standard (for sound absorption coefficient) and ASTM E2611 standard (for sound transmission loss), a newly developed HF Tube allows for measurements of acoustic performance up to 12.8 kHz. The tube was designed with a 15 mm inner diameter and 11.9 mm microphone spacing. It was designed to use Brüel & Kjær's 1/4 inch microphones and pre-amplifiers, Type 4187/2670, from the conventional impedance tubes. In this paper, the HF Tube was verified by measurements an air cavity (empty tube) and some acoustic absorber materials with the results compared with the conventional impedance tubes.

Keywords: Impedance Tube, Absorption, Transmission I-INCE Classification of Subjects Number(s): 72.7

1. INTRODUCTION

Recently, demand for control of high frequency noise has been increasing. For example, Electric Vehicles (EV) and Hybrid Vehicles (HV) are becoming popular in the automotive industry. Inverter noise around 10 kHz that does not occur in a conventional automobile has become a new noise problem. Additionally, the noise in the frequency range above 5 kHz has become one of the important issues for cell phones and smartphones. This frequency range affects sound quality during a call and various remedies have already been taken in small devices to improve the perceived quality. One of the more popular remedies is the use of strategically placed acoustic materials.

One of the ways to characterize acoustic materials used for noise control is the measurement of the normal incidence sound absorption coefficient (SAC) and sound transmission loss (STL). These measurements can easily be performed using an impedance tube. One of the big advantages in using the impedance tube measurement system is that it can measure SACs and STLs using a small test sample (general less than 100mm) of acoustic material. It can also be used to calculate additional acoustic properties (characteristic impedances, propagation wavenumbers, etc.) of porous materials.

To observe acoustic properties around 8 ~ 10 kHz using the tube, a smaller diameter tube with smaller microphone spacing is required. However, it is difficult to increase the maximum frequency

1 Masateru.Kimura@bksv.com
2 Jason.Kunio@bksv.com
3 Andreas.Schuhmacher@bksv.com
4 YunS.Ryu@bksv.com

in conventional designs because with the smaller diameter of the tube comes an increase in the attenuation of the air and the minimum microphone spacing is limited by physical size of the microphone holders.

In this study, a new high-frequency impedance tube (HF Tube) was developed by redesigning the microphone holder to allow smaller microphone spacing and by using a high frequency loudspeaker which can provide sufficient acoustic excitation to 12.8kHz. The performance of the HF tube was verified by measuring an air cavity (zero absorption and zero transmission) and some common acoustic materials then comparing the results with the conventional tubes.

2. IMPEDANCE TUBE TEST FOR MEASURING ACOUSTIC PROPERTY

To measure specific impedances, sound absorption coefficients (SACs), sound transmission losses (STLs) and acoustic properties (characteristic impedances, propagation wavenumbers, effective densities, bulk moduli) of acoustic materials in normal incidence condition, an impedance tube is commonly used.

For measuring specific impedances and SACs, the two microphone transfer function method using an impedance tube is shown in Figure 1. This commonly-used measurement technique is specified in ISO 10534-2 standard[1] and ASTM E1050 standard[2]. In this method, the frequency response function between the sound pressure at Mic. 2 (shown in Figure 1) and the sound pressure at Mic. 1 (H_{21}) is measured, and the sound reflection coefficient (R) is calculated using H_{21} by

$$R = \frac{H_{21} - e^{-jks}}{e^{jks} - H_{21}} e^{2jk(l+s)} \quad , \tag{1}$$

From the calculation of the reflection coefficient we can now calculate additional material properties, such as the specific impedance ratio ($Z/\rho c$) and the SAC (α) using R *by:*

$$\frac{Z}{\rho c} = \frac{1+R}{1-R} \quad , \tag{2}$$

$$\alpha = 1 - |R|^2 \quad . \tag{3}$$

Where ρ is the density of air, c is the speed of sound in air, k is the wave number of air, l is the distance between Mic. 2 and the front of the sample, and s is the spacing between the microphones.

