Simply structured and non-electric weight scale for liquid nitrogen tanks

Kohei Tada (Graduate School of Engineering, Kyoto University, tada.kohei.6c@kyoto-u.ac.jp)

Abstract

With the aim for the easy estimation, as a daily work, of volume of liquid nitrogen in metal tanks in which liquid nitrogen cannot be observed directly, in the present paper a simply structured and non-electric weight scale is proposed. The proposed weight scale consists only of a bedplate with vibration suppression rubber to lift liquid nitrogen tanks, an L-shape component connected to the bedplate, and a conventional ruler. The principle of the mass measurement is the following. The length of the rubber working as spring material changes depending on the amount of liquid nitrogen, i.e. the mass of a liquid nitrogen tank, following the classical Hooke's law; hence, the height of the bedplate also changes. The L-shape component detects the vertical displacement of the bedplate, magnifies it by the ratio of the two arms of this L-shape component, and converts into a horizontal displacement. This magnified displacement is measured with the conventional ruler. With this weight scale the mass and volume of liquid nitrogen in tanks can be estimated with the accuracy of 1.0 kg and 1.2 L, respectively. This accuracy of the proposed scale is not small but within an acceptable range for the rough estimation of liquid nitrogen. Only the Hooke's law and elemental geometry with some trigonometric functions are utilized to construct the proposed weight scale; thus, even in high school and university students can construct and repair this scale by themselves. Moreover, the proposed weight scale may also be suitable for an educational material for classical physics in the field of education in high school and university.

Key words

liquid amount indicator, weight scale, liquid nitrogen, vibration suppression rubber, Hooke's law

1. Introduction

Liquid depth indicating devices or liquid amount indicators for cryogens such as liquid nitrogen and liquid helium are often needed when working with metal tanks or metal vessels in which liquid levels of cryogen are not able to be observed directly. In the case of helium with a quite small liquid density of 0.13 kg/L, several kinds of liquid depth indicators were proposed, developed and have been improved. As a pioneer work, Feldmeier and Serin developed a helium depth indicator, by utilizing the superconductivity of tantalum (Feldmeier and Serin, 1948). Another type of the depth indicator using superconductivity was reported, which uses a Manganin wire coated with a Pb-Sn alloy (Ries and Satterthwaite, 1964). Some groups proposed the methodology using polystyrene floats (Babiskin, 1950; Kitts and Harler, 1954). The spontaneous gas oscillation, which is caused by a significantly large temperature gradient in a tube, can be applied to the helium level indicator. A level indicator using this phenomenon, which consists of a thin rubber membrane and a thin tube, was manufactured in 1955 (Gaffney and Clement, 1955); this kind of level indicator is still often used today, and some groups published the papers reporting the improvements of the indicator of this type (Ikeda and Yoshizaki, 1982; Kato, 1989). Other several groups proposed the level indicators utilizing the capacitance principle (Meiboom and O'Brien, 1963) or the indicators using electric circuits (Canter and Roellig, 1966; Haruyama and Yoshizaki, 1982; Hilton et al., 1999).

In the case of nitrogen, the level indicator using the spontaneous gas oscillation, which is analogous instrument to the case of helium (Gaffney and Clement, 1955), was reported (Aoi and Ueda, 2008). In general, however, the methodology of weight scales is more convenient and often used as relatively large density of 0.81 kg/L of liquid nitrogen.

Weight scales with piezoelectric sensors or load cells are often employed for relatively large cryogen tanks and vessels; however, such scales have a limited availability since they are not available without external power supply or batteries. Furthermore, such electric weight scales are generally expensive and hard to be repaired by the cryogen users. In this study, based on the Hooke's law in classical mechanics, a simply structured weight scale for liquid nitrogen tanks free from any electric supply and financial difficulties, is proposed.

2. Design and principle

Figure 1 depicts the design of the weight scale and the principle of the measurement. The weight scale consists of a bedplate to lift liquid nitrogen tanks, an L-shape component, and a conventional ruler. Spring materials, such as rubber seats, are stuck on the backside of the bedplate, and the thickness of the spring materials changes depending on the weight of the liquid nitrogen tanks, i.e. the amount of liquid nitrogen in the tanks. A pivot point of the L-shape component is connected to an end of the bedplate and the L-shape component is able to rotate with the bedplate shifting.

