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by W.T. Chu

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RÉSUMÉ

Des mesures plus perfectionnées des coefficients de réflexion complexes prise à l'aide d'une excitation monofréquence et d'un amplificateur de blocage pour l'analyse des données ont permis de déceler une faiblesse de la technique de fonction de transfert à deux microphones pour les mesures par tube à impédance. Une position unique des microphones pour toutes les fréquences, comme le recommande la norme actuelle ASTM E1050-86, compromet la précision des mesures. Pour obtenir des mesures exactes, l'un des microphones doit se trouver à un noeud de pression du diagramme d'ondes stationnaires, de préférence au premier noeud. La position de l'autre microphone ne semble pas constituer un facteur critique tant que l'intervalle entre les deux positions ne s'approche pas de la demi-longueur d'onde. La méthode retenue pour cette étude utilise l'échantillonnage séquentiel avec un seul microphone plutôt que l'échantillonnage simultané avec deux microphones. Cette méthode est plus avantageuse que les méthodes standard actuelles pour les mesures par tube à impédance.

Further experimental studies on the transfer-function technique for impedance tube measurements

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More refined measurements of the complex reflection coefficients using single-frequency excitation and a lock-in amplifier for data analysis have revealed a limitation in the two-microphone transfer function technique for impedance tube measurements. A fixed choice of microphone positions for all frequencies as suggested by the current standard ASTM E1050-86 will compromise the accuracy of measurements. For accurate measurements, one of the microphone positions has to be close to a minimum pressure point of the standing-wave pattern, preferably the first minimum point. The choice of the other microphone position does not seem to be critical as long as the separation of the two positions is not close to a half-wavelength. The procedure employed in this study uses sequential sampling with one microphone instead of simultaneous sampling with two microphones. It presents a technique that is better than the existing standard methods for impedance tube measurements.

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INTRODUCTION

The two-microphone transfer function method for absorption and impedance measurements, introduced by Seybert and Ross[1] and further developed by Chung and Blaser,[2] has now been standardized by the American Society for Testing Materials E1050-86.[3] Recently, Fahy,[4] Chu,[5] and Pope[6] have demonstrated the possibility of implementing the method with a single microphone, thereby eliminating any error associated with the phase mismatch problem. Although this technique is much faster than the conventional standing wave ratio (SWR) method, results presented by Fahy[4] and Chu[5] showed that it is not as precise as the SWR method and that a single choice of the microphone positions is not sufficient to cover a broad frequency range. Using numerical simulation, Boden and Abom[7] have shown that the two-microphone transfer function method will have its lowest sensitivity to errors in input data if the microphones are separated by about a quarter wavelength, indicating, also, the necessity of using different microphone positions for different frequencies. In order to establish some guidelines for the proper choice of the microphone positions and to determine the precision that can be obtained by the two-microphone transfer function method, some refined measurements have been performed using single-frequency excitation and a lock-in amplifier for the determination of the transfer function. The procedure and results are reported in this article.

I. APPARATUS AND TEST PROCEDURE

Figure 1 shows a schematic diagram of the apparatus used in this investigation. The impedance tube is a 107-cm-long brass tube with an internal diameter of 5.72 cm. The tube was driven by a horn driver mounted on the side to allow a probe-tube microphone to traverse the center line. The microphone used was a 6.4-mm (1/4-in.) model MK 601R pendant microphone supplied by Metrosonic Inc. An

