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# Modeling of bone-conducted sound transducer on human skin by vibrating system with two degrees of freedom
ヒトに装着した骨導振動子の 2 自由度振動系によるモデル化


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## 1. Introduction

The sound propagates through skin and bone is recognized as bone-conducted sound. The bone-conducted sound is used for hearing aids or radio communication with ear opened. The hearing of bone-conducted sound depends on contact force of the transducer[1)]. The contact force was assessed by using loadcels in research, which is not applicable for consumer use of headphones[2)]. Other method uses headband to maintain approximately constant force. While this method is very common, it does not guarantee constant contact force[3)].

On this problem, we have proposed a method of estimating contact force from the electrical impedance of the transducer[4, 5)]. While the estimation was possible with characteristic change of the electrical impedance, physical cause of the change was not clarified. In this paper, we propose to model the bone-conducted sound transducer by vibrating system with two degrees of freedom. The model was validated with experimental results.

## 2. Frequency response of a two degrees of freedom vibration system and a transducer

The bone-conducted sound transducer on a human consists of housing, diaphragm and human skin. At low frequency, the diaphragm and human skin vibrates in phase. To model the vibration of these parts, vibrating system with two degrees of freedom is considered in this paper. With variables in Fig. 2, the equation of motion is described as:

$$\begin{bmatrix} m_s & 0 \\ 0 & m_h \end{bmatrix}\begin{bmatrix} \ddot{x_s} \\ \ddot{x_h} \end{bmatrix} + \begin{bmatrix} c_s + c_h & -c_h \\ -c_h & c_h \end{bmatrix}\begin{bmatrix} \dot{x_s} \\ \dot{x_h} \end{bmatrix} + \begin{bmatrix} k_s + k_h & -k_h \\ k_h & k_h \end{bmatrix}\begin{bmatrix} x_s \\ x_h \end{bmatrix} = \begin{bmatrix} F \sin \omega t \\ 0 \end{bmatrix}. \quad (1)$$

By solving the equation, the non-dimensional velocity $\bar{\dot{x}}_s$ at non-dimensional frequency $\bar{\omega}$ is given as,

$$\bar{\dot{x}}_s(\bar{\omega}) = \bar{x}_s\bar{\omega} = \left|\frac{x_s\, k_s}{F}\right|\bar{\omega} = \frac{\sqrt{(\beta^2+\bar{\omega})^2 + 4(\zeta_2\beta\bar{\omega})^2}}{\sqrt{A^2+4B^2}}\bar{\omega},$$

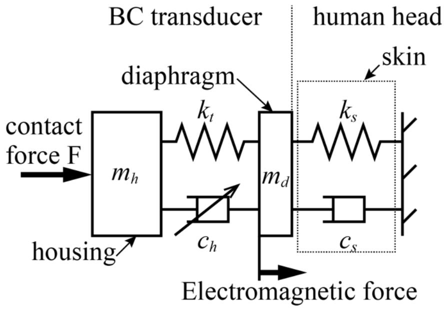

Fig. 1 Proposed model of bone-conducted sound transducer and skin.

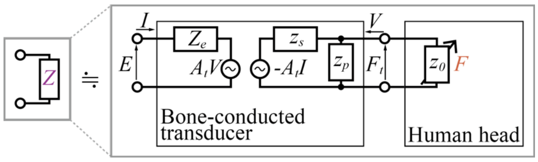

Fig. 2 Equivalent electrical circuit model of the bone-conducted sound transducer.

where $A = \bar{\omega} - \{(\alpha+1)\beta^2 + 4\,\zeta_1\zeta_2\beta + 1\}\bar{\omega} + \beta^2$, $B = -\{\zeta_1 + (\alpha+1)\zeta_2\beta\}\bar{\omega} + (\zeta_1\beta + \zeta_2)\beta\bar{\omega}$,

$$\omega_1 = \sqrt{\frac{k_s}{m_s}},\ \omega_2 = \sqrt{\frac{k_h}{m_h}},\ \zeta_1 = \frac{c_s}{2m_s\omega_1},\ \zeta_2 = \frac{c_h}{2m_h\omega_2},$$
$$\alpha = \frac{m_h}{m_s},\ \beta = \frac{\omega_2}{\omega_1},\ \bar{x}_s = \left|\frac{x_s k_s}{F}\right|,\ \bar{\omega} = \frac{\omega}{\omega_1}. \quad (2)$$

Non-dimensional velocity $\bar{\dot{x}}_s$ is derived as dividing the velocity $\dot{x_s}$ by the amplitude of driving velocity $k_s/(F\,j\omega)$. The mechanical impedance of the bone-conducted sound transducer $Z_m$ is given as,

$$Z_m(\bar{\omega}) = \bar{\dot{x}}_s(\bar{\omega})\ /\ F\ . \quad (3)$$

On the other hand, electrical impedance of the bone-conducted sound transducer $Z_e$ is given as,

$$Z_e(\bar{\omega}) = R + j\omega L + A_t/Z_m(\bar{\omega}), \quad (4)$$

where $R$ and $L$ are electrical components of the transducer, $A_t$ is the force factor of the transducer. If the model shown in Fig. 2 is valid, $|CZ_m|$ is equal to Eq.(2), where $C = k_s/A_t = \text{const.}$ With this relation, the validity of proposed model can be evaluated by measuring $Z_e$ in experiment. To achieve this, electrical impedance $Z_e$ is measured and $C/Z_m$ is estimated from Eq. (4).

