



# Dynamic Level-Detecting Characteristics of External-Heating-Type MgB<sub>2</sub> Liquid Hydrogen Level Sensors Under Liquid Level Oscillation and Its Application to Sloshing Measurement

Maekawa, Kazuma ; Takeda, Minoru ; Hamaura, Takaaki ; Suzuki, Kohei ; Matsuno, Yu ; Fujikawa, Shizuichi ; Kumakura, Hiroaki

---

(Citation)

IEEE transactions on applied superconductivity, 27(4):9000304-9000304

(Issue Date)

2017-06

(Resource Type)

journal article

(Version)

Accepted Manuscript

(Rights)

Copyright © 2017, IEEE

(URL)

<https://hdl.handle.net/20.500.14094/90005491>



# Dynamic Level-Detecting Characteristics of External-Heating-Type $\text{MgB}_2$ Liquid Hydrogen Level Sensors under Liquid Level Oscillation and Its Application to Sloshing Measurement

Kazuma Maekawa, Minoru Takeda, Takaaki Hamaura, Kohei Suzuki, Yu Matsuno, Shizuichi Fujikawa, and Hiroaki Kumakura

**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 ( $\text{MgB}_2$ ) level sensor. An external-heating-type  $\text{MgB}_2$  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  $\text{MgB}_2$  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  $\text{MgB}_2$  level sensors is about 5 mm under these conditions. Thus, the  $\text{MgB}_2$  level sensors have superior response performance for the sloshing measurement of liquid hydrogen.

**Index Terms**—level sensor, liquid hydrogen,  $\text{MgB}_2$  wire, sloshing.

## I. INTRODUCTION

**H**YDROGEN 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 ( $\text{LH}_2$ : 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  $\text{LH}_2$  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 ( $\text{MgB}_2$ ) level sensor for  $\text{LH}_2$  has been developed [1], [2]. We are currently developing an external-heating-type  $\text{MgB}_2$  level sensor for  $\text{LH}_2$  [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  $\text{LH}_2$  using a  $\text{MgB}_2$  level sensor. The purpose of this study is to evaluate the applicability of sloshing measurement using an external-heating-type  $\text{MgB}_2$  level sensor; thus, we examined the dynamic level-detecting characteristics of the external-heating-type  $\text{MgB}_2$  level sensor in a  $\text{LH}_2$  bath subjected to cyclic movement in the horizontal direction.

## II. EXTERNAL-HEATING-TYPE $\text{MgB}_2$ LEVEL SENSOR

The external-heating-type  $\text{MgB}_2$  level sensor used in this study was composed of a  $\text{MgB}_2$  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  $\text{MgB}_2$  wire, 10% SiC was added as an impurity to the  $\text{MgB}_2$  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  $\text{MgB}_2$  wire with a pitch of 2 mm for use as an external heater. In this experiment, we manufactured three 500-mm-long  $\text{MgB}_2$  level sensors (denoted A, B1, and B2), which were cut from two 1.7-m-long  $\text{MgB}_2$  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  $\text{MgB}_2$  wires (wires A and B). The values of  $T_{c,\text{on}}$  were 33.79 K for wire A and 33.81 K for wire B and the values of  $T_{c,\text{off}}$  were 30.98 K for wire A and 30.52 K for wire B [12]. The values of  $R_{\text{on}}$  were 5.053  $\Omega/\text{m}$  for wire A and 5.046  $\Omega/\text{m}$  for wire B and the values of  $dR/dT$  were 0.004  $\Omega/\text{m/K}$  for both wires,

Automatically generated dates of receipt and acceptance will be placed here; Corresponding author: Minoru Takeda (e-mail: takeda@maritime.kobe-u.ac.jp).

This work was supported in part by a Grant-in Aid for Scientific Research, JSPS KAKENHI Grant Number 24246143, Japan.

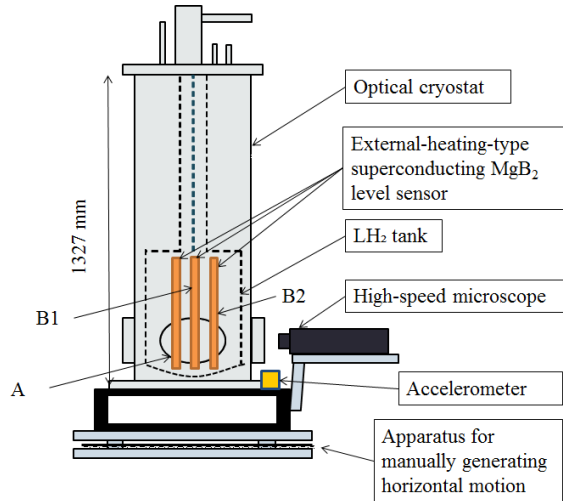
K. Maekawa, M. Takeda, T. Hamaura, and K. Suzuki are with Graduate School of Maritime Sciences, Kobe University, Kobe, Hyogo 658-0022, Japan.

