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Dynamic Level-Detecting Characteristics of External-Heating-Type MgB_2 Liquid Hydrogen Level Sensors under Liquid Level Oscillation and Its Application to Sloshing Measurement

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***Abstract*— To establish the worldwide storage and marine transportation of hydrogen, it is important to develop liquid hydrogen tanks/carriers as well as a long level sensor such as a superconducting magnesium diboride (MgB_2) level sensor. An external-heating-type MgB_2 level sensor is expected to be an excellent choice for liquid hydrogen because of its high linearity, resolution, and reproducibility. The dynamic level-detecting characteristics of three 500-mm-long MgB_2 level sensors have been evaluated under conditions of oscillating liquid level using an optical cryostat and a high-speed microscope. The response time to variations of the liquid hydrogen level is about 0.1 s, and the difference between the level read optically and that detected by the MgB_2 level sensors is about 5 mm under these conditions. Thus, the MgB_2 level sensors have superior response performance for the sloshing measurement of liquid hydrogen.**

***Index Terms*—level sensor, liquid hydrogen, MgB_2 wire, sloshing.**

I. INTRODUCTION

HYDROGEN is attracting attention as a medium for solving global environmental problems and avoiding a future energy crisis. It is highly important to establish a marine transport technology for the global-scale storage and transport of large quantities of hydrogen. Liquid hydrogen (LH_2: 20 K) is the most suitable medium for marine transportation because its density is about 800 times that of gaseous hydrogen (300 K, 0.1 MPa). The sloshing phenomenon inside an LH_2 tank during marine transportation by ship has not yet been experimentally clarified, despite a similar phenomenon occurring inside liquefied natural gas (LNG) tanks.

Recently, a superconducting magnesium diboride (MgB_2) level sensor for LH_2 has been developed [1], [2]. We are currently developing an external-heating-type MgB_2 level sensor for LH_2 [3], [4]. This type of sensor, the electrical resistance of which shows a difference when immersed in the liquid versus the vapor phase, exhibits a high linearity, a high resolution, and good reproducibility. The thermal response of the sensor output and sensor temperature to an external heater and the effect of the sensor length and differences between individual sensors on the sensor performance were previously reported [5]-[13]. It was found that the thermal response of the sensor was excellent and that the sensor performance was independent of the sensor length and individual differences. However, the response time and the level-detecting characteristics of the sensor in the case of variations of the liquid level have not yet been clarified. It is important to carry out measurements of the sloshing of LH_2 using a MgB_2 level sensor. The purpose of this study is to evaluate the applicability of sloshing measurement using an external-heating-type MgB_2 level sensor; thus, we examined the dynamic level-detecting characteristics of the external-heating-type MgB_2 level sensor in a LH_2 bath subjected to cyclic movement in the horizontal direction.

II. EXTERNAL-HEATING-TYPE MgB_2 LEVEL SENSOR

The external-heating-type MgB_2 level sensor used in this study was composed of a MgB_2 wire of 0.32 mm diameter and 500 mm total length that was reinforced by a CuNi (7:3) sheath. It was fabricated by using the powder-in-tube method with a heat treatment of 1 hour at a temperature of 873.15 K in an argon gas atmosphere. To reduce the critical temperature T_c of the MgB_2 wire, 10% SiC was added as an impurity to the MgB_2 core; as a result, T_c was reduced to about 32 K from about 39 K. A polyester-coated manganin wire of 0.2 mm diameter was wound in a spiral around the MgB_2 wire with a pitch of 2 mm for use as an external heater. In this experiment, we manufactured three 500-mm-long MgB_2 level sensors (denoted A, B1, and B2), which were cut from two 1.7-m-long MgB_2 wires (wires A and B). The electrical resistances of short samples of wires A and B were measured by a DC four-wire technique and the measurement current was 10 mA. Table 1 shows the average superconducting properties of the MgB_2 wires (wires A and B). The values of T_{c_on} were 33.79 K for wire A and 33.81 K for wire B and the values of T_{c_off} were 30.98 K for wire A and 30.52 K for wire B [12]. The values of R_{on} were 5.053 Ω/m for wire A and 5.046 Ω/m for wire B and the values of dR/dT were 0.004 Ω/m/K for both wires,

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TABLE 1 AVERAGE SUPERCONDUCTING PROPERTIES OF THE MgB_2 WIRES

	Heat treatment temperature [K]	$T_{c\ on}$ [K]	$T_{c\ off}$ [K]	$\triangle T_c$ [K]	R_{on} [Ω/m]	dR/dT [Ω/(m・K)]
Wire A	873.15	33.79	30.98	2.81	5.053	0.004
Wire B	873.15	33.81	30.52	3.29	5.046	0.004

