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RESEARCH PAPER

Development of Advanced Herbert Hardness Tester by Incorporating Raspberry Pi Microcomputer

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Abstract

The Herbert pendulum, an inverted-pendulum hardness tester, can measure the hardness of various types and shapes of materials from the motion of the pendulum as it swings on a specimen. However, a large experimental system is required to detect the swing angle of the pendulum during the hardness test. This study miniaturized the Herbert hardness system and investigated its accuracy. A new Herbert pendulum was developed, which is equipped with an acceleration sensor to detect the swing angle and a Raspberry Pi microcomputer to calculate the hardness. The new Herbert hardness tester achieves portability because only the pendulum is needed to perform the hardness test. The tester can connect to a personal computer and a smartphone through Wi-Fi to provide remote data transmission. The new Herbert tester was used to perform hardness tests on five kinds of Brinell hardness reference blocks. Smooth free decay curves were obtained, and the hardness was calculated from the curves. The hardness distance between the present tester and conventional swing angle detection using laser displacement meters was less than 5%. Thus, the new Herbert hardness tester can provide reasonable evaluations of material hardness.

Keywords Measurement · Hardness · Accelerometer · Raspberry pi · IoT

Introduction

Hardness testing is widely used for evaluating mechanical properties of products for quality management and reliability assurance. Indentation hardness tests, such as the Vickers hardness test, and rebound hardness tests, such as the Shore hardness test, are commonly used. In these tests, because the specimen must have a smooth, flat surface, it is difficult to carry out these hardness tests on a product with a complex shape. However, a Herbert hardness test, which uses an inverted pendulum, can be carried out on a specimen with a complex shape [1, 2]. The Herbert hardness tester was first proposed in 1923 [2]. In this test, a Herbert pendulum is placed on a specimen, and it rocks on an indenter as a fulcrum. The free decay curve of the pendulum varies because rolling resistance depends on specimen strength, allowing hardness to be evaluated. The advantages of this tester are that it can carry out hardness tests on a product with a complex shape, such as a drill bit or knife edge. In addition, the Herbert pendulum is lightweight and compact, so it is a portable tester. However, the accuracy of the Herbert hardness tester is low because the user must simultaneously observe a clock and a bubble level to measure the swing cycle and swing angle of the pendulum.

We have been improving the Herbert hardness tester [1, 3, 4, 5, 6]. In the current Herbert hardness tester, the swing angle of the Herbert pendulum is detected by two laser displacement meters installed on the outside of the pendulum to increase accuracy [5]. However, the portability of this tester is low because the measurement with laser displacement meters needs many large and heavy devices. To enhance the convenience for using the tester, the portability must be improved.

Recently, the detection of the swing angle of the tester was attempted using a small commercial accelerometer unit [10]. The swing angle could be detected with the accelerometer, and the hardness calculated from the free decay curve of the tester was also reasonable. However, the accelerometer used in the previous study needed to be connected to a personal computer to obtain the angle data and calculate and analyze

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the hardness. In addition, small accelerometer units are expensive.

The single-board microcomputer, Raspberry Pi, developed by the Raspberry Pi Foundation, has recently been applied to measurement [7–9]. The size of a Raspberry Pi is about the same as a credit card, and it has sufficient processing power with low power consumption. In addition, it has general-purpose input/output (GPIO), so it can communicate with sensors and devices. It also has on-board Wi-Fi to connect to a network.

If the Raspberry pi and acceleration sensor chip are mounted on the pendulum, the Herbert hardness test can be carried out with only the pendulum without requiring a personal computer because both the swing angle detection and hardness calculation/analysis can be performed with only the pendulum. In other words, the portability and convenience of a Herbert hardness tester can be improved by installing the measuring components on it.

In this study, we designed and developed a new Herbert hardness tester that does not depend on external measuring equipment, because all measuring components are mounted on it. We used cheap commercial products to reduce the cost. The Raspberry Pi allows the Herbert hardness tester to transmit data by Wi-Fi and is compatible with the Internet of Things concept. A new Herbert hardness tester was built and used to carry out a Herbert hardness test. The free decay curves and the Herbert hardness obtained with the new tester were compared with those obtained with two laser displacement meters as a conventional detection method to clarify the accuracy of the new tester.