Y. Matsuno, and S. Fujikawa are with Iwatani Corporation R&D Center, Amagasaki, Hyogo 661-0965, Japan.

H. Kumakura is with National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan.

TABLE 1 AVERAGE SUPERCONDUCTING PROPERTIES OF THE  $\text{MgB}_2$  WIRES

	Heat treatment temperature [K]	$T_{c \text{ on}}$ [K]	$T_{c \text{ off}}$ [K]	$\Delta T_c$ [K]	$R_{\text{on}}$ [ $\Omega/\text{m}$ ]	$dR/dT$ [ $\Omega/(\text{m}\cdot\text{K})$ ]
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  $\text{LH}_2$  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  $\text{LH}_2$  optical cryostat. The optical cryostat is composed of a vacuum jacket, an  $\text{LH}_2$  space (20 L), an  $\text{LN}_2$  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<sup>®</sup> glass and have an effective diameter of 60 mm. The layout of the three  $\text{MgB}_2$  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  $\text{MgB}_2$  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  $\text{MgB}_2$  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  $\text{MgB}_2$  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  $0.7 \text{ m/s}^2$  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.

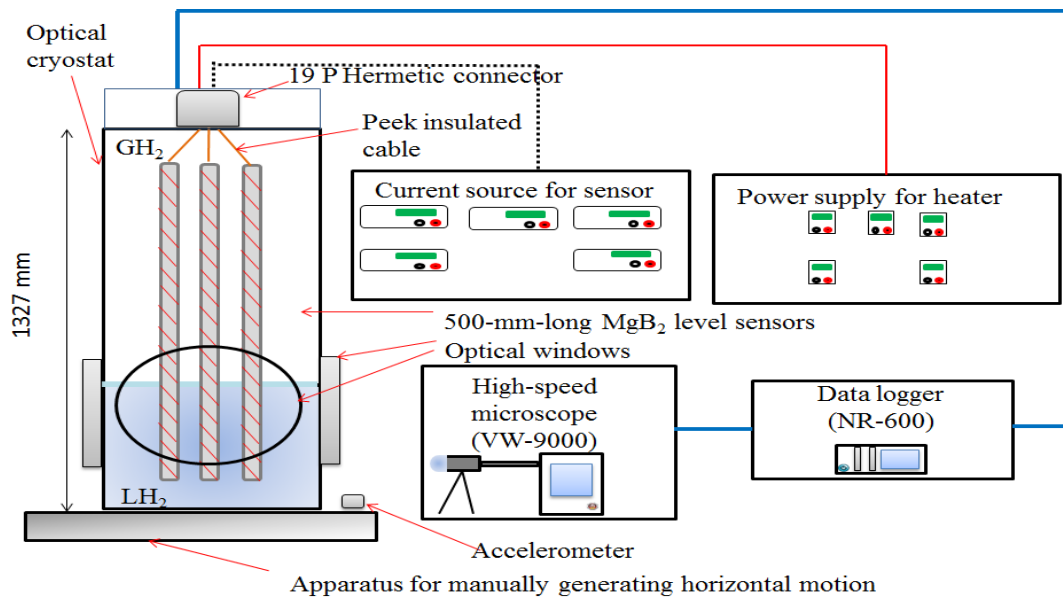


Fig. 2 Measurement system.

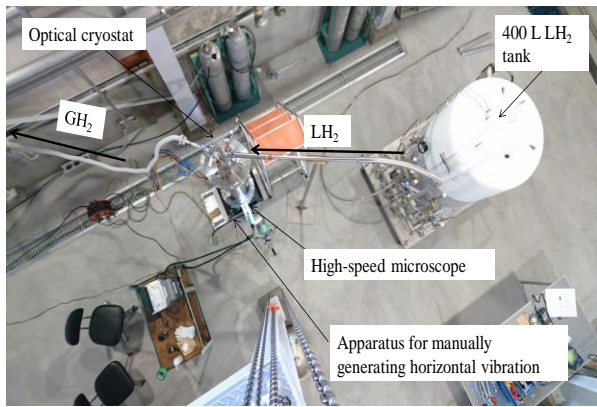


Fig. 3 Photograph of measurement system.