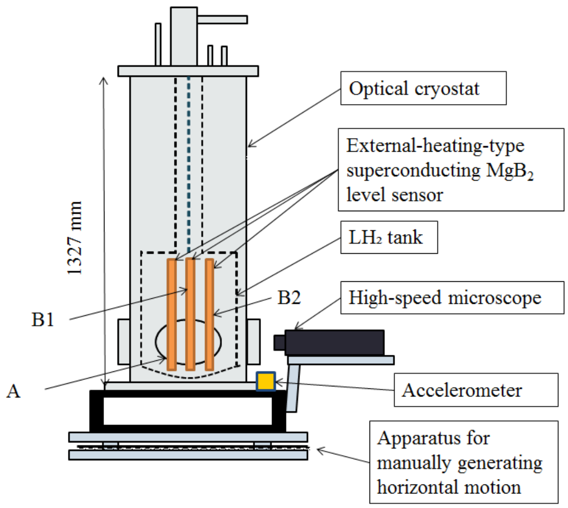

Fig. 1 Schematic diagram of LH_2 optical cryostat.

where R denotes the resistance per unit length [12]. These properties show sharp superconducting transitions, relatively high resistances, and very low temperature dependence of the resistance. In addition, the linear correlation coefficient for the static level-detecting characteristics was 0.999 or more, indicating high linearity for both wires [7], [12].

III. Experimental Apparatus and Method

Fig. 1 shows a schematic diagram of the LH_2 optical cryostat. The optical cryostat is composed of a vacuum jacket, an LH_2 space (20 L), an LN_2 space (15 L), a 77 K aluminum shield, and five optical windows. The optical cryostat has a height of 1327 mm and the optical windows are made of PYREX® glass and have an effective diameter of 60 mm. The layout of the three MgB_2 level sensors are labeled A, B1, and B2 from the left, as shown in Fig. 1. The measurement system consists of an optical cryostat, the three MgB_2 level sensors, three current sources for the sensors, three power supplies for the heaters, an apparatus for manually generating horizontal motion, an accelerometer, a high-speed microscope, and a data logger as shown in Fig. 2. In addition, a high-speed microscope was synchronized with a data logger and all the data were recorded by the data logger. Fig. 3 shows a photograph of the measurement system. We compared the liquid level obtained from the sensor output voltage with that obtained from high-speed microscope images. The experiment was performed on the three MgB_2 sensors (A, B1, and B2) using a DC four-wire technique and a measurement current of 10 mA under atmospheric pressure. We measured the output voltages of the three MgB_2 level sensors at heater inputs of 6 W and 9 W to clarify the external heating effect, the liquid level from the images obtained by the high-speed microscope, and the acceleration while the liquid surface was varied by the manually generated horizontal motion with one push. Fig. 4 shows the acceleration data. The acceleration was set to about 0.7 m/s^2 in each case. The sampling period of the data logger was 10 ms and the frame rate of the high-speed microscope was 125 fps.

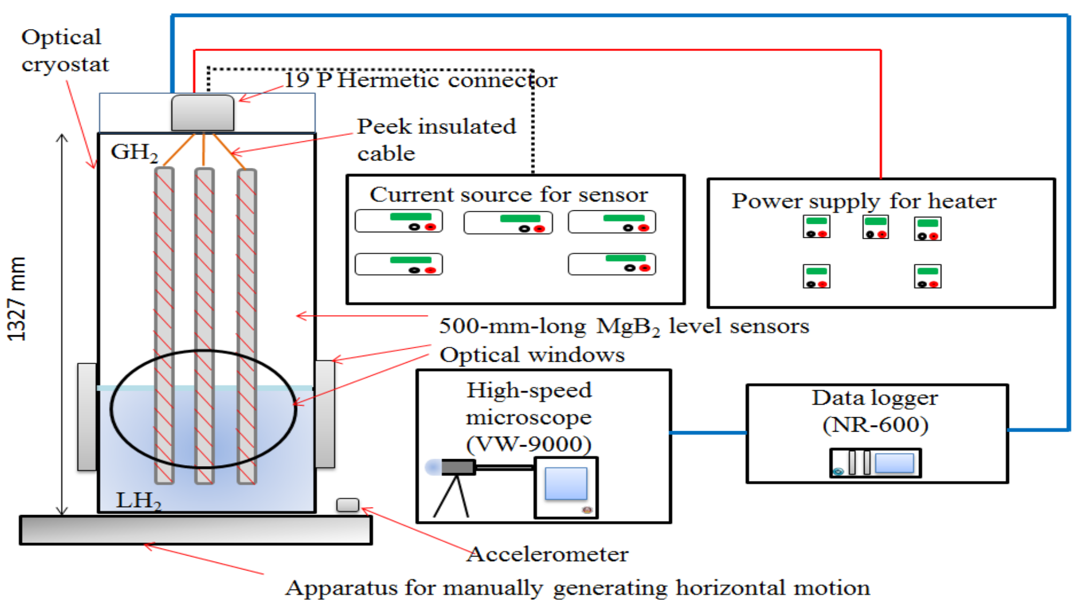

Fig. 2 Measurement system.