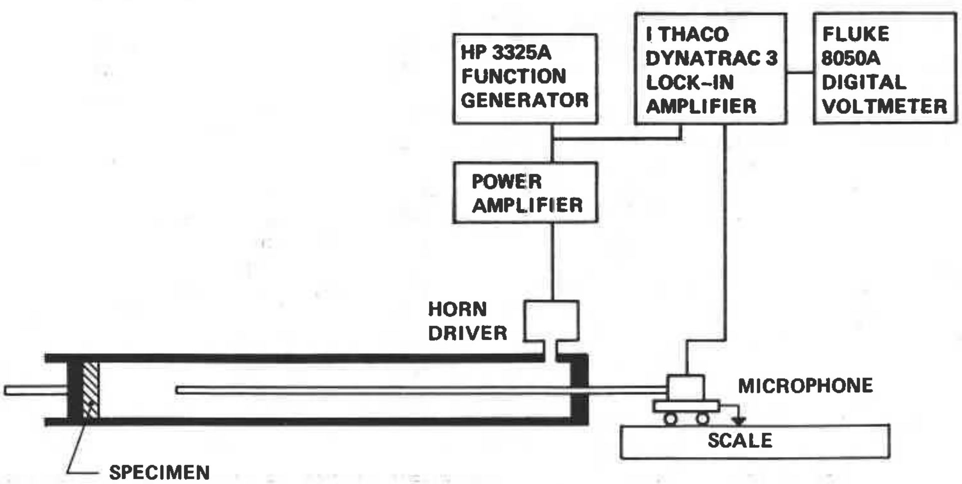

FIG. 1. Schematic diagram of apparatus.

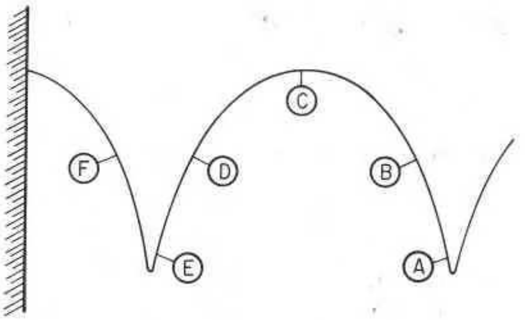

FIG. 2. Approximate locations of microphone No. 1 along the standing-wave pattern.

HP 3325A function generator was used to provide a very stable sine wave for the experiment.

The procedure used is similar to the single microphone technique of Ref. 5 except that the transfer function between the driving signal and the individual microphone signal was measured with an Ithaco Dynatrac 3 lock-in amplifier that has very good output stability. Using a four-digit digital voltmeter to measure the output of the lock-in amplifier, the system can provide an 80-dB dynamic range for the amplitude and 0.1-deg resolution for the phase measurements. The complex reflection coefficient R of a specimen located at one end of the impedance tube is computed from the following equation[5]:

$$R(f) = \{[H_{12}(f) - e^{-s(ik+a)}]/[e^{s(ik+a)} - H_{12}(f)]\}e^{2L(ik+a)}, \quad (1)$$

where H_{12} is the acoustic transfer function for the two microphone locations, f is the frequency, k is the wavenumber, a is the attenuation constant, s is the microphone separation, and L is the distance of microphone No. 1 from the surface of the specimen. The attenuation constant a and the acoustical center of the probe-tube microphone were also determined according to the procedures in Ref. 8. The wavenumber k was computed from the speed of sound that was calculated using the room temperature measured during the experiment.

Four different absorptive specimens were used in this investigation. These were chosen to represent typically the material often tested in an impedance tube. For each sample, the transfer function between the driving signal and the microphone signal was measured for about 20 microphone positions at a few chosen frequencies. From these results, different pairs of microphone positions could be selected for the computation of the complex reflection coefficients of each specimen at the chosen frequencies using Eq. (1) to show the effect of the choice of the microphone positions.

For comparison purposes, the complex reflection coefficients of these specimens were also measured by an improved version of the standard SWR method[9] under identical conditions and using the same apparatus. Although there are also uncertainty and measurement errors associated with the SWR method,[10] it is still considered to be a simple method that can provide results with great precision. The improved procedure is essentially an iterating scheme based on the exact plane-wave analysis of the standing-wave pattern in the tube including the tube attenuation (see the Appendix).

II. SPECIMEN DESCRIPTION

The first specimen used was the hard reflecting surface surface of a 1.27-cm-thick Bakelite disk. It was chosen as a

TABLE I. Deviation from SWR results for magnitude and phase of the complex reflection coefficient of a hard reflecting surface. SWR magnitude $|R| = 1.001$ and phase $\phi(\text{deg}) = 0.4$; frequency = 1000 Hz. Values in bold type indicate microphone near pressure minimum.

