Magnetic Noise Due to Sound of Footsteps on Wooden Free-Access Floor Outside a Magnetically Shielded Room for Biomagnetic and Nondestructive Measurements

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In order to realize the ultimate low magnetic field in magnetically shielded rooms (MSRs) for nondestructive measurements and biomagnetic measurements such as magnetoencephalography and magnetocardiography, we investigated magnetic noises due to microtremors caused by sound pressure and mechanical vibration which arose from footsteps applied on the wooden free-access floor. Using superconducting quantum interference device (SQUID) magnetometers in this MSR, we measured the magnetic noises with and without operating an active microtremor isolation (ACMI) system that reduced microtremors transmitted from the concrete slab underneath the MSR. The microtremors of the MSR due to footsteps were divided into two components. One was caused by mechanical vibrations transmitted through the concrete slab at frequencies from 10 to 25 Hz. Its frequency characteristic depended on the mechanical resonance of the MSR. The other was caused by sound pressure transmitted directly from the free-access floor. This component occurred at frequencies from 25 to 50 Hz even with the operation of ACMI when footsteps were applied on the wooden free-access floor.

Index Terms—**Active microtremor isolation (ACMI) system, footstep, free-access floor, magnetically shielded room (MSR).**

I. INTRODUCTION

BIOMAGNETIC measurements such as magnetoencephalography (MEG) and magnetocardiography (MCG) are usually carried out inside magnetically shielded rooms (MSRs) [1], [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 by environmental magnetic noises, such as those generated by electric trains [3], motorcars, and electrical devices at low frequencies. To reduce magnetic noises due to microtremors caused by mechanical vibrations at frequencies less than 30 Hz [4], an active microtremor isolation (ACMI) system was installed in the basement underneath the MSR of the National Institute of Information and Communications Technology (NiCT).

In hospitals and research institute facilities, MSRs for biomagnetic and nondestructive measurements are often placed on concrete floors and surrounded by free-access floors made of wood and aluminum to conceal the cables underneath them and align the floor levels outside and inside the MSR. In the NiCT, although microtremors transmitted from the concrete floor could be reduced by the ACMI [4], magnetic noises at frequencies higher than 10 Hz were still detected by SQUID magnetometers in the MSR when footsteps were applied on the wooden free-access floor. These magnetic noises were assumed to be produced by microtremors of the wall of the MSR that could be caused by sound pressure.

In order to realize the ultimate low magnetic field in the MSR, this paper reports an experimental investigation of the magnetic noise due to the sound pressure and mechanical vibrations caused by footsteps. We measured the noise using SQUID magnetometers in the MSR. Clarifying the characteristics of such magnetic noises will help us in reducing them.

In this paper, we compared frequency spectra of the magnetic noise and vibration of an MSR with and without the operation of ACMI. First, magnetic noises and vibrations were measured without footsteps. Second, they were measured by applying controlled footsteps on the free-access floor, which included sound pressure and mechanical vibrations. Third, they were measured when only the mechanical vibration was applied to the MSR by controlled footsteps on the concrete slab under the free-access floor. Last, the relation between the sound pressure of footsteps on the free-access floor and magnetic noise was investigated quantitatively.

II. METHODS OF MEASUREMENT

We used an MEG system with its MSR supported by the ACMI (Fig. 1). Magnetic noise (B_x, B_y, and B_z) was measured using the three SQUID magnetometers of the MEG system. Vibration was measured for the walls inside the MSR (L_{wx} and L_{wy}), and the ceilings outside the MSR (A_{rx} and A_{ry}). An ordinary acceleration sensor was used outside the MSR, while a laser vibrometer (PPV100) was used inside the MSR to avoid the magnetic noise. Sound pressure was measured inside and outside the MSR ($S_{\rm in}$ and $S_{\rm out}$). The MSR consists of two permalloy layers (outer layer: 2 mm thick, inner layer: 3 mm) and one aluminum layer (9 mm). A wide flange shape (H-shaped 150 mm $\times$ 150 mm) made of aluminum was used as columns and beams (frame). Its shielding factor was about 40 dB at a frequency of 0.1 Hz.