Design and Development

We used commercially available parts and devices for the new Herbert hardness tester. The new tester is equipped with the Raspberry Pi 3 Model B+ microcomputer. The display is a 2.8-in. capacitive touchscreen, a dedicated screen for the Raspberry Pi (PiTFT, Adafruit) [11]. The pendulum of the new tester is equipped with a battery so it can run off the battery instead of external power supplies. The swing angle of the pendulum is detected by a 3-axis analog-output acceleration sensor chip (KXR94–2050, Kionix) [12]. The data obtained from the acceleration sensor chip are sent to a 12-bit analog-to-digital converter (MCP3204-BI/P, Microchip Technology) [13] before being recorded on the Raspberry Pi. The reference voltage of the acceleration sensor and the analog-to-digital converter is the 5-V output of the GPIO. Both the Raspberry Pi and the analog-to-digital converter support a serial peripheral interface. The data are easily transmitted between these devices by only four wires. These two IC chips are mounted on a breadboard mounted to the pendulum. As a result, the pendulum alone becomes able to carry out hardness testing and data calculation and analysis.

The new Herbert hardness tester was designed in SolidWorks (SolidWorks 2019, Dassault Systèmes SolidWorks Corp.) after determining the concept and the component parts. The designed 3D model is shown in Fig. 1. The pendulum is made of A5052 aluminum alloy. Components are fixed to acrylic stays and the stays are fixed to the pendulum by nuts and bolts for easy assembly and disassembly. The mounting position of the Raspberry Pi and battery was designed to minimize the length of wiring, such as the power cable between the Raspberry Pi and the battery and the communication cables between the Raspberry Pi and the breadboard. The centroid position of the Herbert hardness tester needs to exist just under the indenter tip. The length of the balance weights was adjusted using the 3D model of the new tester in SolidWorks by calculating the centroid position.

The manufactured Herbert hardness tester is shown in Fig. 2a and b. The frame was processed by wire electric discharge machining. A Raspberry Pi, a touch monitor connected to the Raspberry Pi, a battery, and a breadboard were installed on one side of the Herbert pendulum. Two brass fixed weights, two brass balance weights, an SK3 (high-carbon steel) indenter holder, a cemented carbide columnar indenter, and an aluminum reflector were installed on the frame. The cemented carbide columnar indenter, used as a fulcrum, has a 2-mm diameter and a 12-mm length.

A view of the new Herbert hardness tester during operation is shown in Fig. 3. This tester can be operated by smartphone via the same local network using the remote desktop application (VNC Viewer, Real VNC). This application can remotely control the Raspberry Pi and data transmission between the Raspberry Pi and devices like a laptop, smartphone, or tablet. The data analysis software for calculating hardness was developed with Python. The control software features include a user interface, a display of the real-time angle of the tester, a test progress bar, and a trigger function for recording. When the start button is pushed, the tester enters the measurement stand-by mode. When the tester starts swinging the pendulum, the