Microphone No. 2		Microphone No. 1 position (cm)						Microphone No. 1 position (cm)					
		25.7 (A)	23.0 (B)	17.0 (C)	11.0 (D)	8.7 (E)	6.0 (F)	25.7 (A)	23.0 (B)	17.0 (C)	11.0 (D)	8.7 (E)	6.0 (F)
Position (cm)	Pressure (relative)	Deviation of magnitude from SWR value						Deviation of phase from SWR value					
1.0	8.788	0.003	0.058	−0.142	−0.019	**−0.001**	0.020	−0.1	1.7	−0.9	−0.3	**−0.1**	1.3
2.0	8.425	0.003	0.060	−0.063	[−0.015]	**−0.001**	0.018	−0.2	1.2	1.8	[0.1]	**−0.1**	0.8
3.0	7.716	0.002	0.052	−0.009	−0.006	**−0.001**	0.004	−0.2	1.4	1.3	0.1	**−0.1**	0.9
4.0	6.764	0.002	0.061	0.002	−0.003	**0.000**	−0.002	−0.2	1.4	1.3	0.2	**−0.1**	0.8
5.0	5.591	0.003	0.129	−0.002	−0.004	**0.000**	0.005	−0.2	1.1	1.4	0.4	**−0.1**	0.3
6.0	4.205	0.003	*****	0.000	−0.003	**0.000**		−0.2	***	1.0	0.4	**−0.1**	
8.0	1.019	0.003	−0.008	−0.001	−0.002	**−0.001**		−0.2	−0.5	−0.1	−0.2	**−0.1**	
8.4	**0.369**	*****	**−0.002**	**0.000**	**0.000**	**0.000**		***	**−0.2**	**−0.1**	**−0.1**	**−0.1**	
8.7	**0.126**	**0.000**	**0.000**	**−0.001**	**0.000**			**−0.2**	**−0.1**	**−0.1**	**−0.1**		
9.0	0.627	0.001	0.002	−0.009	−0.001			−0.2	−0.1	−0.3	−0.3		
11.0	3.765	0.002	0.011	−0.005				−0.2	0.5	−0.3			
13.0	6.384	0.002	0.025	0.016				−0.1	1.0	−0.3			
15.0	8.188	0.003	[0.034]	0.056				−0.1	[1.3]	0.8			
17.0	8.940	0.002	0.029					−0.2	1.4				
19.0	8.598	0.002	0.026					−0.2	0.7				
21.0	7.078	0.002	0.017					−0.2	0.0				
23.0	4.550	0.001						−0.3					
24.5	2.229	0.001						−0.3					
25.2	1.082	0.002						−0.3					

TABLE II. Deviation from SWR results for magnitude and phase of the complex reflection coefficient of a hard reflecting surface. SWR magnitude $|R| = 1.002$ and phase $\phi(\text{deg}) = 0.2$; frequency = 500 Hz. Values in bold type indicate microphone near pressure minimum.

Microphone No. 2		Microphone No. 1 position (cm)						Microphone No. 1 position (cm)					
		51.3 (A)	47.5 (B)	35.0 (C)	25.0 (D)	17.5 (E)	10.0 (F)	51.3 (A)	47.5 (B)	35.0 (C)	25.0 (D)	17.5 (E)	10.0 (F)
Position (cm)	Pressure (relative)	Deviation of magnitude from SWR value						Deviation of phase from SWR value					
3.0	8.769	-0.001	0.013	0.180	0.036	**-0.001**	0.044	0.2	1.8	-0.6	0.1	**0.0**	2.7
5.0	8.211	-0.001	0.009	0.118	0.038	**0.000**	0.042	0.2	1.8	0.8	0.4	**0.0**	2.8
7.5	7.141	-0.002	-0.001	0.094	[0.041]	**0.000**	0.029	0.2	1.6	1.5	[0.8]	**0.1**	3.0
10.0	5.708	-0.002	-0.011	0.069	0.039	**0.001**		0.1	1.0	2.1	1.2	**0.1**	
12.5	3.892	-0.002	*****	0.039	0.028	**0.000**		0.1	***	1.2	0.9	**0.1**	
15.0	1.866	-0.002	0.000	0.014	0.014	**0.000**		0.1	-0.7	0.4	0.4	**0.1**	
17.0	**0.179**	*****	**-0.001**	**0.000**	**0.000**	**-0.001**		***	**-0.1**	**0.0**	**0.0**	**0.0**	
17.5	**0.235**	**0.000**	**0.000**	**-0.002**	**-0.002**			**0.1**	**0.1**	**0.0**	**0.0**		
20.0	2.317	0.000	0.006	-0.007	-0.016			0.2	0.4	-0.3	-0.6		
25.0	5.931	0.001	0.022	0.011				0.2	1.1	0.2			
30.0	8.296	0.001	[0.033]	0.058				0.3	[1.7]	2.3			
35.0	9.094	0.000	0.028					0.2	1.6				
40.0	8.093	-0.001	0.014					0.1	1.0				
42.5	6.852	-0.001	0.014					0.1	1.2				
45.0	5.279	-0.001	0.013					0.1	1.5				
47.5	3.458	-0.001						0.1					
50.0	1.385	-0.001						0.1					