The lengths of the short arm touching the ground and the another long arm of the L-shape component are defined as L_1 and L_2, respectively. The angles between the long arm and the horizontal line are defined as α (when the tank is light)

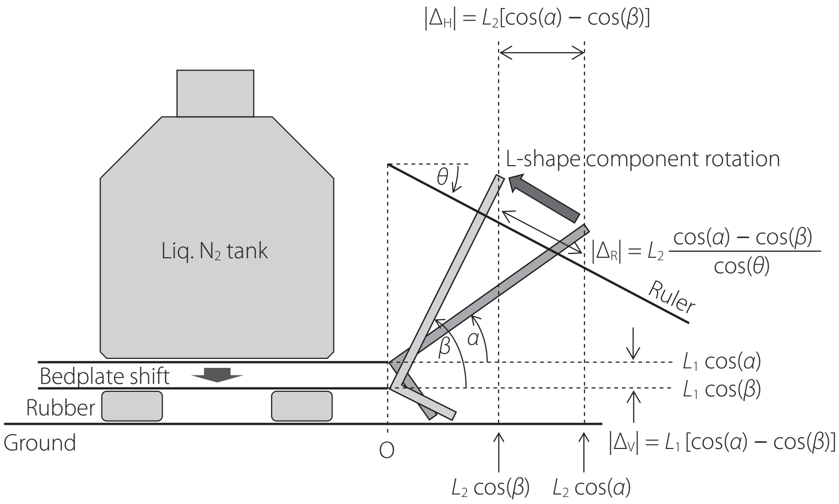

Figure 1: The schematic design of the weight scale and the principle of the measurement

and β (when the tank is heavy). The long and short arms of the L-shape component are set to be perpendicular each other. Hence, the vertical displacement of the bedplate $|\Delta_V|$ is calculated as

$$|\Delta_V| = L_1\,[\cos(\alpha) - \cos(\beta)]. \tag{1}$$

The displacement of the end of the long arm of the L-shape component in the horizontal axis $|\Delta_H|$ is calculated as

$$|\Delta_H| = L_2\,[\cos(\alpha) - \cos(\beta)]. \tag{2}$$

Therefore, the ratio between these values is

$$\left|\frac{\Delta_H}{\Delta_V}\right| = \frac{L_2}{L_1}. \tag{3}$$

Equation (3) suggests that the displacement in the vertical axis can be magnified by L_2/L_1 and converted into the displacement in the horizontal axis. In this study we measure $|\Delta_H|$ with a conventional ruler. When the ruler is inclined at an angle of θ, $|\Delta_H|$ value is furthermore magnified by $1/\cos(\theta)$ on the ruler axis; therefore, the net magnification ratio is

$$\left|\frac{\Delta_R}{\Delta_V}\right| = \frac{L_2}{L_1\cos(\theta)}, \tag{4}$$

where

$$|\Delta_R| = L_2\frac{\cos(\alpha) - \cos(\beta)}{\cos(\theta)} \tag{5}$$

is the projection of $|\Delta_H|$ to the ruler axis. Based on Eq. (4), ideally one can detect even a tiny displacement of $|\Delta_V| = 0.05$ mm as the displacement $|\Delta_R| = 1.4$ mm on the ruler axis, by setting $L_2 / L_1 = 20$ and $\theta = 45°$. If the net magnification ratio represented by Equation (4) is constant and the spring material follows the Hooke's law during the measurement, $|\Delta_R|$ value is proportional to the weight of the liquid nitrogen tanks, i.e. the amount of liquid nitrogen in the tanks.

3. Construction

Commercially available vibration suppression rubber seat (Naigai rubber industry co., ltd., Hanenite GP-35L), whose static shear elastic modulus is $Gs = 0.28$ MPa, was employed as the spring material. The rubber seat was cut to get three rubber cylinders with 30 mm in diameter and 30 mm in height. The spring constant of this rubber cylinder was calculated to 22 N/mm. As the bedplate a square-cut Japanese cypress plate (1 m × 1 m, thickness 30 mm) was used. This area of the wood bedplate of 1 m^2 is enough to load liquid nitrogen tanks or vessels of inner volume up to 50 L. Three rubber cylinders were stuck on the bottom surface of the wood bedplate so as to coincide the median point of the equilateral triangle consisting of the three rubbers with the center of gravity of the bedplate. The spring constant of 22 N/mm corresponds to the ratio of load mass to the vertical displacement $|\Delta_V|$ is 0.14 mm/kg, assuming that the three rubbers follow the Hooke's law.