The frequency spectra of the vibration, magnetic noise, and sound pressure with and without the ACMI (ACMI-ON and -OFF) and with and without footsteps (footsteps-ON and -OFF) were compared to distinguish the components of magnetic noises due to sound pressure caused by footsteps [Fig. 1(b)]

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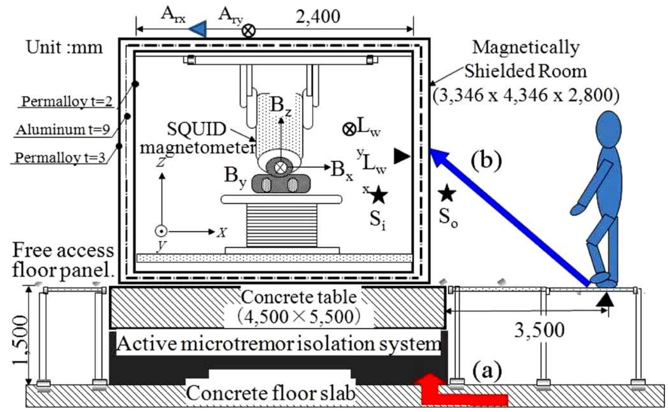

Fig. 1. MSR supported by an active microtremor isolation system and free-access floors, and points for measuring vibration and sound pressure.

from those caused by mechanical vibrations [Fig. 1(a)]. Sampling frequency was 1280 Hz and averaging time was eight.

III. Results and Discussion

A. Magnetic Noises due to Microtremors Caused by Environmental Vibrations

Fig. 2 shows the measured frequency spectra of the velocity of the wall inside the MSR L_{wx} and the magnetic noise B_y without footsteps. Peaks of magnetic noise B_y and L_{wx} at frequencies from 7 to 25 Hz were smaller with ACMI-ON than with ACMI-OFF. With ACMI-OFF, the coherence coefficients (CCs) were very high between L_{wx} and B_y at frequencies of about 13.6 and 18.9 Hz, and between L_{wy} and B_x (figures were omitted) at frequencies of about 13.6 and 16.8 Hz. With ACMI-OFF, the measured acceleration of the ceiling outside the MSR A_{rx} and A_{ry} had peaks of 16.8 and 18.9 Hz (figures were omitted). Those were assumed to reflect the mechanical resonance properties (MRPs) of the frame of the MSR, as predicted by modal analysis [5]. Furthermore, the other peak at 13.6 Hz was considered to be due to the MRP of the panels of the MSR. This suggests that the ACMI could primarily reduce magnetic noises due to microtremors caused by environmental vibrations depending on the MRPs of the frame and panels of the MSR at frequencies from 10 to 25 Hz.

B. Magnetic Noises due to Microtremors Caused by Footsteps on the Wooden Free-Access Floor Outside an MSR

Fig. 3 shows the measured frequency spectra of the magnetic noise B_x, when controlled footsteps were applied on the free-access floor (with footsteps-ON) and were not applied (with footsteps-OFF) with ACMI-ON. Although microtremors transmitted from the floor should have been reduced by the ACMI, magnetic noises due to the footsteps remained at frequencies from 10 to 90 Hz.

Fig. 4 shows the measured frequency spectra of the magnetic noise B_x, the velocity of the wall inside the MSR L_{wx}, and the sound pressure outside the MSR (S_{out}) with footsteps-ON, for ACMI-ON and -OFF, and with footsteps-OFF for ACMI-OFF.

A peak of the magnetic noise B_x at frequencies from 10 to 25 Hz, was larger for ACMI-OFF and footsteps-ON, than for

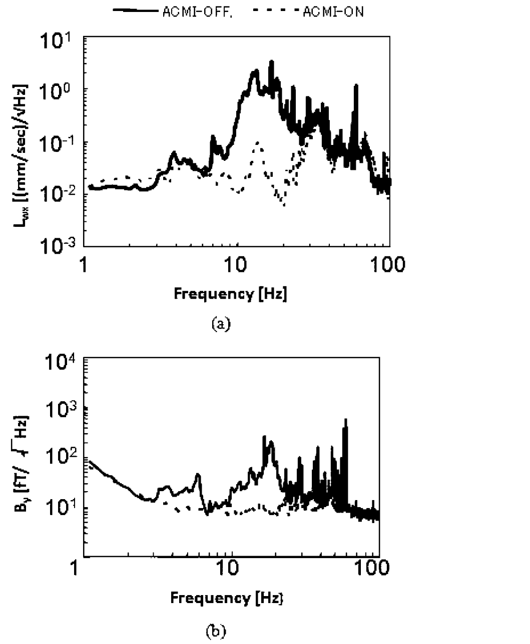

Fig. 2. Measured frequency spectra of velocity of the wall inside the MSR L_{wx} and magnetic noise B_y.