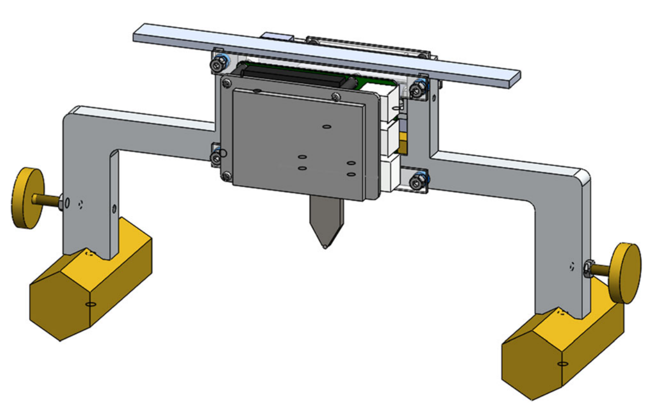

Fig. 1 3D model of the new Herbert hardness tester

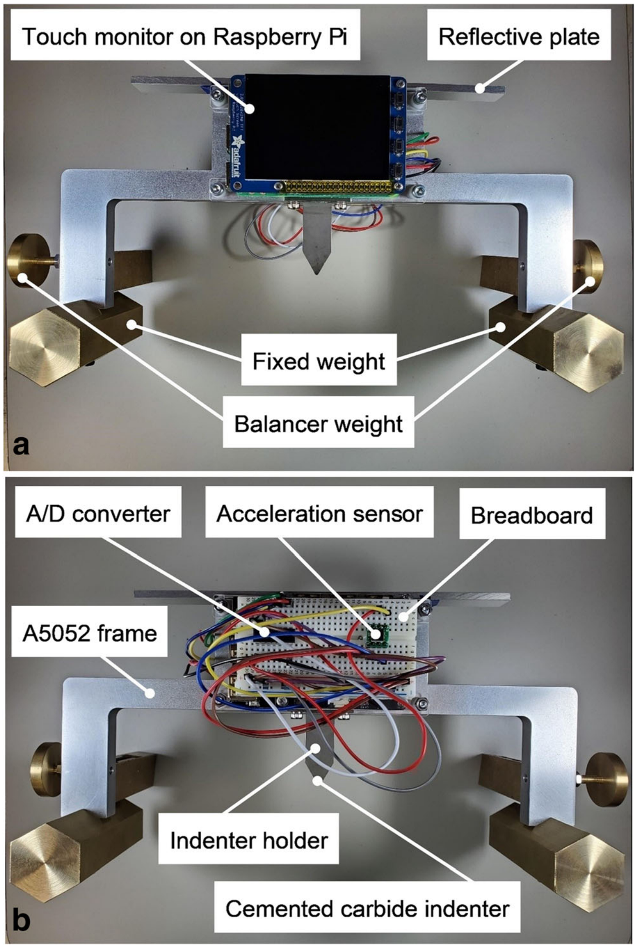

Fig. 2 **a** Front appearance of the new Herbert hardness tester. **b** Rear appearance of the new Herbert hardness tester

recording of the pendulum swing angle begins. At the end of the measurement, the recorded data are saved as a comma-separated values file that shows the automatically calculated hardness value.

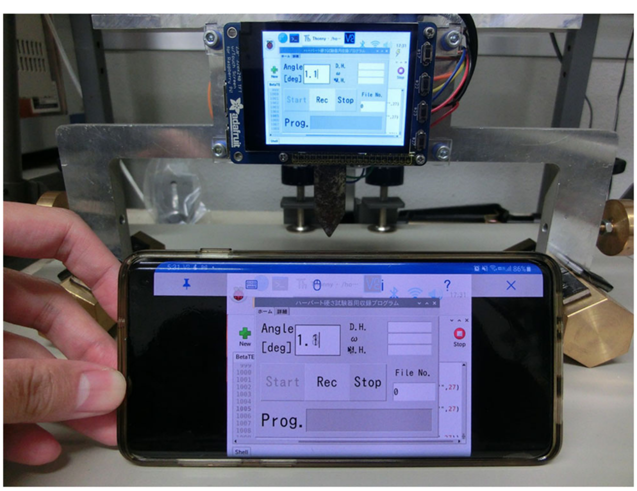

Fig. 3 Operation of the tester via a networked smartphone

Experimental

Herbert Hardness Tester

A schematic illustration of the Herbert hardness tester is shown in Fig. 4. A solenoid was installed on a test stand as a fix-and-release apparatus for the pendulum. Two laser displacement meters (IL-100, KEYENCE) were also installed on the test stand. The time and swing angle data obtained from the two laser displacement meters were sent to power amplifiers (IL-1000 and IL-1050, KEYENCE) and an analog-to-digital converter (GL220, GRAPHTEC) before being recorded on a personal computer. The data were also obtained by the installed acceleration sensor chip. The data obtained from the acceleration sensor chip were sent to an analog-to-digital converter before being recorded on the Raspberry Pi.