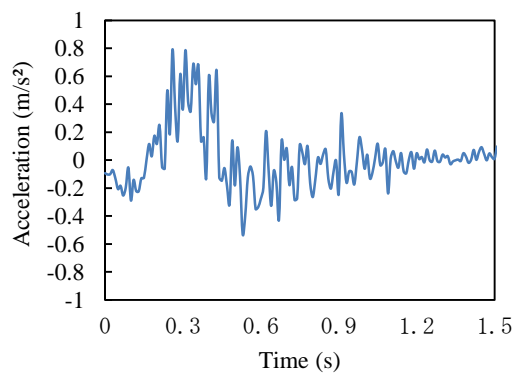


Fig. 4 The acceleration data with one push.

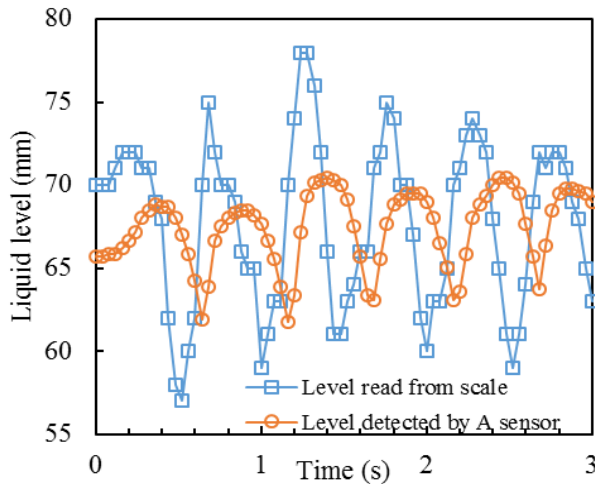


Fig.5 Comparison between the level read from the scale and that detected by MgB<sub>2</sub> level sensor A at a heater input of 6 W.

#### 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<sub>2</sub> level sensors A, B1, and B2 at a heater input of 6 W, respectively. Continuous images showing the LH<sub>2</sub> level with a scale and the MgB<sub>2</sub> level sensors with interval of 0.04 s is

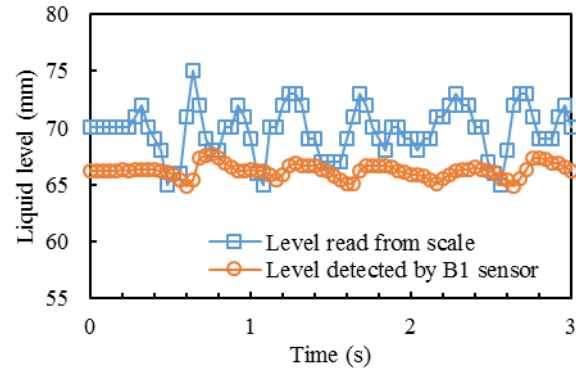


Fig. 6 Comparison between the level read from the scale and that detected by MgB<sub>2</sub> level sensor B1 at a heater input of 6 W.

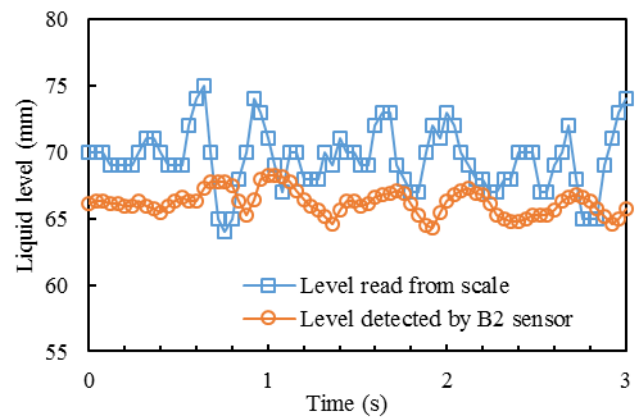


Fig. 7 Comparison between the level read from the scale and that detected by MgB<sub>2</sub> level sensor B2 at a heater input of 6 W.

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<sub>2</sub> level sensor was obtained.

Table 2 shows the average response time of the MgB<sub>2</sub> level sensors to the variation of the liquid level at heater inputs of 6 W and 9 W. The response time of each MgB<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> tank ( $\phi$ : 200 mm) is small, therefore the liquid surface oscillation depends on the natural sloshing frequency of LH<sub>2</sub> 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<sub>2</sub> tank for ship. The natural sloshing cycle of the large

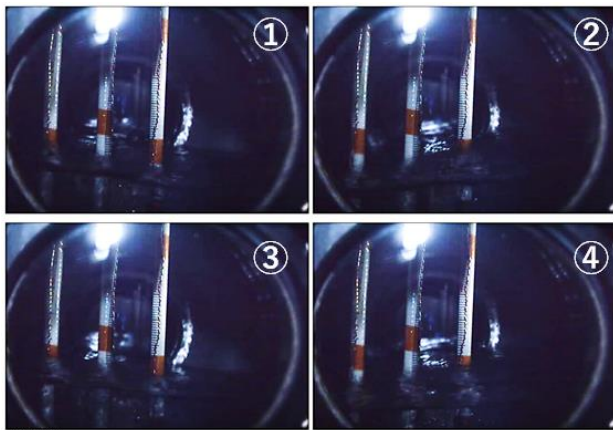


Fig. 8 Example of continuous images obtained from high-speed microscope with interval of 0.04 s.