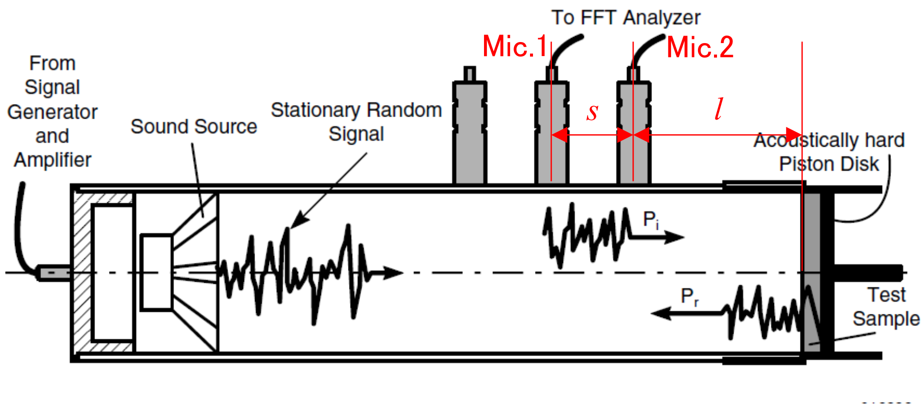


Figure 1 – Setup for the Impedance tube for SAC measurement

For calculating the normal incidence STL, a transfer matrix method using a modified four microphone impedance tube is used as shown in Figure 2. This method is specified in the ASTM E2611 standard [3]. In this method, the 2x2 transfer matrix of the sample,

$$\mathbf{T} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \quad , \tag{4}$$

is identified from the measurement of the sound pressures and the calculated particle velocities on the front and back surfaces of the sample[4] based on the measurement of the sound pressures at the four microphone locations. The normal incidence transmission loss (TL_n) and the other acoustic properties (characteristic impedances Z_p, propagation wavenumbers k_p, etc.) are also calculated using the transfer matrix **T**:

$$TL_n = 20\log_{10}\left|\frac{T_{11} + (T_{12}/\rho c) + \rho c T_{21} + T_{22}}{2e^{jkd}}\right| , \tag{5}$$

$$Z_p = \sqrt{\frac{T_{12}}{T_{21}}} , \tag{6}$$

$$k_p = \frac{1}{d}\cos^{-1} T_{11} . \tag{7}$$

Where d is the thickness of the sample.

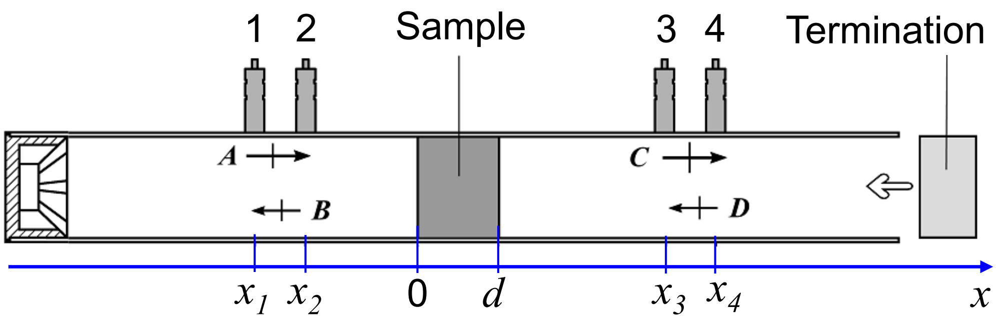
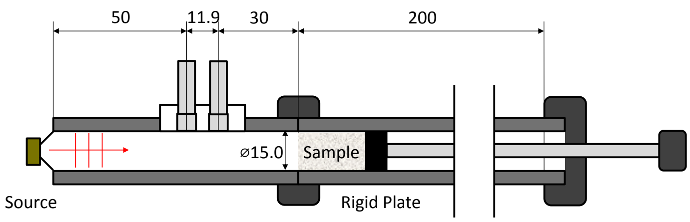