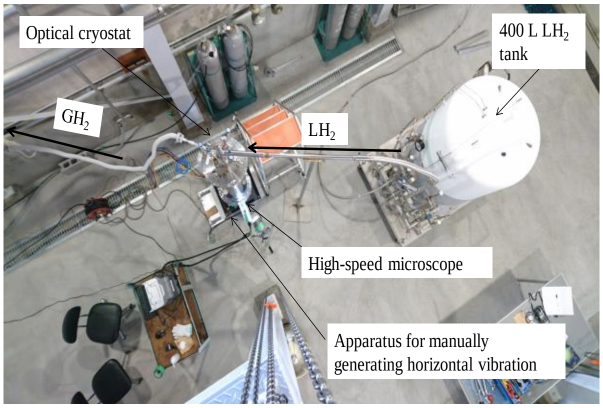

Fig. 3 Photograph of measurement system.

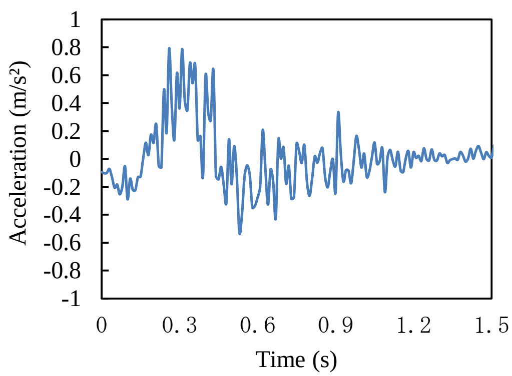

Fig. 4 The acceleration data with one push.

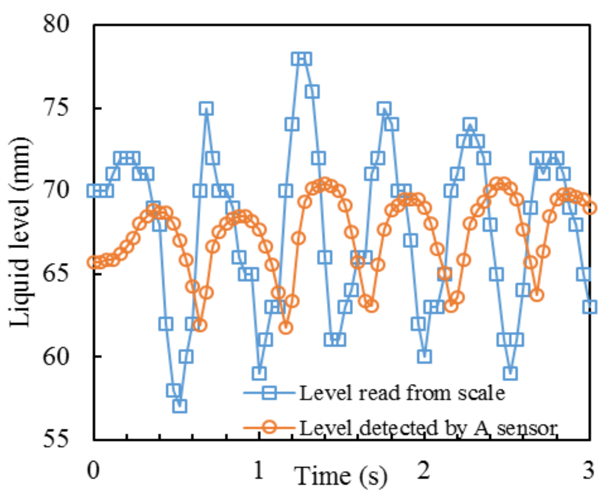

Fig.5 Comparison between the level read from the scale and that detected by MgB_2 level sensor A at a heater input of 6 W.

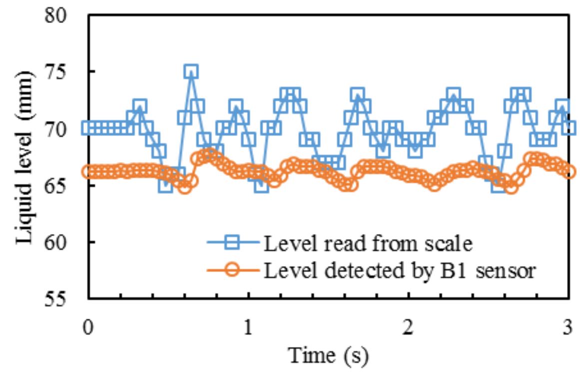

Fig. 6 Comparison between the level read from the scale and that detected by MgB_2 level sensor B1 at a heater input of 6 W.

