Influences of Air Fluctuation and Mechanical Vibration on Magnetic Noise in a Magnetically-Shielded Room


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This paper describes the experimental investigation of relatively weak magnetic noise at low frequencies, which was caused by the fluctuation of air currents through ducts in a magnetically shielded room (MSR). The noises were measured by SQUID magnetometers in the MSR installed on an active microtremor isolation system. First, the paper clarifies that magnetic noise depended only on air fluctuation at frequencies less than 10 Hz, whereas on both air fluctuation and mechanical vibration via floor at frequencies from 10 to 30 Hz. Second, the major contributor to magnetic noise at low frequencies was identified by evaluating the coherence coefficients between magnetic noises, vibrations of the MSR, and sound pressure inside and outside the MSR. The deformations of the wall and those of the ceiling in directions perpendicular to their planes due to air fluctuation mainly contributed to magnetic noise. Third, by measurement, we inferred that the peak frequencies of the sound pressure resulting in magnetic noise were generated by the air duct.

Key words: air duct, air fluctuation, magnetically shielded room, sound pressure, SQUID magnetometer.

1. Introduction

The biomagnetic measurements such as magnetoencephalography (MEG) and magnetoencephalography (MEG) and magnetoencephalography (MEG) and magnetocardiography (MCG) are usually carried out inside magnetically shielded rooms (MSRs) (1)(2). Recent systems enable us to measure weak biomagnetic signals with the sensitivity as low as 10 fT/Hz1/2. The sensitivity of the measurements is limited by the residual magnetic noises in the MSR, which are caused by mechanical microtremors as well as environmental magnetic noises generated by electric trains(3), motorcars, and electrical devices at low frequencies. The magnetic noises due to microtremors are caused by mechanical vibrations at low frequencies of less than 30 Hz(4), and had some peak frequencies reflecting the mechanical resonance properties. To reduce the noise, an Active Microtremor Isolation (ACMI) system which was developed in 1998, was installed in the basement underneath the central 6 m shielding cube of the MSR of National Institute of Information and Communications Technology (NICT) (4) (5).

Although microtremors transmitted from the floor could be reduced by the ACMI, weak magnetic noises at low frequencies of less than 30 Hz were still detected by SQUID magnetometers when the MSR was being air-conditioned. The MSR is connected to an air-conditioning system that supplies hot or cool air. A part of the air currents are blown from the air ducts through a latticed air outlet in the ceiling of the room and then diffused by the ceiling plate of the MSR, while the other part of the air currents are fed into the MSR through circular flexible ducts connected to holes in the wall of the room. Such air paths may cause fluctuation in air currents. We assumed that the remaining
We used an MEG system inside the MSR placed on the ACMI (Fig. 1). The raw magnetic noises \( B_x, B_y, \) and \( B_z \) were measured using three of 148 SQUID magnetometers of the MEG system whereas a software cancellation was stopped for the present measurements. (Fig.1). Vibration was measured in the vicinity of SQUIDs of the gantry \( (L_x, L_y, \) and \( L_z) \), at walls inside MSR \( (L_{wx}, L_{wy}, \) and \( L_{wx}) \), and at ceilings outside \( (A_x, A_y, \) and \( A_z) \) and inside \( (L_{rz}) \) MSR, where an ordinary acceleration sensor was used outside the MSR, while a laser vibrometer (PPV100) was used inside the MSR to avoid the magnetic noise as described below. Unlike ordinary acceleration sensors that were composed by steel magnetic materials, laser vibrometer used in the present measurements was composed of non-magnetic materials, placed at a distance of 1.5 m from SQUID magnetometers, and powered by battery. Sound pressure was measured by an ultra-low-frequency sound-meter (NA-17, RION) inside and outside the MSR \( (S_{in}, S_{out}) \). The measured quantities were shown in Table 1.

The frequency dependence of acceleration and magnetic noise, with and without operation of the ACMI (ACMI-ON and -OFF) and with and without air-conditioning (AC-ON and -OFF), were compared to distinguish whether magnetic noise primarily depended on air fluctuation or not.
3. Results and discussion

3.1 Frequency spectra

Measured acceleration of ceiling outside the MSR, $A_x$ and $A_z$, velocity of the wall and ceiling inside the MSR, $L_{wx}$ and $L_{wz}$, and of the gantry, $L_x$ and $L_z$, magnetic noise, $B_x$ and $B_z$, and sound pressure outside ($S_{out}$) and inside ($S_{in}$) the MSR were shown in Figs. 2, 3, 4, 5 and 6, respectively. Since $A_y$, $L_{wy}$, and $B_y$, which were similar to $A_x$, $L_{wx}$, and $B_x$, respectively, were omitted.