Figure 2 – Setup for the Impedance tube for STL measurement

3. HIGH FREQUENCY IMPEDANCE TUBE

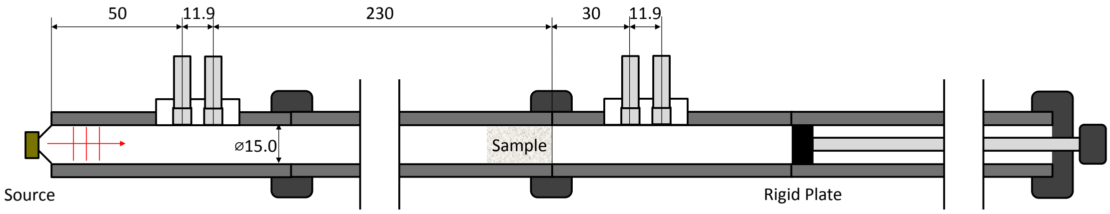
A high frequency impedance tube (HF tube) was developed for the purpose of measuring acoustic properties around 8k ~ 10 kHz. The unique features of the HF tube are as follows:

- Capable of measuring up to 12.8 kHz with a narrowband FFT, in conjunction with the Brüel & Kjær PULSE system, Type 7770 and 7758 software and Type 3160 LAN Xi module.
- Possible to re-use 1/4 inch microphones and pre-amplifiers, Type 4187/2670 designed for Brüel & Kjær Type 4206 impedance tube

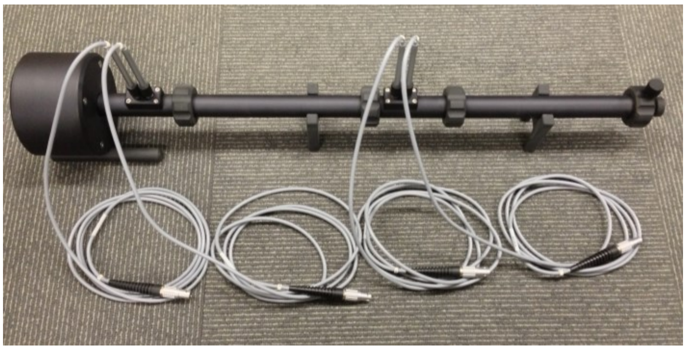


(3a) Outline drawing (3b) Picture

Figures 3a and 3b – Setup of the High frequency impedance tube for absorption meaurement



(4a) Outline drawing (hard wall termination)



(4b) Picture

Figures 4a and 4b – Setup of the High frequency impedance tube for transmission loss measurement

Table 1 – Specification of High-Frequency Impedance Tube (*d* is thickness of sample [mm])

	SAC setup	STL setup
Lower Frequency	1.0 kHz (for ASTM E1050) 1.5 kHz (for ISO 10534-2)	1.0 kHz (for ASTM E2611)
Upper Frequency	12.8 kHz	12.8 kHz
Inner Diameter	15.0 mm	15.0 mm
Distance from source to Mic.1	50.0 mm	50.0 mm
Distance from Mic.1 to Mic.2	11.9 mm	11.9 mm
Distance from Mic.2 to front surface of sample	30.0 mm	(230.0 – d) mm
Distance from front surface of sample to Mic.3	---	(30.0 + d) mm
Distance from Mic.3 to Mic.4	---	11.9 mm