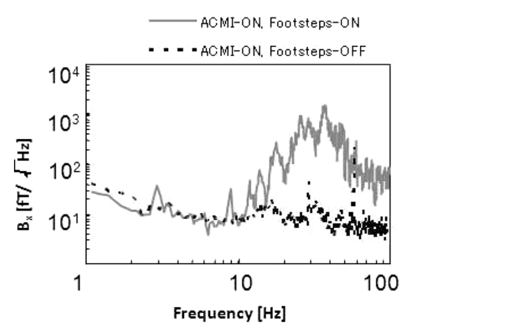

Fig. 3. Measured frequency spectra of magnetic noise B_x when controlled footsteps were applied on the free-access floor with footsteps-ON and footsteps-OFF with ACMI-ON.

ACMI-OFF and footsteps-OFF, and for ACMI-ON and footsteps-ON, showing that the magnetic noise caused by mechanical vibration transmitted from the concrete floor [Fig. 1(a)] was larger than that caused by sound pressure [Fig. 1(b)]. With footsteps ON, the L_{wx} and B_x with ACMI-ON and those with ACMI-OFF at frequencies higher than about 25 Hz were almost the same, suggesting that the magnetic noise caused by sound pressure was greater than that caused by mechanical vibration.

S_{out} and S_{in} (figures are omitted) due to footsteps had peaks at frequencies from 10 to 90 Hz.

With ACMI-OFF, the CCs were very high between S_{out} and B_x at frequencies from about 20 to 40 Hz, and between S_{out} and L_{wx} at frequencies from about 25 to 40 Hz. But, the CCs were also very high between B_x and L_{wx} at frequencies of about 13.6 and 18.9 Hz, which was considered to reflect the MRPs of the frame and panels of the MSR. With ACMI-ON, the CCs were very high between S_{out} and B_x, and between S_{out} and L_{wx} at frequencies from about 15 to 40 Hz. The frequency bandwidth of high CC with ACMI-OFF was narrower than that with ACMI-ON. This result shows that the magnetic noise and vibration of the wall with ACMI-OFF were accompanied by mechanical vibration but not the sound pressure.

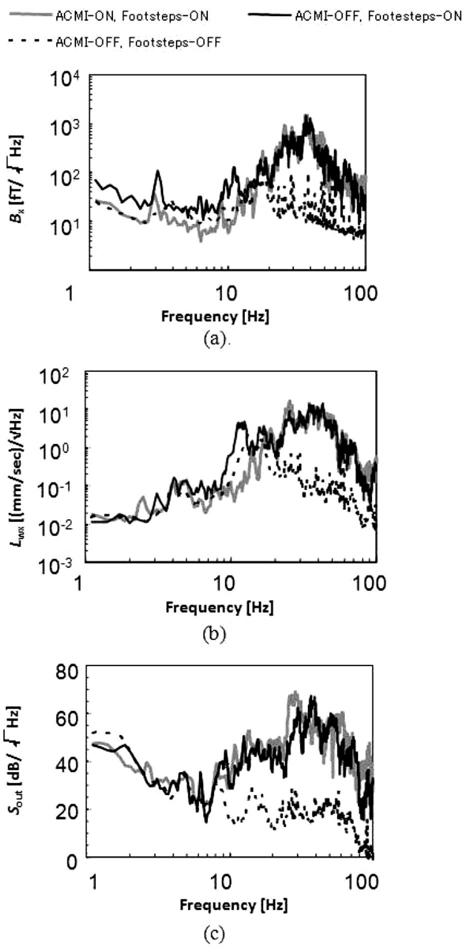

Fig. 4. Measured frequency spectra of magnetic noise B_x and B_y, velocity of the wall inside the MSR L_{wx}, and sound pressure outside the MSR S_{out}, with footsteps-ON with ACMI-ON and -OFF, and with footsteps-OFF with ACMI-OFF. (a) B_x. (b) L_{wx}. (c) S_{out}.

C. Magnetic Noises due to Microtremors Caused by Footsteps on Concrete Slab Outside an MSR

Fig. 5 shows the measured frequency spectra of the magnetic noise B_x and the velocity of the wall inside the MSR L_{wx}, when controlled footsteps were applied on the concrete slab (with footsteps-ON, concrete slab) with ACMI-ON and ACMI-OFF and on the free-access floor (footsteps-ON, free-access floor) with ACMI-OFF. With ACMI-OFF, the B_x and L_{wx} differed between footsteps-ON, free-access floor and footsteps-ON, concrete slab at frequencies higher than about 25 Hz. This indicates that the vibration of the walls and magnetic noise due to the sound pressure on the free-access floor are more significant than that due to mechanical vibration through the concrete floor. Peaks of L_{wx} at frequencies below 25 Hz were higher than those above 25 Hz (with footsteps-ON, concrete slab), showing that the resonance frequencies of the MSR were below 25 Hz. At frequencies higher than about 10 Hz, B_x and L_{wx} were smaller with ACMI-ON than with ACMI-OFF. These results show that magnetic noises from mechanical vibrations due to footsteps on the concrete slab were mostly reduced by the ACMI.