calibrating device for the experiment since its reflection coefficient is known to be real and equal to 1. The second specimen used was a 4.9-cm-thick open cell plastic foam with a fairly uniform surface. The third specimen used was a modification of the second sample. The modification involved taping the first and third quadrant of the circular surface with masking tape to provide a nonuniform absorptive surface. The fourth specimen used was a resonant absorber consisting of a 0.8-mm-thick perforated plate backed by a 3.5-cm air space. The plate has three 0.32-cm-diam holes giving the system a resonant frequency of about 500 Hz.

III. RESULTS AND DISCUSSIONS

From each set of the results taken for about 20 microphone positions, six were picked for the No. 1 microphone position to give a fair representation of locations along the standing-wave pattern (A to F in Fig. 2). For each chosen position of microphone No. 1, the complex reflection coefficients were computed for all the possible choices of the No. 2 microphone position from the set. Some typical results are presented in Table I–V for the different specimens.

In these tables, the positions of microphone No. 2 are shown in the first column. The magnitudes of the corre-

TABLE III. Deviation from SWR results for magnitude and phase of the complex reflection coefficient of a 4.9-cm-thick plastic foam. SWR magnitude $|R| = 0.724$ and phase $\phi(\text{deg}) = -49.2$; frequency = 400 Hz. Values in bold type indicate microphone near pressure minimum.

Microphone No. 2		Microphone No. 1 position (cm)						Microphone No. 1 position (cm)					
		57.0 (A)	47.0 (B)	37.0 (C)	22.0 (D)	16.5 (E)	10.0 (F)	57.0 (A)	47.0 (B)	37.0 (C)	22.0 (D)	16.5 (E)	10.0 (F)
Position (cm)	Pressure (relative)	Deviation of magnitude from SWR value						Deviation of phase from SWR value					
1.0	4.351	-0.001	0.031	-0.017	[-0.005]	**0.002**	0.014	-0.1	2.3	0.6	[0.0]	**-0.1**	-0.1
2.5	4.086	0.000	0.049	-0.011	-0.004	**0.003**	0.015	-0.2	2.2	0.9	0.1	**-0.1**	-0.3
4.5	3.624	-0.001	*****	-0.014	-0.006	**0.001**	0.020	0.0	***	-0.1	-0.1	**-0.1**	0.3
6.5	3.107	-0.004	0.018	0.005	0.000	**0.002**	0.007	-0.4	-2.5	-0.1	-0.3	**-0.3**	0.0
8.0	2.692	-0.003	0.009	0.003	0.000	**0.002**	0.013	-0.4	-1.2	0.0	-0.2	**-0.3**	-0.1
10.0	2.094	-0.005	0.012	0.006	0.002	**0.003**		-0.6	-0.7	-0.1	-0.3	**-0.4**	
12.0	1.489	-0.010	0.006	0.002	0.000	**0.001**		-0.6	-0.8	-0.4	-0.5	**-0.3**	
14.5	**0.897**	*****	**0.002**	**0.000**	**0.000**	**0.002**		***	**-0.3**	**-0.2**	**-0.3**	**-0.1**	
16.5	**0.864**	**0.001**	**0.004**	**0.001**	**0.002**			**0.1**	**-0.2**	**-0.3**	**-0.4**		
18.0	1.174	-0.001	0.002	0.000	0.001			-0.1	-0.1	-0.3	-0.4		
22.0	2.342	-0.003	0.000	-0.003				-0.2	0.1	-0.3			
27.0	3.710	-0.002	[-0.003]	-0.010				-0.3	[0.0]	-0.9			
32.0	4.615	-0.002	0.003	0.004				-0.2	0.4	-1.0			
37.0	4.936	-0.003	0.001					-0.2	1.0				
42.0	4.653	-0.002	0.008					-0.2	1.2				
47.0	3.783	-0.001						-0.4					
52.0	2.437	0.000						-0.2					

TABLE IV. Deviation from SWR results for magnitude and phase of the complex reflection coefficient of a 4.9-cm-thick plastic foam with taped surface. SWR magnitude $|R| = 0.506$ and phase $\phi(\text{deg}) = -65.3$; frequency = 500 Hz. Values in bold type indicate microphone near pressure minimum.