## 3. Experiment conditions

Experimental setup is shown in Fig. 1. The electrical impedance of a bone-conducted sound transducer (AS400, AfterShockz) was measured by an impedance analyzer (E5061B, Agilent). The transducer was placed on approximately 5 mm anterior to the external acoustic opening of right ear. The contact forces $F$ were evaluated for 0, 0.1, 0.3, 0.5, 1, 3, and 5 (N), covering a comfortable contact force range[7]. The contact forces were controlled by placing weights on the transducer. The electrical impedance was measured for 300 points in logarithmic scale with a range of 1 Hz to 60 kHz. The electrical impedance was measured 10 times for each contact force.

The parameters of the model are. The scaling of the mechanical impedance is $C$ = 1. The value of electrical parameters $R$ = 9 Ω and $L$= 10 mH were estimated by fitting impedance curve.

Table 1 Mechanical parameters for simulation

| | | | | | |
|---|---|---|---|---|---|
| $m_h$ | 3.0 | g | $m_d$ | 3.0 | g |
| $c_h$ | - (variable) | | $c_s$ | $1\times 10^{-3}$ | Ns/m |
| $k_h$ | 350 | N/m | $k_s$ | 1000 | N/m |

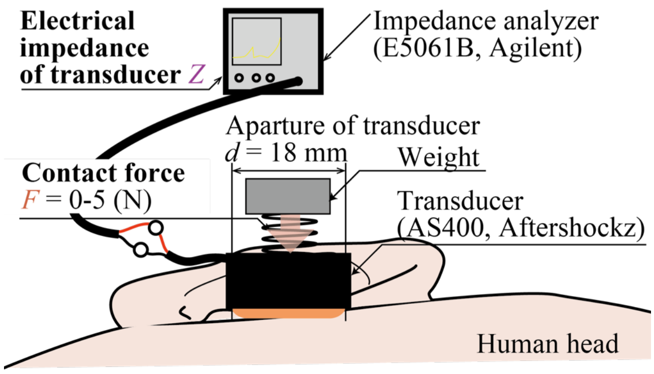


Fig. 3 Experimental setup for measuring electrical impedance at different contact force.

## 3. Results and discussions

Experimental results for each subject are shown in Fig. 4(a) – (g). Theoretical values were calculated by Eq. (3). Horizontal axes were normalized by the resonance frequency of diaphragm and skin $\omega_1$ = 574.1 rad/s. The velocity Viscosity was changed for each condition. However, the range of viscosity $c_h$ was from 0.05 to 10 (Ns/m) and it is unlikely to have this range of change. There might be a mechanism which causes the apparent change of the viscosity and further investigation is required.

The peak of the measured frequency response shows significantly asymmetrical shape for $F > 3$ N. One possible cause of the shape is nonlinear response of the skin. For this high viscosity, the two masses in the model moves in phase and only one resonance is induced by the spring component of the skin and sum of two masses. The proposed model in this paper does not consider the nonlinearity of human tissues.

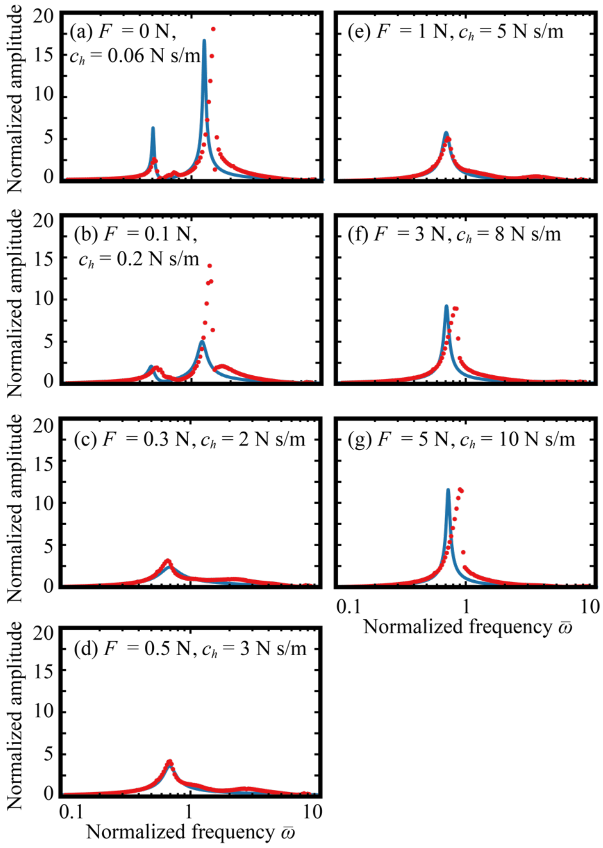


Fig. 4 Experimental results and fitted theoretical values. (a) $F$ = 0 N, $c_h$ = 0.06 Ns/m, (b) $F$ = 0.1 N, $c_h$ = 0.2 Ns/m, (c) $F$ = 0.3 N, $c_h$ = 2 Ns/m, (d) $F$ = 0.5 N, $c_h$ = 3 Ns/m, (e) $F$ = 1 N, $c_h$ = 5 Ns/m, (f) $F$ = 3 N, $c_h$ = 8 Ns/m, (g) $F$ = 5 N, $c_h$ = 10 Ns/m

## 4. Conclusions

**A** model of the bone-conducted sound transducer was proposed as vibrating system with two degrees of freedom. The model was validated with experimental results. The peaks measured in the experiment was partially expressed by the proposed model. Further investigation on nonlinear response of the skin is required.

## References

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