D. Discussion

The present results suggest that the magnetic noise due to footsteps on the wooden free-access floor with ACMI-OFF depends on mechanical vibrations at frequencies from about 10 to 25 Hz, and on sound pressure at frequencies between 25 and 50 Hz. Thus, these frequency bandwidths separated the components of magnetic noises due to the sound pressure from footsteps [Fig. 1(b)] from those caused by mechanical vibrations [Fig. 1(a)]. This can be illustrated as follows. The sound pressure due to footsteps on the free-access floor was larger at higher than 25 Hz. As shown in Fig. 2, the MRPs of the MSR appeared at frequencies from 10 to 25 Hz. Thus, the MSR was susceptible to mechanical vibration at these frequencies, but was not susceptible at frequencies higher than 25 Hz. As a result, the ACMI could effectively eliminate magnetic noise and vibration of the wall between 10 and 25 Hz, as shown in Fig. 5. However, ACMI could not reduce the magnetic noises due to footsteps at frequencies from 25 to 50 Hz. They are considered to be caused via sound pressure. This suggests that it is important to suppress occurrence of sound noises or attenuate them during biomagnetic measurements in the MSR even when using ACMI.

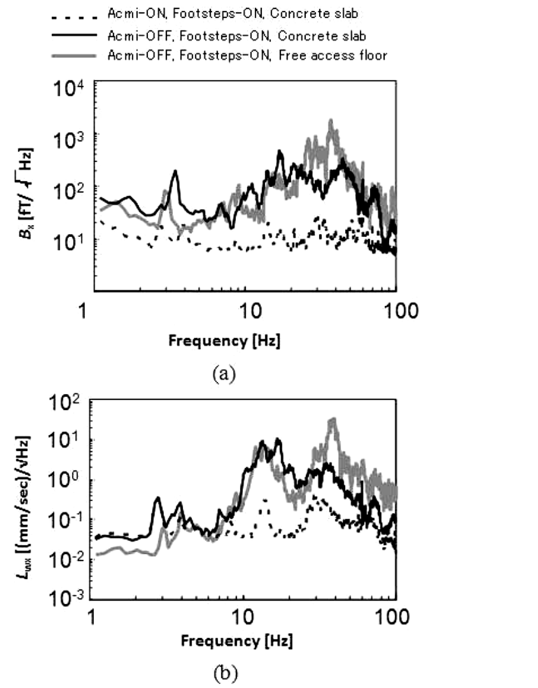

Fig. 5. Measured frequency spectra of magnetic noise B_x and velocity of the wall inside the MSR L_{wx}, when controlled footsteps were applied on the concrete slab (with footsteps-ON, concrete slab) with ACMI-ON and ACMI-OFF and on the free-access floor (with footsteps-ON, free-access floor) with ACMI-OFF. (a) B_x. (b) L_{wx}.

IV. Relation Between Sound Pressure and Magnetic Noise

At frequencies from 15 to 40 Hz with ACMI-ON, the CCs between the sound pressure outside the MSR S_{out} and the velocity of the walls inside the MSR, L_{wx} and those between the magnetic noise B_x and S_{out} were high. We investigated the relation between these quantities.

Fig. 6 shows the relation between S_{out} [Pa] computed from S_{out} [dB] and the displacement ΔL_{wx} of the inner wall in the perpendicular direction obtained from the measured velocity L_{wy} for 23 frequencies from 15 to 40 Hz (the frequencies where the CC was lower than 0.9 were excluded). ΔL_{wx} is approxi-

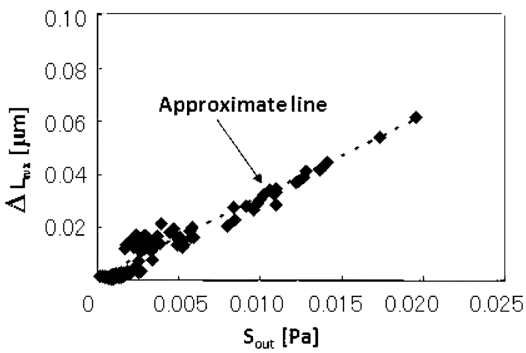

Fig. 6. Relationship between $S_{\rm out}$ [Pa] and the displacement of the inner wall in perpendicular direction ΔL_{wx}.