Microphone No. 2 Position (cm)	Pressure (relative)	Microphone No. 1 position (cm) — Deviation of magnitude from SWR value: 44.0 (A)	38.0 (B)	29.0 (C)	20.0 (D)	12.0 (E)	6.0 (F)	Microphone No. 1 position (cm) — Deviation of phase from SWR value: 44.0 (A)	38.0 (B)	29.0 (C)	20.0 (D)	12.0 (E)	6.0 (F)
1.0	5.908	−0.001	0.011	0.013	−0.001	**−0.006**	0.008	0.5	−0.8	−0.3	−0.5	**0.2**	0.5
2.0	5.524	−0.003	0.017	0.009	−0.002	**−0.007**	0.008	0.6	0.8	−0.8	−0.7	**0.2**	1.2
3.0	5.142	−0.002	*****	0.013	[0.002]	**−0.005**	0.007	0.3	***	0.1	[−0.4]	**0.0**	0.3
4.5	4.501	−0.003	−0.001	0.011	0.003	**−0.005**	0.010	0.2	3.4	0.2	−0.4	**−0.1**	0.4
6.0	3.831	−0.004	0.004	0.011	0.004	**−0.004**		−0.1	1.3	0.3	−0.4	**−0.4**	
8.0	3.035	0.000	−0.006	0.004	0.002	**−0.003**		0.2	0.8	0.7	0.1	**−0.2**	
9.5	**2.581**	*****	**−0.005**	**0.001**	**0.001**	**−0.005**		***	**0.1**	**0.5**	**0.0**	**−0.4**	
12.0	**2.508**	**−0.002**	**−0.007**	**−0.005**	**−0.002**			**−0.5**	**−0.1**	**0.7**	**0.5**		
16.0	3.856	−0.001	−0.004	−0.007	0.001			0.2	−0.1	0.9	1.6		
20.0	5.596	0.003	[0.001]	−0.010				0.2	[−0.7]	−0.1			
25.0	7.027	0.002	0.004	−0.021				0.3	−0.8	−0.6			
29.0	7.278	0.002	0.012					0.7	−0.5				
35.0	6.092	−0.002	−0.001					0.3	−1.1				
38.0	4.941	−0.005						0.4					
41.0	3.669	−0.002						0.1					

sponding acoustical pressures at these positions are recorded in the second column to indicate the relative locations of the microphone with respect to the standing-wave pattern. Results for the six chosen locations of microphone No. 1 are tabulated in columns 3 to 8 for the magnitude $|R|$ and in columns 9 to 14 for the phase ϕ of the reflection coefficients, omitting those cases (marked ****) where the separation of the microphone positions was approximately equal to one-half wavelength. They are presented as differences from the SWR results which are also shown in these tables. In columns 4, 6, 10, and 12, values presented with the square brackets are for those cases where the microphone separation was close to one-quarter wavelength. Data presented in these tables show a fairly consistent picture from which one can make the following observations.

First, when microphone No. 1 is located close to the first minimum pressure point (position E), both magnitude and phase of the measured reflection coefficients show little dependence on the position of microphone No. 2 as indicated by the results shown in columns 7 and 13 of these tables. The consistency of the results for position E shown in Tables I and II for the hard reflecting surface indicates that the present experimental setup is capable of resolving the magnitude and phase of the reflection coefficient to 0.001 and 0.1 deg,

TABLE V. Deviation from SWR results for magnitude and phase of the complex reflection coefficient of a resonant absorber. SWR magnitude $|R| = 0.812$ and phase $\phi(\text{deg}) = -68.5$; frequency = 400 Hz. Values in bold type indicate microphone near pressure minimum.