TABLE 2 AVERAGE RESPONSE TIMES OF THE MgB<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> level sensors was about 5 mm. Therefore, the external-heating-type MgB<sub>2</sub> level sensor can be applied to sloshing measurement because of its good dynamic level-detecting characteristics. Sloshing measurement inside the small LH<sub>2</sub> tank during a voyage on board of a training ship will be carried out as a future work.

## ACKNOWLEDGMENT

The authors would like to thank Dr. Mineo Tanaka for helpful discussions and technical support.

## REFERENCES

- [1] C. Haberstroh and G. Zick, "A superconductive MgB<sub>2</sub> level sensor for liquid hydrogen," *Advances in Cryogenic Engineering*, vol. 51A, pp. 679-684, 2006.
- [2] K. Kajikawa, K. Tomachi, N. Maema, M. Matsuo, S. Sato, K. Funaki, H. Kumakura, K. Tanaka, M. Okada, K. Nakamachi, Y. Kihara, T. Kamiya and I. Aoki, "Fundamental investigation of a superconducting level sensor for liquid hydrogen with MgB<sub>2</sub> wire," *Journal of Physics: Conference Series*, vol. 97, 012140, 2008.
- [3] M. Takeda, Y. Matsuno, I. Kodama and H. Kumakura, "Characteristics of MgB<sub>2</sub> sensor for detecting level of liquid hydrogen," *Advances in Cryogenic Engineering*, vol. 53B, pp. 933-939, 2008.
- [4] M. Takeda, Y. Matsuno, I. Kodama, H. Kumakura and C. Kazama, "Application of MgB<sub>2</sub> Wire to Liquid Hydrogen Level Sensor — External-Heating-Type MgB<sub>2</sub> Level Sensor," *IEEE Trans. Appl. Supercond.*, vol. 19, no.3, pp. 764-767, Jun. 2009.
- [5] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Thermal response of MgB<sub>2</sub> level sensor for liquid hydrogen using external heater," *Proceedings of ICEC24-ICMC2012*, pp.59-62, 2013.
- [6] M. Takeda, Y. Matsuno, S. Fujikawa, K. Maekawa, T. Kuroda and H. Kumakura, "Synchronous measurements of liquid level, temperature and pressure inside a 2000 liter liquid hydrogen tank during a truck transportation," *Proceedings of ICEC24-ICMC2012*, pp.311-314, 2013.
- [7] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Optimization of external-heating-type MgB<sub>2</sub> level sensor for liquid hydrogen," *TEION KOGAKU (J. Cryo. Super. Soc. Jpn)*, vol. 49, no. 2, pp. 69-75, 2014 (in Japanese).
- [8] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Effect of sensor length on thermal response of external-heating-type MgB<sub>2</sub> level sensor for liquid hydrogen," *Journal of the JIME*, vol. 49, no. 4, pp. 122-128, 2014 (in Japanese).
- [9] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Fundamental study of tank with MgB<sub>2</sub> level sensor for transportation of liquid hydrogen," *Physics Procedia*, vol. 67, pp. 1164-1168, 2015.
- [10] M. Takeda, H. Nara, K. Maekawa, S. Fujikawa, Y. Matsuno, T. Kuroda and H. Kumakura, "Simulation of liquid level, temperature and pressure inside a 2000 liter liquid hydrogen tank during truck transportation," *Physics Procedia*, vol. 67, pp. 208-214, 2015.
- [11] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Individual difference performance evaluation of external-heating-type MgB<sub>2</sub> level sensor for liquid hydrogen," *TEION KOGAKU (J. Cryo. Super. Soc. Jpn)*, vol. 50, no. 4, pp. 368-373, 2015 (in Japanese).
- [12] M. Takeda, Y. Inoue, K. Maekawa, Y. Matsuno, S. Fujikawa and H. Kumakura, "Superconducting characteristics of short MgB<sub>2</sub> wires of long level sensor for liquid hydrogen," *Materials Science and Engineering*, vol. 101, 012156, 2015.
- [13] K. Maekawa, M. Takeda, Y. Matsuno, S. Fujikawa, T. Kuroda and H. Kumakura, "Fundamental study of sloshing inside liquid hydrogen tank with external-heating-type MgB<sub>2</sub> level sensors for marine transportation," *Journal of the JIME*, vol. 51, no. 3, pp. 125-131, 2016 (in Japanese).