Procedure

Five types of Brinell hardness reference blocks of were prepared (100, 200, 300, 400, and 500 HBW). Each specimen was placed on the test stand. The Herbert pendulum was calibrated [5] and then placed on the specimen. The Herbert pendulum was tilted up to initial swing angle of 30° and fixed with the fix-and-release device. The pendulum was released and started to swing. The swing angle of the pendulum was detected by the acceleration sensor and the two laser displacement meters. The swing angle S (in degrees), obtained using the acceleration sensor, is expressed as

$$S = (180/\pi)\, sin^{-1} a/g, \tag{1}$$

where a is the acceleration obtained from the acceleration sensor and g is the standard acceleration of gravity (9.80665 m/s^2). The free decay curve obtained from the acceleration sensor was compared with that obtained from the two laser displacement meters. The Herbert hardness was calculated from these free decay curves. The Herbert hardness test can measure five types of hardness, namely the scale hardness,

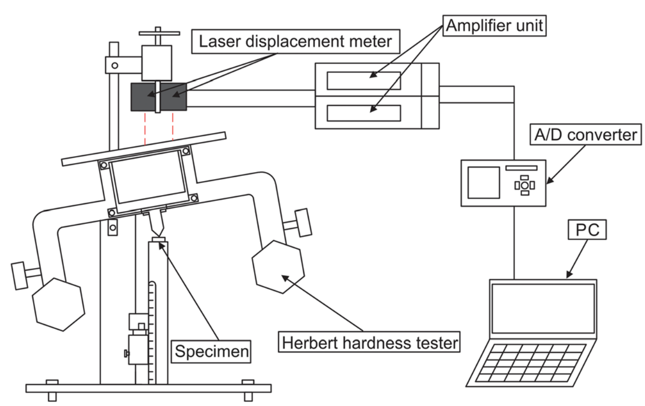

Fig. 4 Evaluation setup for new Herbert hardness testing system

time hardness, flow hardness, damping hardness, and Matsubara hardness [14]. In this study, damping hardness was used. The damping hardness is the logarithmic decrement α of the free decay curve,

$$S = S_0 exp(-\alpha t), \tag{2}$$

where S_0 is the initial swing angle of the pendulum and t is the swing time. α was calculated using six positive peaks of the free decay curve. The damping hardness, *DHP6*, is defined as an absolute value of α. The damping hardness decreases with increasing specimen hardness. *DHP6* obtained with the acceleration sensor was compared with that obtained from the two laser displacement meters. The test was performed five times at the same point on each specimen. Thus, the damping hardness of each specimen was the average of the results of five tests. Each obtained dataset was processed as a moving average for noise reduction before calculating the Herbert hardness.

Results and Discussion

The free decay curve comparison carried out on the reference block of 200 HBW obtained with the two laser displacement meters and the acceleration sensor is shown in Fig. 5. Both free decay curves are smooth and well synchronized. In previous studies, the measurement of the swing angle of a Herbert hardness tester with an accelerometer succeeded, but the phase difference between the free decay curves increased with time, by about 1 s after 100 s [10]. This caused a damping hardness error. In this study, the phase difference increased only by about 0.2 s after 100 s, indicating a higher phase accuracy. The damping hardness obtained with the two laser displacement meters ($DHP6_L$) is plotted against that obtained with the acceleration sensor ($DHP6_A$) in Fig. 6. The relationship between $DHP6_L$ and $DHP6_A$ is linear, and the coefficient of determination, R^2, is about 0.962. Thus, they have extremely strong correlation. The error between $DHP6_L$ and $DHP6_A$ is expressed in eq. (3) and shown in Fig. 7.

$$Error = (DHP6_L - DHP6_A)/DHP6_A \tag{3}$$

The errors are all positive values in the range of +1% to +5%. The peak angle of the Herbert pendulum obtained from the acceleration sensor is bigger than that of the two laser displacement meters. This is due to the noise around the peak angle. The noise is noticeable when angular velocity of the pendulum is low. The error can be reduced by using correcting formula of approximation straight line in Fig. 6 expressed as

$$DHP6_C = 1.0610 \times DHP6_A - 0.0558 \tag{4}$$

$DHP6_C$ and $DHP6_L$ are plotted against the Brinell hardness in Fig. 8. Both $DHP6_C$ and $DHP6_L$ decrease with increasing Brinell hardness and $DHP6_C$ shows good agreement with $DHP6_L$. The accuracy of the Herbert hardness test using the acceleration sensor is thus equivalent to that obtained using the two laser displacement meters.