Figure 2 shows an overview image of the constructed weight scale, and Figure 3 focuses on the measurement part consisting of the L-shape component and a commercially available conventional ruler with a minimum scale value of 0.5 mm. In case of the weight scale shown in Figure 2 and Figure 3, the values L_1, L_2 and θ were set to 4 cm, 40 cm, and 0°, respectively; thus, the net magnification ratio represented by Equation (4) was set to ten. Hence, the ratio of load mass to the displacement on the ruler axis was estimated to 1.4 mm/kg (= 0.14 mm/kg × 10). In Figure 3, the position indicator was needed to find the horizontal position of the long arm end of the L-shape component on the ruler, and the indicator weight was needed to make the position indicator always vertical.

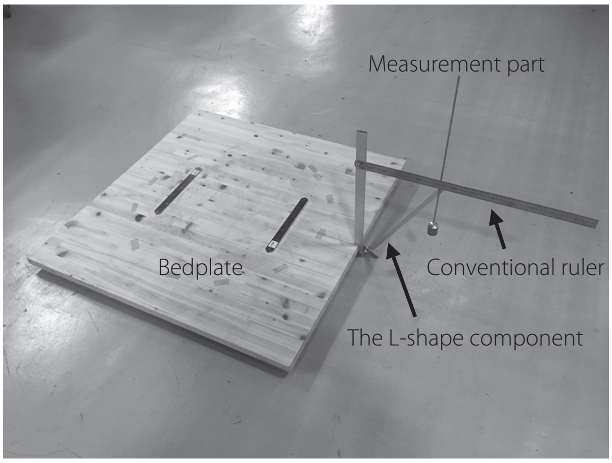

Figure 2: An overview image of the constructed weight scale

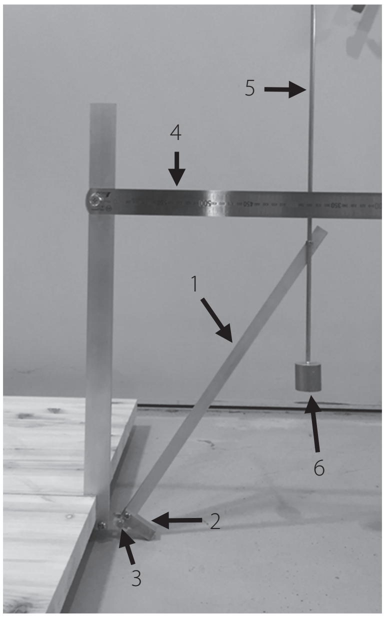

Figure 3: The measurement part of the constructed weight scale

Notes: (1) The long arm of the L-shape component of L_2 = 40 cm. (2) The short arm of the L-shape component of L_1 = 4 cm. (3) The pivot point. (4) The conventional ruler. (5) The position indicator. (6) The indicator weight.

4. Evaluation

The performance of the constructed weight scale shown in Figure 2 and Figure 3 was evaluated and the result is shown in Figure 4, where the ordinate and abscissa axes respectively represent the displacement from the load-less condition on the ruler axis and the load mass. The experimental data clearly shows that the displacement is proportional to the load mass up to 70 kg. Typical weight of an aluminum 50 L liquid nitrogen tank is 50 – 70 kg when filled fully. Therefore, this weight scale is available to liquid nitrogen tanks up to 50 L. The slope of the linear fitting function was determined to 1.54 mm/kg, which is in agreement with the estimated ratio (1.4 mm/kg) in the previous section.

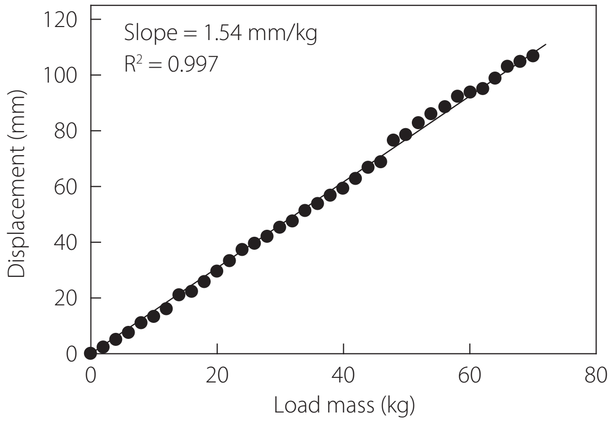

Figure 4: Performance of the constructed weight scale

In this experiment the standard deviation of the measurement was 1.0 kg. This corresponds to the standard deviation of the estimation of the volume of liquid nitrogen of 1.2 L (= 1.0 kg / 0.81 kg L^{-1}), where gaseous nitrogen in the tank is neglected because of its smaller density than that of liquid nitrogen. The measurement accuracies of other manufactures to measure load masses are better than that of the weight scale in this study; for example, the accuracy of commercially available analog bathroom scales is 100 g – 1 kg, and the accuracy of specially manufactured scales using load cells reaches 50 g or better. However, the former scales cannot load large cryogen tanks because of the size of their load-tops, and the latter scales are generally expensive and need electricity. The standard deviation of the proposed scale is not small but within an acceptable range, when we roughly estimate the volume of liquid nitrogen as a daily work in laboratories and when this scale is considered to be a measurement method being free from the volume of cryogen tanks, financial difficulties and electricity.

