THE ABSOLUTE SENSITIVITY CHARACTERISTICS OF LUNG-SOUND TRANSDUCERS COUPLED TO CHEST WALL

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Abstract - We studied the absolute sensitivity characteristics of air-coupled microphone and accelerometer when they are coupled to chest wall. The frequency response of these transducers were theoretically predicted based on an equivalent circuit model and verified by model experiment. The experimental results were well agreed with the theoretical predictions. Due to the capacitive impedance of the air-chamber the pressure response of air-coupled microphone shows low-pass characteristics. It is important to set the air-chamber dimension as small as possible, however, practically it is difficult to have the cut-off frequency above 1kHz. Accelerometer acts, on the chest wall, as a pressure sensor rather than an acceleration sensor, because the mechanical impedance of the accelerometer is much higher than that of the chest wall. We can measure stop-surface sound pressure on the chest wall either by air-coupled microphone or by accelerometer. Accordingly we can quantitatively compare the data measured by air-coupled microphones with the data measured by accelerometers.

I. INTRODUCTION

Microphones with coupling chamber and accelerometers are commonly used in the measurement of lung sounds. Several attempts have been made to assess the performance of these transducers [1]-[4]. The frequency response discussed in these papers were, however, relative or comparative. Absolute response was not fully characterized yet. This drawback causes some problems in lung-sound measurement; for example we are not sure how the measured lung-sound is affected by the transducer characteristics. We had studied the absolute characteristics of air-coupled microphone assuming that chest wall has the same acoustical property as water [5]. In the present study we analyzed the absolute sensitivity characteristics of air-coupled microphone and accelerometer incorporating actual viscoelastic property of chest wall. The frequency response of these transducers were theoretically predicted and verified by model experiment.

II. METHODS

A. Theoretical considerations

To assess the performance of an air-coupled microphone, we define pressure response (PR) as

$$PR = \frac{P_m}{P} \tag{1}$$

where P_m is the sound pressure measured by an air-coupled microphone, and P is the sound pressure produced when the vibration of the measured surface is completely stopped or obstructed by the transducer itself. This stop-surface pressure is, for example, equal to the pressure exerted on the firmly fixed rigid body attached to the chest wall surface. Based on Norton's theorem, PR is written as

$$PR = \frac{Z_m}{Z_r + Z_m} \tag{2}$$

where Z_m is the mechanical impedance of the air-coupled microphone. We assume a cylindrical air-chamber and take its capacitive impedance into account:

$$Z_m = \frac{\pi a^2 \rho_{air} c^2{}_{air}}{j\omega d} \tag{3}$$

where a, d, ρ_{air}, and c_{air} is the radius of the air chamber, the depth of the air chamber, the density of air and the sound speed in the air respectively.

Z_r is the mechanical impedance of the chest wall. Oestreicher theoretically analyzed the mechanical impedance of human soft tissue [6] and the result has been commonly used. His modeling, the vibrating sphere in infinite viscoelastic medium, seems, however, rather rough approximation to the actual situation where chest wall surface exists. We studied mechanical impedance of soft tissue with more realistic model. Based on the theory of vibrating disc on a semi-infinite elastic medium [7], we derived the following equation:

$$Z_r = 8a\mu\left(\frac{2.621\sqrt{\dfrac{\rho}{\mu}}a}{\pi} + \frac{1}{j\omega}\right) + j0.4244\pi\rho a^3\omega \tag{4}$$

with $\mu = \mu_1 + j\omega\mu_2$ where μ_1, μ_2 and ρ is the medium's coefficient of shear elasticity, coefficient of shear viscosity and density respectively.

Acceleration response (AR) is usually employed to assess the performance of accelerometer, defined as

$$AR = \frac{A_a}{A_f} \tag{5}$$

where A_a is the acceleration measured by the accelerometer and A_f is the unloaded vibrating acceleration of the measured surface. Based on Norton's theorem, AR is written as

$$AR = \frac{Z_r}{Z_r + Z_a} \tag{6}$$

where Z_a is the mechanical impedance of the accelerometer. We neglect the accelerometer's internal resonance to simplify the analysis. Then Z_a is written as

$$Z_a = j\omega m \tag{7}$$

where m is the mass of the accelerometer.