Microphone No. 2 Position (cm)	Pressure (relative)	Microphone No. 1 position (cm) — Deviation of magnitude from SWR value: 54.0 (A)	44.0 (B)	34.0 (C)	24.0 (D)	15.0 (E)	9.0 (F)	Microphone No. 1 position (cm) — Deviation of phase from SWR value: 54.0 (A)	44.0 (B)	34.0 (C)	24.0 (D)	15.0 (E)	9.0 (F)
1.0	1.612	−0.006	*****	0.006	−0.005	**−0.002**	0.003	−0.6	***	−2.2	0.7	**−0.2**	0.4
2.0	1.530	−0.004	0.084	0.006	[−0.003]	**0.000**	0.006	−0.9	1.6	−0.9	[−0.1]	**−0.1**	−0.1
3.0	1.435	−0.001	0.008	−0.001	[−0.006]	**0.000**	0.011	−0.9	3.7	−0.1	[0.3]	**0.0**	−0.3
4.5	1.259	−0.002	0.010	0.001	−0.004	**0.000**	0.010	−0.9	1.1	−0.4	0.0	**−0.1**	−0.2
6.0	1.075	0.000	−0.004	−0.003	−0.007	**−0.001**	0.019	−0.9	0.5	−0.4	0.0	**0.0**	0.0
7.5	0.875	−0.001	−0.002	−0.002	−0.006	**−0.002**	0.028	−0.9	−0.1	−0.6	−0.2	**−0.1**	0.9
9.0	0.674	−0.005	0.009	0.007	0.001	**0.001**		−1.8	0.1	−0.3	−0.1	**−0.2**	
10.5	0.471	*****	0.007	0.006	0.002	**0.001**		***	−0.1	−0.3	−0.2	**−0.3**	
12.0	**0.290**	**0.009**	**0.005**	**0.005**	**0.002**	**0.000**		**0.7**	**−0.3**	**−0.4**	**−0.4**	**−0.4**	
15.0	**0.336**	**−0.005**	**−0.002**	**0.000**	**0.000**			**−0.3**	**−0.1**	**0.0**	**−0.2**		
19.0	0.860	−0.005	−0.005	−0.003	0.001			−0.5	−0.2	0.3	−0.3		
24.0	1.465	−0.005	[−0.009]	−0.010				−0.6	[−0.2]	0.8			
29.0	1.888	−0.005	−0.012	−0.022				−0.7	−0.3	2.2			
34.0	2.083	−0.002	−0.005					−0.8	−1.3				
39.0	1.989	−0.002	−0.003					−0.8	−1.7				
44.0	1.631	−0.002						−0.7					
49.0	1.082	−0.001						−0.9					

respectively. For the majority of cases mentioned here, deviations from the SWR results are less than 1% for the magnitudes and less than 0.5 deg for the phase angles. Similar findings applied to the case when microphone No. 1 is located close to the second minimum pressure point (position A) except for a slight decrease in accuracy. Results are not as accurate when microphone No. 1 is located at other positions, except for the special situations when the position of microphone No. 2 is near a minimum pressure point (see corresponding rows in bold type of these tables). Thus, one can conclude that, for each particular frequency, one of the microphone positions has to be close to a minimum pressure point, preferably the first minimum point. The choice of the microphone separation is not critical as long as it is not close to one-half wavelength. These results also show that the position of microphone No. 2 can be as close as 1 cm from the specimen for the four different types of absorptive materials tested.

Second, if the minimum pressure point criterion is not followed, the suggestion of using one-quarter wavelength for the microphone separation[7] seems to be the best alternative for specimens with low and medium reflection coefficients as indicated by the results shown with square brackets in columns 4, 6, 10, and 12 of Tables III to V. Corresponding results shown in Tables I and II suggest that it does not work well for the specimen with high reflection coefficient.

Finally, the procedure used in this investigation presents a good alternative approach to the transfer function technique for impedance tube measurements. Even though a longer time is required in using single frequency excitation instead of broadband excitation, the procedure used in the present experiment was about three times faster than the conventional SWR method since it eliminated the tedious work of searching for the maximum and a few minima of the standing-wave pattern. Yet, it is as accurate as the SWR method. Further improvement in speed could be achieved by interfacing the signal generator and the lock-in amplifier with a microcomputer. It is estimated that a single frequency result could be obtained in about 30 s.