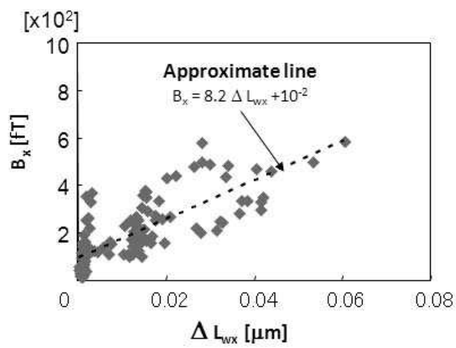

Fig. 7. Relationship between the displacement of the inner wall in perpendicular direction ΔL_{wx} obtained from L_{wx} and magnetic noise B_x.

mately proportional to the sound pressure $S_{\rm out}$. This depends on the construction of the MSR including frames, columns, beams, and shielding panels.

Fig. 7 shows the relation between the displacement ΔL_{wx} of the inner wall in the perpendicular direction obtained from L_{wy} and the magnetic noises B_x for 23 frequencies from 15 to 40 Hz (the frequencies where the CC was lower than 0.9 were excluded). It was demonstrated that B_x is approximately proportional to ΔL_{wx}. In this MSR, a 1-μm displacement of the inner wall in the perpendicular direction resulted in about 8 pT of magnetic noise.

Fig. 8 shows the relation between $S_{\rm out}$ [Pa] and B_x for 56 frequencies from 15 to 40 Hz (the frequencies where the CC was lower than 0.9 were excluded). This shows the tendency for magnetic noise B_x to increase as the sound pressure outside due to footsteps on the wooden free-access floor increases. Magnetic noise of 200 and 600 fT corresponded to 0.005 Pa (50 dB) and 0.2 Pa (60 dB), respectively.

V. Conclusion

An experimental investigation of the magnetic noise due to the sound pressure and mechanical vibrations caused by footsteps on the free-access floor was carried out by comparing the conditions where an ACMI in the basement underneath the MSR was operated or not operated.

1) Without footsteps, the ACMI could mainly reduce magnetic noises due to microtremors caused by mechanical vibrations depending on the mechanical resonance properties of the frame and panels of the MSR at frequencies from 10 to 25 Hz.
2) When footsteps were applied on the wooden free-access floor, the ACMI effectively eliminated magnetic noise due to microtremors caused by mechanical vibrations between 10 and 25 Hz, but not those caused by sound pressure between 25 and 50 Hz. The microtremors transmitted from the concrete floor depended on the mechanical resonance properties of the frame and panels of the MSR, but those directly transmitted from free-access floor did not.
3) The displacement of the wall was approximately proportional to the sound pressure caused by footsteps and the magnetic noise was approximately proportional to the displacement of the wall. Thus, the magnetic noise was approximately proportional to the sound pressure. That is, 1 μm of wall displacement resulted in about 8 pT of magnetic noise. Magnetic noise of 200 and 600 fT corresponded to about 0.005 Pa (50 dB) and 0.2 Pa (60 dB), respectively.
4) The implications of the present results are summarized as follows. Both mechanical vibration and sound pressure produce magnetic noises in the MSR, which may deteriorate the biomagnetic measurements such as MEG. The noises due to them have different frequency components, depending on the mechanical properties of the MSR and the constructions related to sound pressures. It is effective to suppress these mechanical vibrations and sound noises for minimizing the magnetic noises during biomagnetic measurements.

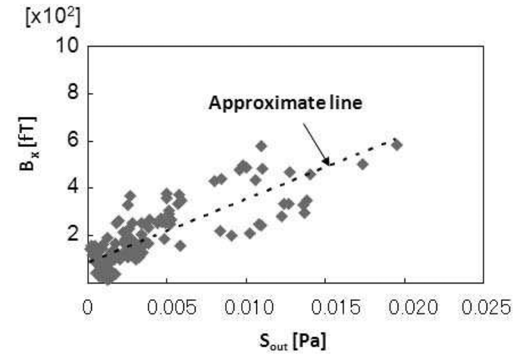

Fig. 8. Relationship between $S_{\rm out}$ [Pa] and magnetic noise B_x.

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