Direct-Reading One-Port Acoustic Network Analyzer*

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A novel measurement instrument is proposed to perform reflection measurements of guided acoustic waves. Both the magnitude and the phase of the reflection coefficient are measured simultaneously. The compact construction and the direct-readout feature facilitate an attractive measurement alternative for traditional standing-wave-ratio (SWR) detectors with movable microphones. These advantages are decisive for infrasonic frequencies where traditional SWR detectors require setups of 10 m or more.

0 INTRODUCTION

In a recent publication [1] acoustic one-ports and two-ports were introduced to facilitate a full description of (segments of) a closed linear acoustic system, including an instrument to measure these N-port parameters. Reflection measurements were performed with traditional standing-wave detection methods [2], which implies that the locations of the minima and the maxima were detected by manual adjustment of the positions of movable microphones. The disadvantages of this method are that 1) reflection measurements are laborious, 2) the method is based on movable microphones and therefore not suitable for real-time measurements, and 3) the minimum instrument length must exceed one-half the longest wavelength of interest. While infrasonic standing-wave-ratio (SWR) measurement instruments would require a minimum length of 35 m below 5 Hz, the length of the instrument proposed here is irrelevant and can be kept below 0.2 m.

Alternative methods, using two or more fixed microphones, are known from the literature. In [5] a measurement setup is described based on a loss-free acoustic wave guide and two wall-mounted microphones. Because the reflection is a function of spatial difference in pressure, a computer was used for the reconstruction of the reflection coefficient. The low end of this frequency range is limited by the accuracy with which the minimum phase difference can be detected. In [5] reflection measurements are reported using an offset distance of 0.13 m, with a usable frequency range from 100 Hz to 3.6 kHz. At the lowest frequency, the phase difference of the reported setup has been reduced to 13.6° in the case of traveling waves. Down scaling the measurement setup to 1 Hz with the same accuracy would require a microphone offset distance of at least 13 m.

We propose an improved one-port network analyzer (NWA) to measure acoustic reflections in regular tubes. The method proposed here is also based on two fixed microphones, but separates the microphones by an acoustic attenuator instead of a loss-free transmission line. Next, the microphone signals are interfered in a virtual bridge circuit to generate two related signals. As a result, the reflection coefficient in magnitude and phase has become linear proportional to the ratio of the two signals. Signal processing in a computer is not required, because magnitude and phase are directly measurable with, for example, an oscilloscope (using Lissajous figures).

The overall instrument length is remarkably short, compared to the longest wavelength of interest. The lowest usable frequency is limited mainly by the performance of the loudspeaker and microphones, and not restricted by the distance between the two microphones. The highest usable frequency is limited by the tube diameter [2] and the internal construction. Below that frequency limit the propagation of plane waves is guaranteed. The usable frequency band of the experimental setup ranges from 1 Hz to 100 Hz and is therefore useful for measurements on, for example, loudspeaker cabinets and tubes of air conditioning systems.

1 BASIC PRINCIPLE

The reflection of guided acoustic waves in a tube to obstacles and irregularities is fully related to the associated acoustic impedance. The equivalent input impedance Z_x of such a set of obstacles, observed at a

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well-defined reference plane [1], is defined as the quotient of the complex transformed representation of the average sound pressure p and the volume flow rate u at that reference plane. When this impedance is not equal to the characteristic impedance $\mathbb{Z}_0$ of the tube, the reference plane will pass both incident (ψ^+) and reflected (ψ^-) waves. Following the definition[1] of acoustic plane waves through this reference plane in its complex transformed form [1], the relation between impedance Z_x and reflection coefficient $\Gamma_x = (\psi^-/\psi^+)$ can be derived as follows:

$$\psi^+ = \tfrac{1}{2}\sqrt{\mathbb{Z}_0}\left(\frac{p}{\mathbb{Z}_0} + u\right)$$

$$\psi^- = \Gamma_x \cdot \psi^+ = \tfrac{1}{2}\sqrt{\mathbb{Z}_0}\cdot\left(\frac{p}{\mathbb{Z}_0} - u\right) .$$

Then

$$\Gamma_x = \frac{\psi^-}{\psi^+} = \frac{p/\mathbb{Z}_0 - u}{p/\mathbb{Z}_0 + u} = \frac{p/u - \mathbb{Z}_0}{p/u + \mathbb{Z}_0} = \frac{Z_x - \mathbb{Z}_0}{Z_x + \mathbb{Z}_0} .$$

Due to this relation between Γ_x and Z_x, reflection measurements on one-port networks can be obtained from impedance measurements and do not necessarily require the detection of standing waves.