IV. CONCLUSION

A set of refined measurements using single frequency excitation and a lock-in amplifier for the determination of the equivalent transfer function between microphone signals at two positions has been made. Results obtained for four representative specimens indicate that, for precise measurements of the reflection coefficient for the determination of the absorption and impedance by the two-microphone transfer function technique, one of the microphone positions has to be close to a minimum pressure point, preferably the first minimum point. No such limitation has been discussed by Boden and Abom[7] and further theoretical investigation is required for its explanation. However, this is beyond the scope of the present article. The choice of the other microphone position is not critical as long as the microphone separation is not close to one-half wavelength. The position of microphone No. 2 can be closer than one tube diameter from the specimen.

It is conceivable that one can use a few geometries to cover the whole frequency range using broadband excitation and a digital frequency analysis system to achieve equally accurate results. However, for the extra time involved in selecting the geometries and sorting answers after the measurements, one might as well use single frequency excitation and pick the particular frequencies of interest.

The procedure used in this study presents a method for absorption and impedance measurements of acoustical materials that is definitely better than the conventional SWR method and the two-microphone transfer function technique using fixed microphone separation and broadband excitation.

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APPENDIX: IMPROVED SWR METHOD

Consider a plane wave of pressure p_i, incident on the absorptive material. The combination of the incident wave p_i and the reflected wave p_r produces a standing-wave pattern inside the tube. The magnitude of the total acoustic pressure at a distance x from the sample surface can be expressed by the following equation:

$$|p_x| = |p_+|[e^{2ax} + |R|^2 e^{-2ax} + 2|R|\cos(2kx - \phi)]^{1/2}, \quad \text{(A1)}$$

where $|p_+|$ is the amplitude of the incident pressure wave, a is the attenuation coefficient whose value depends on the side wall of the tube and the gas inside it, $k = 2\pi/\lambda$ is the wavenumber, and $R = |R|e^{i\phi}$ is the complex reflection coefficient of the sample at $x = 0$.

The basis of the improved method is an iterating process performed on Eq. (A1) where the attenuation coefficient a is assumed known. The wavenumber or wavelength can be obtained from the frequency and the speed of sound, the latter to be determined from the room temperature. In principle, Eq. (A1) can be solved for the three unknowns $|p_+|$, $|R|$, and ϕ if pressures at three locations are measured. This has been tried by Gatley and Cohen[11] with little success because of the interdependence of ϕ and $|R|$ in their iteration procedure. It is recognized, however, that ϕ can be estimated from the positions of any one of the pressure minima or maxima. The method is based on this fact. The relationship for the position of the pressure minimum or maximum can be obtained by differentiating Eq. (A1) and setting the results equal to zero to give

$$\sin(2kx - \phi) = (a/2k|R|)(e^{2ax} - |R|^2 e^{-2ax}). \quad \text{(A2)}$$

Thus, for the first pressure minimum, we have

$$\phi = -\pi + 2kd + \sin^{-1}[(a/2k|R|)(e^{2ad} - |R|^2 e^{-2ad})], \quad \text{(A3)}$$

where d is the distance from the surface of the sample to the first pressure minimum. To complete the iteration scheme, we need only one more pressure point in addition to the first minimum pressure point. The following ratio is obtained from Eq. (A1):

$$\frac{|P_{\min}|^2}{|p|^2}=\frac{e^{2ad}+|R|^2e^{-2ad}+2|R|\cos(2kd-\phi)}{e^{2ax}+|R|^2e^{-2ax}+2|R|\cos(2kx-\phi)}. \tag{A4}$$

The next step is to find values for $|R|$ and ϕ that satisfy Eq. (A3) and Eq. (A4) simultaneously. Since a/k is usually very small, the arcsin term in Eq. (A3) does not contribute significantly to ϕ except when ϕ approaches zero, and dropping this term provides a good first approximation for ϕ. Then, Eq. (A4) is solved as a quadratic equation for $|R|$. Only the positive root of $|R|$, which is < 1, is used. A new ϕ is then computed using the full Eq. (A3) and another value of $|R|$ is obtained by solving Eq. (A4) again. The iteration process is continued until $|R|$ and ϕ reach their limiting values. In general, only three iterations are required to reach final results. This method will eliminate the extra process of locating the maximum pressure point.

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