Field reference technique for ac magnetic susceptibility measurements under pressure

N. Kabeya, K. Deguchi and N. K. Sato
Department of Physics, Graduate School of Science, Nagoya University, Nagoya 464-8602, Japan
E-mail: kabeya.noriyuki@d.mbox.nagoya-u.ac.jp

Abstract. In the present study, we propose a new simple technique based on Faraday law of induction for the ac magnetic susceptibility measurement under high pressure. Although the technique needs a simple additional change from the conventional method, it performs certain separation a real ($\chi'$) from imaginary ($\chi''$) variable of magnetic susceptibility and free from the change of the ac field amplitude. A typically result obtained from this technique and the shielding effect of ac magnetic field by a pressure cell are shown.

1. Introduction
An ac magnetic susceptibility measurement has been employed to investigate magnetic and superconducting properties of heavy fermion systems for a wide range of temperature and magnetic field [1, 2, 3, 4]. The conventional technique of a high-pressure ac magnetic susceptibility experiment has a difficulty arising from a shielding effect of modulation field: An eddy current induced in a metallic pressure cell will modulate an amplitude and phase of the oscillation field at a sample site. This effect makes it difficult to unambiguously separate a real ($\chi'$) from imaginary ($\chi''$) part of the magnetic susceptibility. This motivates us to develop a method for a more precise magnetic susceptibility measurement under high pressure.

2. Experimental method
An external pressure was applied using a CuBe-NiCrAl hybrid piston-cylinder. Daphne oil 7373 was used as a pressure transmitting medium. Pressure was determined using a superconducting transition of indium. In what follows, we give a detailed description of the measuring system of the ac magnetic susceptibility.

Figure 1a shows a schematic illustration of coil setting. A primary coil generates an ac magnetic field $B = B_0 e^{i\omega t}$. Here, $B_0$ and $\omega$ is an amplitude and frequency of the magnetic field, respectively. The primary coil is placed outside the pressure cell. A pair of secondary (signal detection) coils marked (iii) are put in the pressure cell with a sample. (One may notice that there is another coil marked (iv); this is described below.) These coils and the sample are immersed in the pressure transmitting medium. The field felt by the sample is modulated by an eddy current produced in the pressure cell and described as $B' = B |a| e^{i\theta}$. Here, $|a|$ and $e^{i\theta}$ is an amplitude ratio and phase of the modulated field, respectively. These experimental settings are the same as those of the conventional method. The difference lies in the secondary coil system; to monitor the modulated field $B'$ which the sample feels, we put an additional...
Figure 1. Schematic illustration of the ac measurement system presented. a. Schematic illustration of coil setting. (i): primary coil, (ii): pressure cell, (iii): field reference coil, (iv): secondary coil, (v): sample. $B$ and $B'$ represent the oscillated magnetic field outside and inside the pressure cell, respectively. b. Schematic illustration of the measurement system. Gray circles represent oscillated magnetic fields. The pressure cell is described as an effective circuit consisting of coil and resistance. $V_R$ and $V_S$ represent the voltage induced in the field reference coil and the secondary coil, respectively. The field reference coil is connected to the reference input of the lock-in-amplifier via a filter and amplifier.

pick-up coil, referred to as “field reference coil” hereafter, which is often used in a vibrating sample magnetometer (VSM) [5]. This coil is isolated from the secondary coil.

Figure 1b shows a schematic illustration of the measurement system. The reference coil generates an ac voltage $V_R$ as output. The voltage is amplified and then input into a lock-in-amplifier as a reference signal. This signal correctly gives a phase of the filed felt by the sample. Therefore, X and Y outputs of the lock-in-amplifier with respect to $V_S$ unambiguously yield $\chi'$ and $-\chi''$, respectively.

The secondary coil consists of a pair of coils as usual, and each (clockwise and counterclockwise) coil has 600 turns. The reference coil has about 100 turns. For the frequency $f$, we obtained good performance between 10 Hz and 1.3 kHz. For $f < 10$ Hz, the voltage is too small to use as a reference signal. This is because the voltage induced by the field is in proportion to frequency. For $f > 2$ kHz, on the other hand, the capacitance component of the coil produces a spurious phase in the voltage $V_R$. The results presented below were obtained using the amplitude and frequency of 1.0 Oe and 100 Hz, respectively.

3. Results
Figure 2 shows the temperature dependence of the ac magnetic susceptibility of indium and lead, both of which were put inside the coil together. In the real part of the susceptibility $\chi'$, a step like diamagnetic signal is observed at 3.4 K and 7.2 K. The former corresponds to the indium, and the latter to the lead. Although a small peak is observed at 3.4 K, the imaginary part $\chi''$ is almost independent of temperature as expected. This clearly demonstrates that the present technique works properly.

We show the temperature dependence of the ratio $B'/B$ in Fig. 3a. For a reference, we give the result for the case in which no pressure cell was used: The ratio of $B'/B = 1$ means that there is no shielding effect. For the case in which the samples were put into the pressure cell although they were not pressurized, the ratio was decreased down to about 0.95, which means that the
eddy current produced in the pressure cell shields 5 percent of the external magnetic field. This shielding effect decreases with increasing temperature, due to the increase in the electrical resistivity of the pressure cell with temperature. We note that similar phenomena occur in a vacuum can made of copper: more than 50 percent of the oscillation field was shielded (not shown here).

Figure 3b shows the phase difference $\theta$ between $B'$ and $B$ as a function of temperature. At ambient pressure with no pressure cell, we observe $\theta = 0$, indicating that there is no phase shift between $B'$ and $B$. For the case in which the sample is put in the pressure cell, a phase difference emerges, $\theta \sim -21$ degree at low temperature.

4. Conclusion
We presented a new, simple technique for the ac magnetic susceptibility measurement under high pressure. This technique only needs a small modification; an additional pick-up coil to monitor the magnetic field felt by the sample is put into the pressure cell together with a pair of pick-up coils to probe the sample signal. Using this technique, we avoid the difficulty arising from the eddy current effect of the pressure cell, which enables us to safely separate the real part $\chi'$ from the imaginary part $\chi''$ of the ac magnetic susceptibility.

Acknowledgments
This work was partially supported by Grant-in-Aid for Scientific Research (Nos. 20224015, No. 20102006 and No. 21008593). One of the author (N. K.) was supported by a Grant-in-Aid for JSPS Fellows.

References
[1] Huxley A, Sheikin I and Braithwaite D 2000 Physica B 284-288 1277
[2] Petrova A E, Krasnorussky V, Sarrao J and Stishov S M 2006 Phys. Rev. B 73 052409
[3] Slooten E, Naka T, Gasparini A, Huang Y K and de Visser A 2009 Phys. Rev. Lett. 103 097003
[4] Kabeya N, Iijima R, Osaki E, Ban S, Imura K, Deguchi K, Aso N, Homma Y, Shiokawa Y and Sato N K 2009 Physica B 404 3241
[5] Foner S 1956 Rev. Sci. Instrum. 27 548