4. VALIDATION OF SOUND ABSORPTION COEFFICIENT MEASUREMENTS SETUP

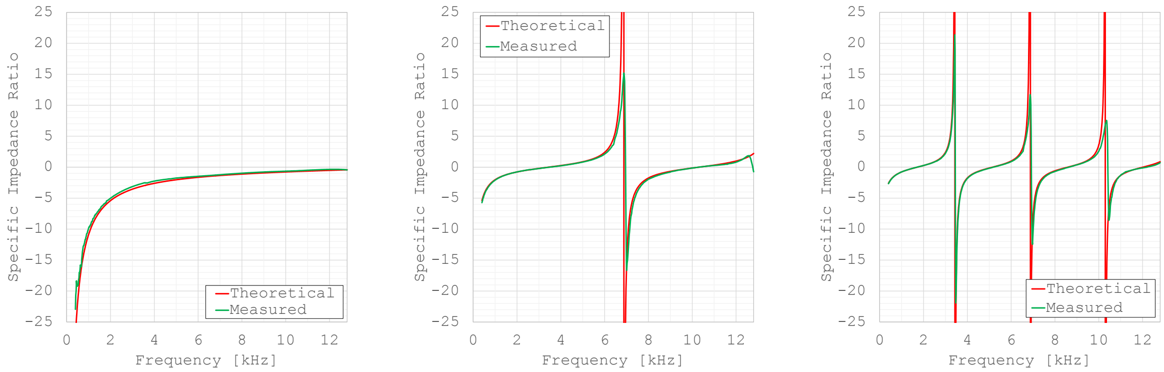
In this section, performance of the HF tube is verified by measuring an air cavity (zero absorption) and some commonly used acoustic materials then comparing the impedance ratio and the sound absorption coefficient results with the conventional tube.

4.1 Validation by measuring specific impedance of air cavity

To validate the performance of the HF tube, specific impedance ratios of three thicknesses of air cavities (5 mm, 25 mm and 50 mm) were measured, and the imaginary part of the impedance ratios were compared with the theoretical value of an air cavity with thickness d [5]:

$$\mathrm{Im}\left(\frac{Z}{Z_0}\right) = -\cot(kd) \tag{8}$$

The imaginary part of the theoretical and measured specific impedance ratios of the air cavities are shown in Figure 5. In the case of the 5 mm air cavity (Figure 5a), both values are in good agreement. Also, in the cases of the 25 mm and 50 mm air cavities (Figure 5b, 5c), several divergences of cot(kd) at $kd = n\pi$ (n is integer value) are observed. Other than the slight frequency shift and additional attenuation in the measured data both values are in good agreement.



(5a) 5 mm Air (5b) 25 mm Air (5c) 50 mm Air

Figures 5a, 5b and 5c – Comparison of the theoretical and measured specific impedance ratios of air cavities

Additionally, measured SACs are compared with theoretical SACs with consideration of the tube attenuation in reference [6]. Note that theoretical SACs, were calculated using the complex wave number k' with respect to the tube attenuation:

$$k' = k - jk'' \quad , \tag{9}$$

instead of the wave number $k = 2\pi f / c$ (where f is frequency and c is speed of sound in air). The term k'' is called the attenuation constant and A is a constant:

$$k'' = \frac{A\sqrt{f}}{cd} \quad . \tag{10}$$

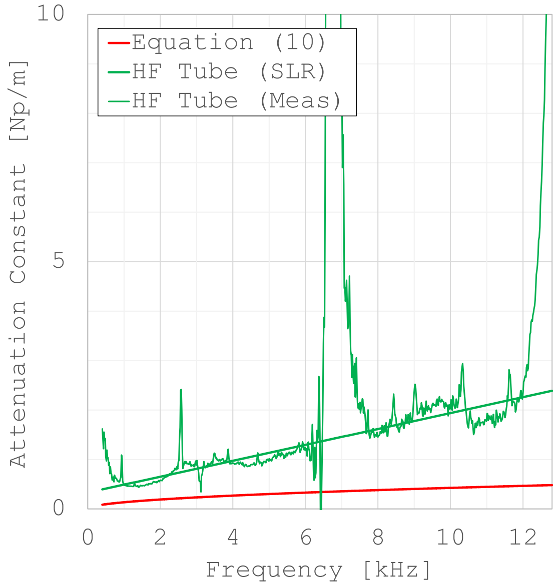
For the purposes of this paper A= 0.02203, which is defined in the ASTM E1050 standard [2], was used.