Table 2 summarizes the results. When the ACMI was operated, the velocity of the wall and ceiling inside the MSR, magnetic noises and sound pressure inside and outside the MSR differed between AC-ON and OFF at frequencies less than 10 Hz (Figs. 3, 5 and 6), suggesting that these were related to air-fluctuations. The magnetic noises and the velocity of the wall and ceiling inside the MSR increased from ACMI-ON and AC-OFF to either ACMI-OFF or AC-ON at frequencies from 10 to 30 Hz (Figs. 3 and 5). This suggests that the noises were related to both the mechanical vibrations via floor and air-fluctuations at frequencies from 10 to 30 Hz, while they were related to only air-fluctuation at frequencies less than 10 Hz. On the other hand, the horizontal accelerations of outside the MSR were
similar between AC-ON and AC-OFF, showing that the microtremors due to mechanical vibrations were dominated.

It should be noted to add the following point for the noises with AC-OFF. Since the horizontal accelerations of ceiling outside the MSR were reduced by the ACMI at frequencies from 1 to 100 Hz (Fig. 2), they were considered to be caused by mechanical vibration via floor. However, the velocity of the wall and ceiling inside the MSR and the magnetic noises with AC-OFF were reduced by the ACMI at frequencies higher than 10 Hz, but not less than 10 Hz (Figs. 3 and 5). Since the velocities mean relative ones measured by the vibrometer inside the MSR, this suggests that the mechanical vibration caused the MSR trembling without deformation at frequencies less than 10 Hz, but with deformation at frequencies higher than 10 Hz. Only the latter resulted in magnetic noise (Fig. 5).

3.2 Coherence Coefficients

The coherence coefficients (CCs) were evaluated between two quantities among the accelerations outside the MSR ($A_k$ and $A_l$), vibrations inside the MSR ($L_{wx}$ and $L_{rz}$), vibrations of the gantry ($L_x$ and $L_z$), magnetic noises ($B_x$ and $B_z$), and the sound pressures inside and outside the MSR ($S_{in}$ and $S_{out}$) as shown in Figs. 7-16 with ACMI-ON and AC-ON. The following features were observed.

Here, $CC(\beta)$ between two measured quantities $X(\beta)$ and $Y(\beta)$ was calculated using Equation (1),

$$CC(\beta) = \frac{|W_{xy}(\beta)|^2}{W_{xx}(\beta) \cdot W_{yy}(\beta)}$$

where $W_{xx}(\beta)$, $W_{yy}(\beta)$, and $W_{xy}(\beta)$ denote power-spectra of $X(\beta)$ and $Y(\beta)$, and cross-spectrum between $X(\beta)$ and $Y(\beta)$, respectively.

These results (1)-(3) were summarized in Table 3. This suggested that the vibrations of the wall and those of the ceiling in a perpendicular direction were accompanied with the sound pressure, inside MSR (2-3 and 3-7 Hz) and outside MSR (2-3, and around 8.5 and 17.5 Hz), and the vibrations were the major contributor to magnetic noise at the low frequencies. In addition, the following should be remarked. At the peak frequency of the vibrations, $L_{wx}$ and $L_{rz}$ (13.2 Hz, Fig. 3), although the CCs were high between $L_{wx}$, $L_{rz}$, and $S_{in}$,
between Lx and Brx (Fig. 3), respectively. In this MSR, 1 µm of displacement of the inner wall in a perpendicular direction resulted in about 3.3, 12 and 22 pT of magnetic noise. A ratio of the noise to displacement is larger than the one expected from the fact that 1 µm of the displacement in horizontal direction of the MSR ceiling panel resulted in 1.0 pT of magnetic noise (4). The difference is considered to reflect difference in mechanical vibrations between the wall and ceiling of the MSR.

3.4 Measurement of residual magnetic field

Distributions of residual magnetic field in x (Brx), y (Bry) and z (Brz) direction along x, y and z axis around the SQUID magnetometer in the MSR were measured by a flux-gate magnetometer, respectively (Fig. 18). The measured fields were shown in Fig. 19 with second-order approximated lines for Brx, Bry and Brz. We read the displacements Δx, Δy and Δz of SQUID gantry at the peak frequency for ACMI-ON and AC-ON (Fig. 4) and evaluated magnetic noises ΔBrx, ΔBry and ΔBrz by multiplying the slope of Brx, Bry and Brz curves to Δx, Δy and Δz, respectively.

Table 3 Quantities having high CC with Brx and Bry.