In addition to acceleration response, we consider the pressure response of accelerometer similarly to the case of air-coupled microphone. The pressure exerted on the accelerometer is obtained by multiplying the output of the accelerometer output by the mass of the accelerometer and divided by the contact surface area. The pressure response of the accelerometer is also written as

$$PR = \frac{Z_a}{Z_r + Z_a}. \tag{8}$$

B. Measurement of absolute response

Fig. 1 shows the schematic diagram of the measurement system. Uniform viscoelastic material (Kitecko, 3M) was used as a chest wall mimicking medium. It is important to use the medium which has similar mechanical property to chest wall because the mechanical impedance of chest wall is the most important factor to assess the response of lung-sound transducer. To measure the pressure response of air-coupled microphone, wide band noise was injected to the medium from the one side of the medium surface. On the opposite surface the sound pressure was measured by a piezoelectric force transducer (B&K 8001) and an air-coupled microphone (B&K 4136 with a cylindrical air-chamber). The force transducer was used with a firm support to measure the stop-surface pressure. The transfer function from the sound source pressure to the sound pressure measured by an air-coupled microphone was measured. The transfer function from the sound source pressure to the force transducer was also measured. The pressure response of the air-coupled microphone was then obtained by taking the ratio of these two transfer functions. Acceleration response and pressure response of an accelerometer (B&K 4393) were measured in a similar way. The unloaded vibrating acceleration of the surface was measured by a laser vibrometer.

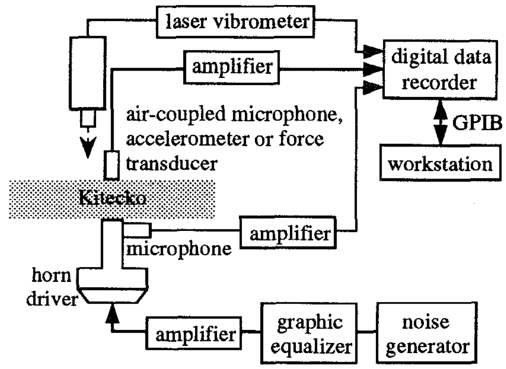

Fig. 1. Schematic diagram of the measurement system

III. RESULTS

Fig. 2 (a) shows theoretically predicted pressure response of an air-coupled microphone with various air-chamber depths. The radius of the air-chamber was 3.5mm. Typical values of mechanical constants of human soft tissue ($\mu_1 = 2.5\times10^3\mathrm{N/m^2}$, $\mu_2 = 15\mathrm{Ns/m^2}$, $\rho = 1.1\times10^3\mathrm{kg/m^3}$) [8] were used in theoretical predictions. Fig. 2 (b) shows corresponding experimental result. The response shows low-pass characteristics, and below the cut-off frequency the microphone measures the stop-surface sound pressure.

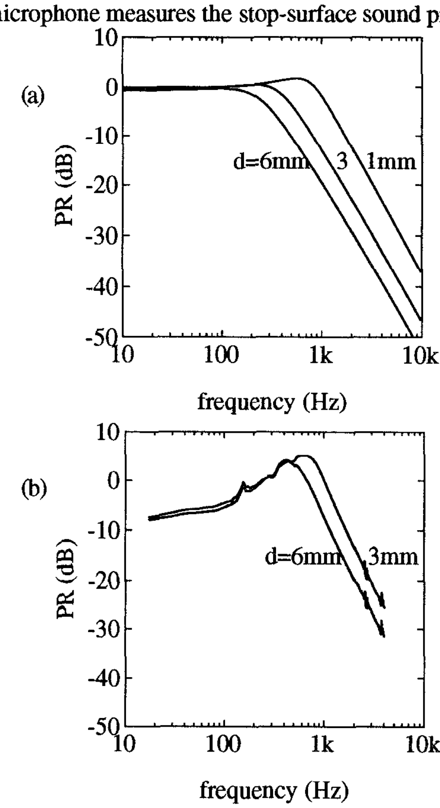

Fig. 2. Pressure response of an air-coupled microphone with various air-chamber depth d. (a) Theoretical prediction and

(b) the corresponding experimental result.

Fig. 3 (a) shows the predicted acceleration responses of the three commercially available accelerometers. Fig. 3 (b) shows measured acceleration response of an accelerometer. The results show poor characteristics as acceleration sensor; the measured acceleration is much lower than unloaded acceleration. Fig 4 (a) shows predicted pressure responses of the three accelerometers. Fig. 4 (b) shows measured pressure response of an accelerometer. The results show that the HP and the B&K accelerometer accurately measure the stop-surface pressure except in the very low frequency range.