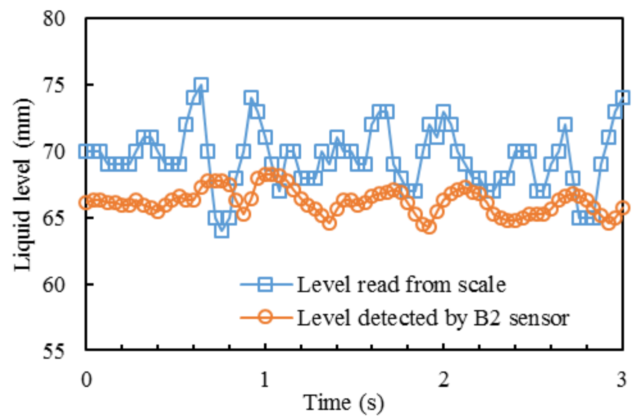

Fig. 7 Comparison between the level read from the scale and that detected by MgB_2 level sensor B2 at a heater input of 6 W.

IV. Experimental Results

Figs. 5-7 show a comparison between the experimental results for the level read from the scale and that detected by MgB_2 level sensors A, B1, and B2 at a heater input of 6 W, respectively. Continuous images showing the LH_2 level with a scale and the MgB_2 level sensors with interval of 0.04 s is shown in Fig. 8. The variation of the liquid level obtained from the sensor output voltage and that obtained from the liquid level images monitored by the high-speed microscope showed a similar tendency over time with a time lag as shown in Figs. 5-7. The response time defined as a time lag between the peaks of the liquid level read from scale and those of the liquid level detected by MgB_2 level sensor was obtained.

Table 2 shows the average response time of the MgB_2 level sensors to the variation of the liquid level at heater inputs of 6 W and 9 W. The response time of each MgB_2 level sensor was about 0.15 s at a heater input of 6 W and about 0.12 s at a heater input of 9 W. The response time of each MgB_2 level sensor decreased with increasing the heater input because the heating effect of the external heater on the sensor was improved. As a result, the variation of the liquid level was large at the position of the sensor A, while that was small at the position of the sensors B1 and B2. This is because the LH_2 tank (φ: 200 mm) is small, therefore the liquid surface oscillation depends on the natural sloshing frequency of LH_2 tank. Accordingly, the sensor A indicated large oscillation, while the sensors B1 and B2 indicated small oscillation.

The goal of this study is the measurement of sloshing of the large LH_2 tank for ship. The natural sloshing cycle of the large

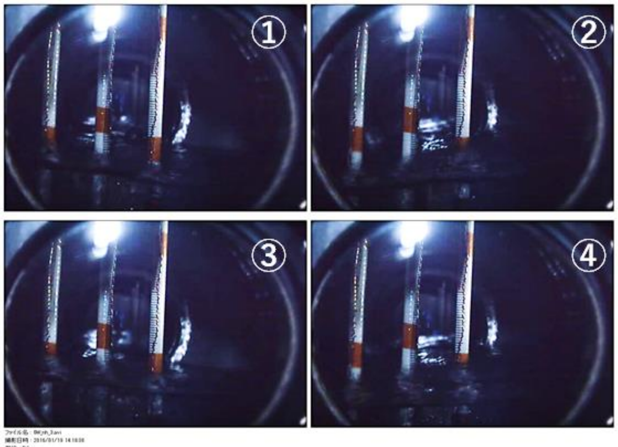

Fig. 8 Example of continuous images obtained from high-speed microscope with interval of 0.04 s.

TABLE 2 AVERAGE RESPONSE TIMES OF THE MgB_2 LEVEL SENSORS TO VARIATIONS OF THE LIQUID LEVEL

	A (S)	B1 (S)	B2 (S)	Ave (S)
6 W	0.162	0.144	0.147	0.151
9 W	0.127	0.121	0.110	0.119

tank during the marine transportation is about 5-10 s or more and the oscillation of the liquid surface is large on the order of 1 m. Thus, the MgB_2 level sensors have superior response performances for sloshing measurement because the response time to variations of the liquid level was about 0.1 s. Also, the difference between the level read from the scale and that detected by the MgB_2 level sensors was about 5 mm (about 1% of the total sensor length) at heater inputs of 6 W and 9 W, thereby showing good dynamic level detection.

In conclusion, an external-heating-type MgB_2 level sensor can be expected to be applied to sloshing measurement because it exhibited good dynamic level detection. Moreover, we successfully measured the time variations in the liquid level of a 2000 L LH_2 tank during transportation by a truck [6].

V. Conclusion

We examined the dynamic level-detecting characteristics of three 500-mm-long external-heating-type superconducting MgB_2 level sensors. The response time to the variation of the liquid level was about 0.1 s at heater inputs of 6 W and 9 W, and the difference between the level read from the scale and that detected by the MgB_2 level sensors was about 5 mm. Therefore, the external-heating-type MgB_2 level sensor can be applied to sloshing measurement because of its good dynamic level-detecting characteristics. Sloshing measurement inside the small LH_2 tank during a voyage on board of a training ship will be carried out as a future work.

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