The proposed weight scale consists of the several simple parts, as shown in Figure 2 and Figure 3. Even high school students and university students can construct and repair this weight scale by themselves. Hence, this weight scale is suitable for one of educational materials for classical physics in high school and university. For the beginners in classical physics, this weight scale can be employed when they learn the Hooke's law in one dimension, i.e. the relationship between the magnitude of force vector applied to a spring and the displacement of the spring from an equilibrium length along the force vector direction. For undergraduate students in university and upper grades in high school, they can also learn the Hooke's law for continuous media, i.e. a displacement in one direction causes the displacements in the other directions, with tensorial calculations, by measuring the length and diameter of the rubbers (spring material) of the proposed scale.

5. Conclusion

By using vibration suppression rubber and the L-shape component, a simply structured and non-electric weight scale for liquid nitrogen tanks was proposed. The standard deviation of the mass measurement was 1.0 kg. Therefore, one can estimate the volume of liquid nitrogen in tanks with an accuracy of 1.2 L as an easy way in the laboratories with the proposed weight scale.

The methodology for observing tiny spatial displacements by magnifying and converting into other axes with the L-shape component can be applicable to lots types of measurement instruments. In addition, only the Hooke's law of classical physics and elemental geometry with some trigonometric functions are applied to constructing the present weight scale. Therefore, this weight scale may be applicable to not only liquid nitrogen tanks but also other instruments and basic physics educations in educational field.

Acknowledgements

The author is indebted to the referee(s) of this paper for improving the manuscript significantly via the thoughtful suggestions. This work was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP18H00556.

References

Aoi, Y. and Ueda, Y. (2008). Measurement of liquid nitrogen level using thermoacoustic spontaneous gas oscillation. *Journal of Cryogenic Society of Japan*, Vol. 43, No. 12, 556-560.

Babiskin, J. (1950). A float for liquid helium. *Review of Scientific Instruments*, Vol. 21, No. 11, 941.

Canter, K. F. and Roellig, L. O. (1966). Low temperature liquid helium level indicator. *Review of Scientific Instruments*, Vol. 37, No. 9, 1165-1167.

Feldmeier, J. R. and Serin, B. (1948). Liquid helium depth gauge. *Review of Scientific Instruments*, Vol. 19, No. 12, 916-917.

Gaffney, J. and Clement, J. R. (1955). Liquid helium level-finder. *Review of Scientific Instruments*, Vol. 26, No. 6, 620-621.

Haruyama, T. and Yoshizaki, R. (1982). Kantan na heriumu ekimenkei no seisaku (II). *Journal of Cryogenic Society of Japan*, Vol. 17, No. 1, 60. (in Japanese)

Hilton, D. K., Panek, J. S., Smith, M. R., and Van Sciver, S. W. (1999). A capacitive liquid helium level sensor instrument. *Cryogenics*, Vol. 39, No. 5, 485-487.

Ikeda, H. and Yoshizaki, R. (1982). Kantan na heriumu ekimenkei no seisaku (I). *Journal of Cryogenic Society of Japan*, Vol. 17, No. 1, 59. (in Japanese)

Kato, K. (1989). Liquid helium level meter by audio-sound detection. *Review of Scientific Instruments*, Vol. 60, No. 7, 1343-1345.

Kitts, W. T. and Harler, F. L. (1954). Liquid helium level indicator for metal storage dewars. *Review of Scientific Instruments*, Vol. 25, No. 9, 926-927.

Meiboom, S. and O'Brien, J. P. (1963). Level indicator for liquid helium. *Review of Scientific Instruments*, Vol. 34, No. 7, 811-812.

Ries, R. and Satterthwaite, C. B. (1964). Another liquid helium level indicator. *Review of Scientific Instruments*, Vol. 35, No. 6, 762-763.

(Received: January 31, 2019; Accepted: February 27, 2019)