To compare with k'' calculated by equation (10), k was calculated by Utsuno's 2 Cavity method [7]. In this method, characteristic impedance Z_p and propagation constant $\gamma = jk_p$ are calculated using specific impedance Z_1 of front and back surface of the "sample" and $Z_2 = -j\rho c\cot(kd)$ for the two back cavity conditions using the cavity thicknesses $d^{(a)}$ and $d^{(b)}$.

$$Z_p = \rho c Z_c = \rho c \sqrt{\frac{Z_1^{(a)} Z_1^{(b)}\left(Z_2^{(a)} - Z_2^{(b)}\right) - Z_2^{(a)} Z_2^{(b)}\left(Z_1^{(a)} - Z_1^{(b)}\right)}{\left(Z_2^{(a)} - Z_2^{(b)}\right) - \left(Z_1^{(a)} - Z_1^{(b)}\right)}} \quad . \tag{11}$$

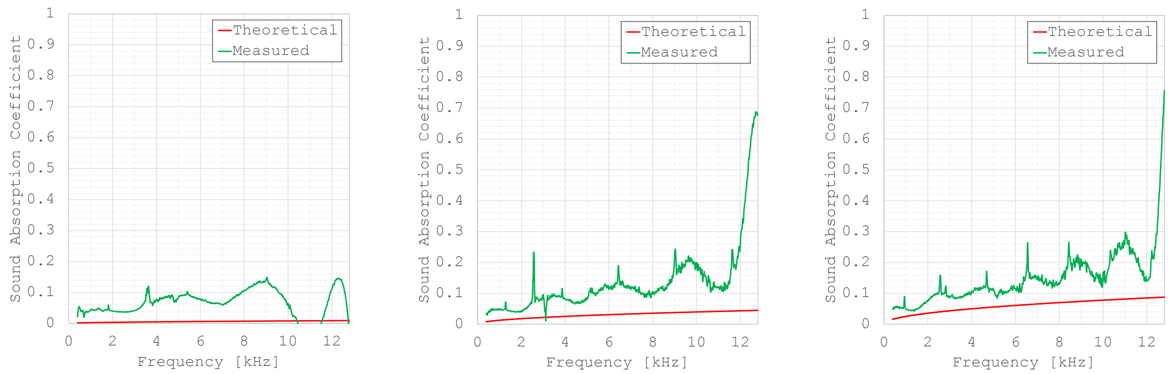
$$\gamma = jk'_p = k''_p + jk_p = \frac{1}{2d}\ln\left(\frac{Z_1 + Z_c}{Z_1 - Z_c}\,\frac{Z_2 - Z_c}{Z_2 + Z_c}\right) \quad . \tag{12}$$

Figure 6 shows the attenuation constant k'' of a 25 mm thick air cavity calculated using the 2 cavity method. The specific impedance ratio of 25 mm and 50 mm thicknesses of air (which assumed 0 mm and 25 mm thick back cavities respectively with a 25 mm thick front air cavity "sample"), are compared with k'' calculated from equation (10).



Figures 6 – Comparison of the theoretical and measured attenuation coefficient of 25 mm thickness air cavities. *SLR is a linear regression of the measured data*

The theoretical and measured SACs of the air cavities are shown in Figure 7. The measured attenuation coefficient and SACs are larger than the theoretical SACs. We can attribute the differences in the measured and predicted results to the attenuation of actual tube being larger than the predicted values. The phase match of the measurement system can also add error to the results especially for a sample with very low absorption such as the air cavity. It has been shown that the procedures recommended by the standards [2,3], though adequate when the specimen has high absorption, are insufficient when measuring small sound absorption coefficients.



(7a) 5 mm Air (7b) 25 mm Air (7c) 50 mm Air

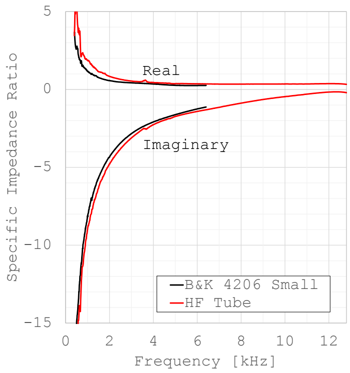
Figures 7a, 7b and 7c – Comparison of the theoretical and measured sound absorption coefficient of air cavities