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>2-3 Hz</th>
<th>3-7 Hz</th>
<th>8.5 Hz</th>
<th>17.5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brx</td>
<td>Axx</td>
<td>Axx</td>
<td>Axx</td>
<td>Axx</td>
</tr>
<tr>
<td>Bty</td>
<td>Lxxy</td>
<td>Lxxy</td>
<td>Lxxy</td>
<td>Lxxy</td>
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<tr>
<td>Lx, Lz, Lz</td>
<td>Lyz</td>
<td>Lyz</td>
<td>Lyz</td>
<td>Lyz</td>
</tr>
<tr>
<td>Lx, Ly, Lz, Lz</td>
<td>Bx-Brx</td>
<td>Bx-Brx</td>
<td>Bx-Brx</td>
<td>Bx-Brx</td>
</tr>
<tr>
<td>Sout</td>
<td>Sout</td>
<td>Sout</td>
<td>Sout</td>
<td>Sout</td>
</tr>
</tbody>
</table>

Sout (Figs. 15 and 16), and magnetic noise, Brx and Bry (Figs. 9 and 10), these quantities had no peak at the frequency (Figs. 5 and 6). Thus, the vibration peak (Fig. 3) might not be real perpendicular velocity, but reflect the resonance of the stand that supported the laser vibrometer.
Table 4 shows the calculated and measured magnetic noises at the peak frequencies in Fig. 5. The magnetic noises calculated from residual magnetic fields were small compared with those of measured ones, showing that magnetic noises due to the movement of gantry were negligible.

Table 4 Calculated and measured magnetic noises at same peaks.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Displacement [μm]</th>
<th>(\Delta B_x [μT])</th>
<th>(\Delta B_y [μT])</th>
<th>(\Delta B_z [μT])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>3.59</td>
<td>0.102</td>
<td>2.58</td>
<td>39.78</td>
</tr>
<tr>
<td>(y)</td>
<td>6.41</td>
<td>0.038</td>
<td>1.18</td>
<td>21.37</td>
</tr>
<tr>
<td>(z)</td>
<td>4.06</td>
<td>0.146</td>
<td>4.28</td>
<td>51.09</td>
</tr>
</tbody>
</table>

Fig. 17 Relation between the displacement of the inner wall in perpendicular direction and magnetic noise, (a) \(\Delta y\) and \(B_x\), (b) \(\Delta x\) and \(B_y\), and (c) \(\Delta x\) and \(B_z\).

Fig. 18 Measured axis of residual magnetic field in the MSR.

Fig. 19 Measured distributions of residual magnetic field \(B_x\), \(B_y\) and \(B_z\) around the SQUID magnetometer in the MSR, along (a) \(x\) axis, (b) \(y\) axis, and (c) \(z\) axis.

3.5 Frequency Dependences of Static Pressure and Sound pressure
3.5.1 Measurement method
The frequency dependences of sound pressure were measured by ultra-low-frequency sound-meter at the measured points B, C, D, and E along the duct, from the machine room to the MSR in the building, as shown in Fig. 20.

### 3.5.2 Results

Figure 21 shows the frequency dependences of sound pressure P, measured directly by the sound pressure meter at points along the duct and inside the MSR.

![Fig. 20 Measured points of sound pressure at duct. (a) Layout of the duct from the machine room to the MSR in the building, (b) layout of the duct near the MSR.](image)

![Fig. 21 Frequency dependence of sound pressure at points along the air duct and inside the MSR.](image)

Frequency peaks of P became clearer as the distance from the machine room is longer from B to E; the peaks of sound pressure appeared at frequencies from 3 to 7 Hz and 11.0 Hz in the MSR. These frequencies agree with the peak frequencies of magnetic noises, vibrations of wall and sound pressure inside the MSR. This suggested that the source of air fluctuation was air duct.

### 4. Conclusions

We measured the weak magnetic noise due to the fluctuation of air currents and mechanical vibrations by SQUID magnetometers in magnetically shielded room (MSR). Magnetic noise due to air-current of air-conditioning was distinguished from that caused by mechanical vibration.

1) The magnetic noises depended on both air-fluctuations and mechanical vibrations at frequencies from 10 to 30 Hz, but only on air-fluctuations at frequencies less than 10 Hz.
2) The mechanical vibrations caused the MSR trembling without deformation at frequencies less than 10 Hz, but with deformation at frequencies higher than 10 Hz. The deformation resulted in the displacement of the inner wall and ceiling that was relative to the MSR floor, and produced magnetic noise. Thus, the ACMI was effective to reduce the magnetic noise due to mechanical vibration at frequencies higher than 10 Hz.
3) The vibrations of the wall and those of the ceiling in a perpendicular direction were accompanied with the air-fluctuation inside MSR (2-3 and 3-7 Hz) and outside MSR (2-3, and around 8.5 and 17.5 Hz).
4) The measurement of sound pressure along air duct suggested that the source of air fluctuation was air duct.
5) The vibrations were identified as the major contributor to magnetic noise that reached about 300 fT/Hz^{1/2} at the low frequencies: 1 μm of displacement of the inner wall in a perpendicular direction resulted in magnetic noise of about 3.3, 12 and 22 pT.

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### References


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