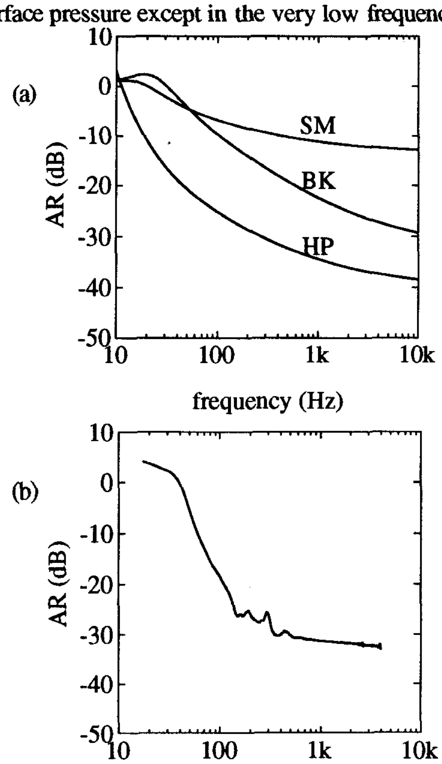

Fig. 3. Acceleration response of accelerometers. (a) Predicted response of three commercially available accelerometers; B&K 4393 (BK, weight 2.8g, radius 3.5mm), HP 21050 (HP, weight 52.2g, radius 7mm) and Siemens EMT25C (SM, weight 15.4g, radius 14mm). (b) Measured acceleration response of B&K 4393.

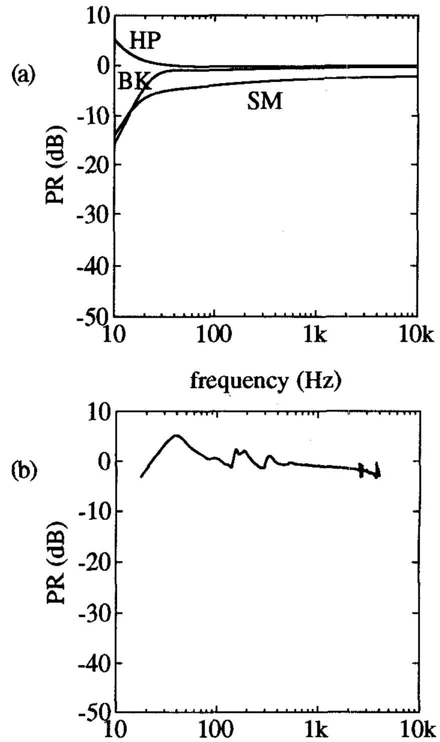

Fig 4. Pressure response of the accelerometers. (a) Predicted response of the three accelerometers and (b) measured pressure response of B&K 4393.

IV. DISCUSSION

The absolute sensitivity characteristics of lung-sound transducers when they were coupled to the chest wall were analyzed by the theory and the model experiment. The experimental results well agreed with the theoretical predictions.

In order to operate air-coupled microphone to measure the stop-surface pressure, its mechanical impedance should be much higher than that of the chest wall throughout in the frequency range of interest. The capacitive impedance of the air-chamber, however, decreases as frequency increases and the pressure response shows low-pass characteristics. Since the cut-off frequency of the air-coupled microphone decreases as the dimension of the air-chamber increases, it is quite important to set the dimension as small as possible. The result shows, however, practically it is difficult to have the cut-off frequency above 1kHz.

In the case of accelerometer, although we use a relatively light-weight accelerometer, the mechanical impedance of the accelerometer is still much higher than that of the chest wall except in the very low frequency range. Therefore the accelerometer acts as a pressure sensor rather than an acceleration sensor. We can improve the acceleration response by increasing the contact-surface area of the accelerometer without increasing the total weight, because the mechanical impedance of the chest wall increases as the contact-surface area increases. This is also the reason why, in Fig. 3 (a), the Siemens accelerometer shows better acceleration response than the B&K accelerometer in spite of its heavier weight. Although this method is not difficult to implement, we should use accelerometer as pressure sensor as long as the accelerometer has sufficient sensitivity, because this method degrade the spatial resolution in the measurement.

Most importantly, the results show that we can measure the stop-surface sound pressure on the chest wall either by air-coupled microphone or by accelerometer. This means that we can accurately compare the data measured by air-coupled microphones with the data measured by accelerometers.

V. CONCLUSION

We have analyzed, by the theory and model experiment, the absolute sensitivity characteristics of lung-sound transducers when they were coupled to the chest wall. The experimental results well agreed with the theoretical predictions. Due to the capacitive impedance of the air-chamber the pressure response of air-coupled microphone shows low-pass characteristics. It is quite important to set the dimension as small as possible, however, practically it is difficult to have the cut-off frequency above 1kHz. The mechanical impedance of the accelerometer is much higher than that of the chest wall, therefore the accelerometer acts as a pressure sensor rather than an acceleration sensor. The results show that we can measure the stop-surface sound pressure on the chest wall either by air-coupled microphone or by accelerometer. Accordingly, we can quantitatively compare the data measured by air-coupled microphones with the data measured by accelerometers.

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