4.2 Validation by comparing results of conventional tube

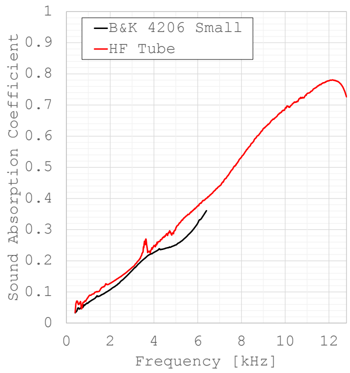
To validate the accuracy of HF tube, specific impedance ratios and SACs were measured and compared using the same materials in both the HF tube and the small Brüel & Kjær Type 4206 impedance tube. The standard small tube has a 29 mm diameter with a 20 mm microphone spacing giving an upper useable frequency of 6.4 kHz.

Measurement results of thin recycled felt and the 25 mm thick polyurethane foam, which is provided as the calibration sample of the Brüel & Kjær Type 4206, are shown in Figures 8 and 9.

(8a) Image of samples (Left: for Brüel & Kjær 4206 small tube, Right: for HF tube)

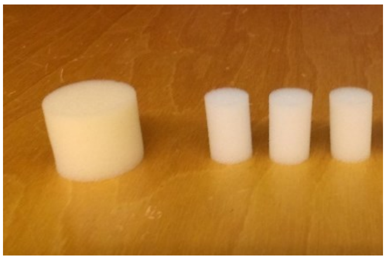


(8b) Specific Impedance Ratios

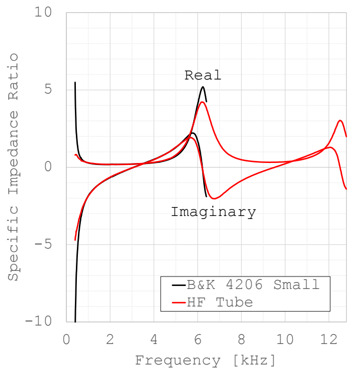


(8c) Sound Absorption Coefficients

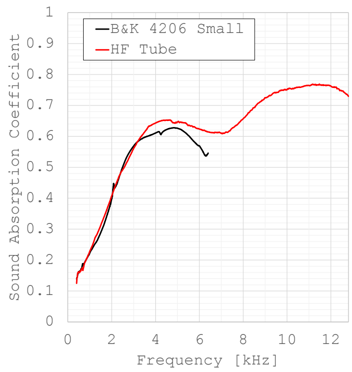
Figures 8a, 8b and 8c – Comparison of acoustic properties of recycled felt



(9a) Image of samples (Left: for Brüel & Kjær 4206 small tube, Right: for HF tube)



(9b) Specific Impedance Ratios



(9c) Sound Absorption Coefficients

Figure 9a, 9b and 9c – Comparison of acoustic properties of polyurethane foam

A more rigorous examination of the variability in the measured results can be achieved through examination of the repeatability and reproducibility intervals, I(r) and I(R). The "within" and "between" laboratory precision of this test method, expressed in terms of the within-laboratory, 95 % Repeatability Interval, I(r), and the between-laboratory, 95 %, Reproducibility Interval, I(R), is listed in Table 2. These statistics are based on the results of a round-robin test program involving ten laboratories [2].

Table 2 – Comparison of the SAC results from figures 8c and 9c with the Repeatability and Reproducibility from Table 2 of the ASTM E1050 Standard [2]

Felt (Figure 8c)	**Normal Incidence SAC**			
	500 Hz	1000 Hz	2000 Hz	4000 Hz
Small tube 29mm	0.043	0.065	0.107	0.227
HF tube 15mm	0.071	0.085	0.128	0.249
Difference	0.028	0.019	*0.020*	0.022
Repeatability I(r)	0.040	0.050	0.010	0.040
Reproducibitlity (IR)	0.110	0.120	0.030	0.070