A simple way to measure an impedance is the detection of the drop in sound pressure over an acoustic impedance in series with the impedance of interest. Fig. 1 shows the basic setup of such a measurement, in which the series impedance is realized with absorbing material. Two fixed microphones sense the sound pressure and generate sinusoidal voltages with associated complex transformed values U_s and U_t. The voltage drop $U_s - U_t$, which is proportional to the sound pressure, will be maximum when the acoustic network analyzer is terminated by an open end ($Z_x = 0$; $\Gamma_x = -1$) and minimum in the case of a covered end ($Z_x = \infty$; $\Gamma_x = +1$).

Fig. 2 shows the equivalent electric circuit model of the acoustic network analyzer of Fig. 1. The impedance Z_x is defined as the ratio of voltage to current in their complex transformed forms. This ratio is equivalent to the following ratio between the microphones voltages U_s and U_t:

$$U_s = \frac{Z_s + Z_x}{Z_{ss} + Z_s + Z_x} * U_{ss}$$

$$U_t = \frac{Z_x}{Z_{ss} + Z_s + Z_x} * U_{ss} .$$

Hence,

$$Z_x = \frac{U_t}{U_s - U_t} * Z_s .$$

The reflection coefficient Γ_x is defined as the ratio of incident wave to reflected wave in their complex transformed forms. Similar to impedance, this ratio can be transformed into a ratio of microphone voltages. For that purpose we define the quantities "reflective" voltage U_r and "reference" voltage U_{ref} as the following combination of U_s and U_t:

$$U_r = -\left(U_s - \frac{\mathbb{Z}_0 + Z_s}{\mathbb{Z}_0}\cdot U_t\right)$$

$$= \frac{Z_x - \mathbb{Z}_0}{Z_{ss} + Z_s + Z_x} * \left(\frac{Z_s}{\mathbb{Z}_0} * U_{ss}\right)$$

$$U_{ref} = +\left(U_s - \frac{\mathbb{Z}_0 - Z_s}{\mathbb{Z}_0}\cdot U_t\right)$$

$$= \frac{Z_x + \mathbb{Z}_0}{Z_{ss} + Z_s + Z_x} * \left(\frac{Z_s}{\mathbb{Z}_0} * U_{ss}\right) .$$

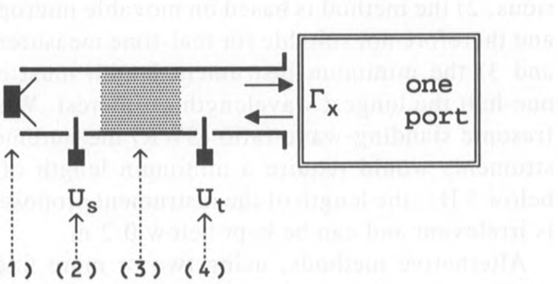

Fig. 1. Basic setup of proposed one-port acoustic network analyzer for measurement of reflection coefficient Γ_x. 1—loudspeaker; 2—first microphone producing voltage U_s; 3—series absorber; 4—second microphone producing voltage U_t.

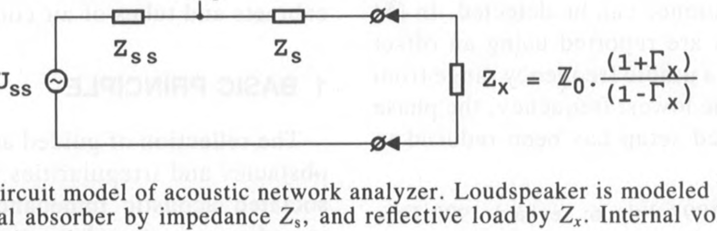

Fig. 2. Equivalent electric circuit model of acoustic network analyzer. Loudspeaker is modeled by voltage source U_{ss} with internal impedance Z_{ss}, serial absorber by impedance Z_s, and reflective load by Z_x. Internal voltages U_s and U_t represent sound pressure detected by microphones.

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[1] In the definitions for ψ^+ and ψ^- specified in [1], unfortunately, we neglected to scale ψ with a factor (½), which did not affect the conclusions in [1]. In microwave electronics this scaling factor was added to simplify various power relations. For compatibility, we use the correct definitions here.