Foam (Figure 9c)	Normal Incidence SAC			
	500 Hz	1000 Hz	2000 Hz	4000 Hz
Small tube 29mm	0.162	0.224	0.398	0.611
HF tube 15mm	0.161	0.230	0.407	0.643
Difference	0.001	0.006	0.009	0.032
Repeatability I(r)	0.040	0.050	0.010	0.040
Reproducibitlity (IR)	0.110	0.120	0.030	0.070

It can be seen that the differences for all the tests are within the criteria for both within- and between-laboratory precision, except for the felt sample which had low absorption at 2kHz. Based on the results in Table 2 and figures 8c and 9c, the measurement results in both tubes were in good agreement without tube attenuation correction.

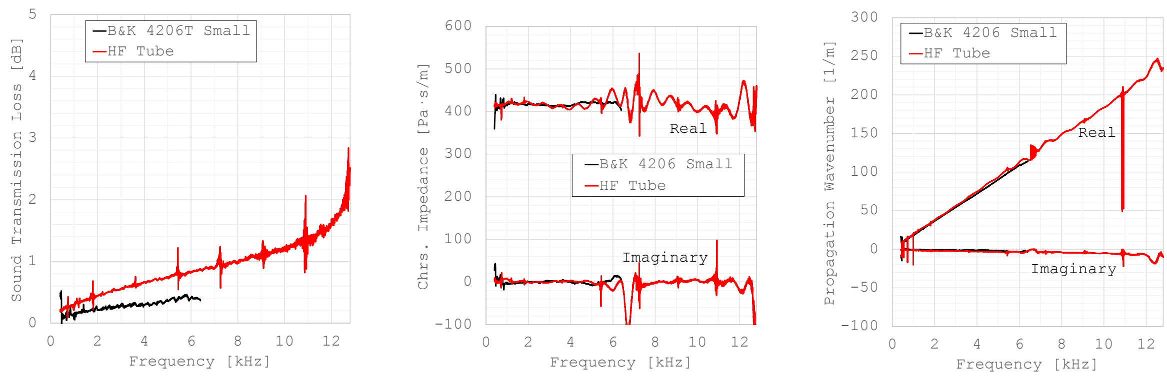
5. VALIDATION OF SOUND TRANSMISSION LOSS MEASUREMENTS SETUP

In this section, performance of the HF tube is verified by measuring an air cavity (zero transmission loss) and some commonly used acoustic materials then comparing the STLs, characteristic impedances and propagation wavenumbers results with the conventional tubes.

5.1 Validation by measuring sound transmission losses of 25 mm thick air cavity

To validate the performance of the HF tube, STLs, characteristic impedances and propagation wavenumbers of a 25 mm thick air cavities were measured, and compared with the results measured by small tube setup of Brüel & Kjær Type 4206 impedance tube. The results are compared in Figure 10. Also Figure 11 shows the comparison of attenuation constants obtained from the imaginary part of the wave number Figure 10c with equation (10).

By comparing Brüel & Kjær Type 4206, the STL of HF tube (Figure 10a) is larger which is due to tube attenuation caused by the smaller tube diameter. The tube attenuation can be calculated from the imaginary part of the propagation wavenumber (Figures 10c). However, the characteristic impedances are in good agreement (real value: approximately 420, imaginary value: approximately 0).



(10a) Sound Transmission Losses (10b) Characteristic Impedances (10c) Propagation Wavenumbers

Figure 10a, 10b and 10c – Comparison of acoustic properties of 25 mm thick air cavity

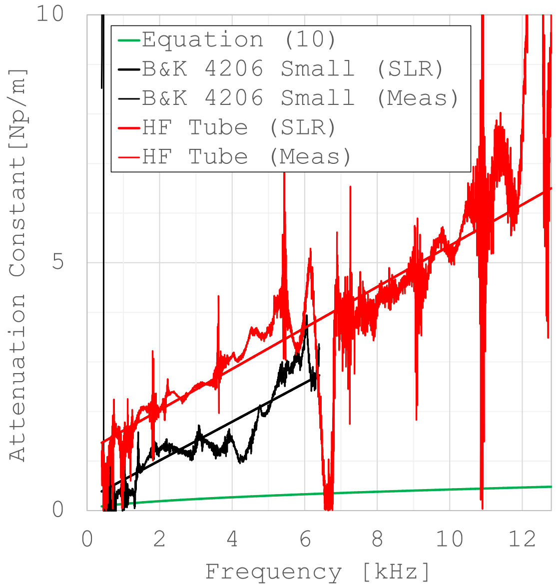
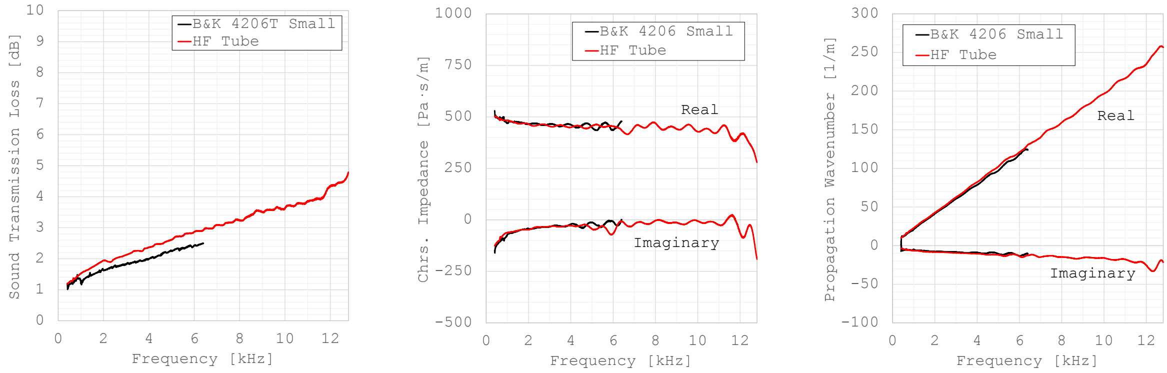


Figure 11 – Comparison of the theoretical and measured attenuation coefficient of 25 mm thickness air cavity. *SLR is a linear regression of the measured data*

5.2 Validation by measuring sound transmission losses of 25 mm polyurethane foam

The STL, characteristic impedance and propagation wavenumber of the 25 mm thick polyurethane foam were measured by both HF tube and small tube setup of Brüel & Kjær Type 4206 impedance tube. The results are shown in Figure 12.

By comparing Brüel & Kjær Type 4206, STL of the HF tube (Figure 12a) is little larger which again can be attributed to the tube attenuation caused by smaller tube diameter, however, both results are in good agreement.



(12a) Sound Transmission Losses (12b) Characteristic Impedances (12c) Propagation Wavenumbers

Figure 12a, 12b and 12c – Comparison of acoustic properties of 25 mm thick polyurethane foam

6. CONCLUSIONS

By the validation tests that were performed, it is verified that the sound absorption coefficient and the sound transmission loss in the normal incidence condition can be measured practically by using the newly developed HF tube.

This was quantitatively verified through comparison of the absolute differences of absorption to the Repeatability Interval I(r) and Reproducibility Interval I(R) criteria as given in Table 2 of the standard [2]. Most of the calculated differences in the absorption results met the required 95% criteria. From this, it can be reasonably concluded, either tube design can be used with the expectation of valid results for the absorption coefficient and transmission loss. Any differences in results between the two tube diameters are most likely attributed to imprecision associated with the preparation and installation of the test samples or the air attenuation and not the impedance tube diameter.

There is a greater influence of air attenuation in the HF tube when compared with the conventional tubes. Therefore, in the case when the sound absorption coefficient or transmission loss of a sample is small, it is necessary to perform attenuation correction by the complex propagation wavenumber obtained by the measurement of a sample with zero absorption such as a hard reflective surface.

Additional work needs to be conducted to understand the differences in the measured propagation wave number between the transfer matrix method (Figure 11) and the two cavity method (Figure 6).

ACKNOWLEDGEMENTS

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