$DHP6_L$ and $DHP6_C$ are plotted against the Brinell hardness in Fig. 9. $DHP6_L$ and $DHP6_C$ have good agreement. The coefficient of determination, R^2, of the power approximation curve between $DHP6_C$ and *HBW* is about 0.965, so they have extremely strong correlation. Thus, *HBW* can be estimated by using formula expressed as

$$HBW = 7.8823 \times 10^6 \times (DHP6_C)^{-5.067} \tag{5}$$

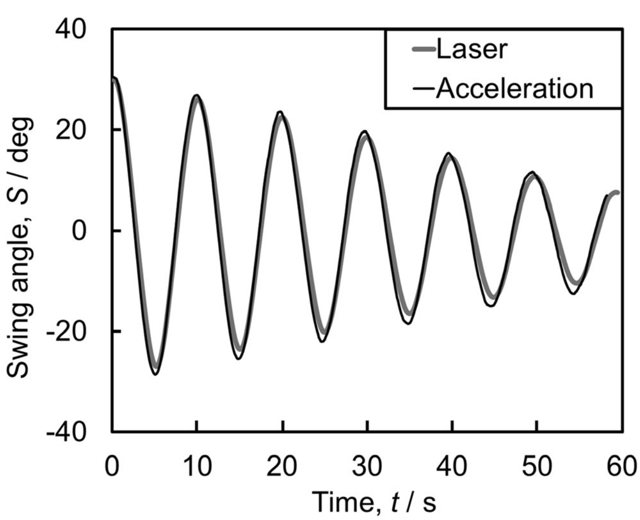

Fig. 5 Free decay curves for the reference block of 200 HBW obtained with the acceleration sensor and two laser displacement sensors

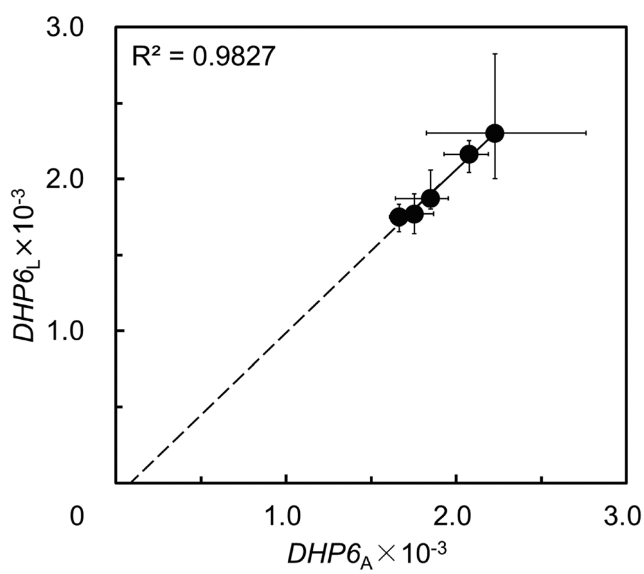

Fig. 6 Damping hardness obtained with the two laser displacement sensors ($DHP6_L$) plotted against that obtained with the accelerometer ($DHP6_A$)

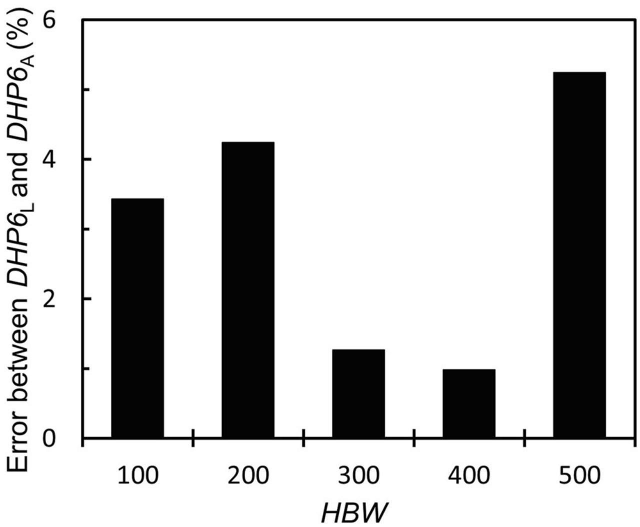

Fig. 7 Error between $DHP6_L$ and $DHP6_A$

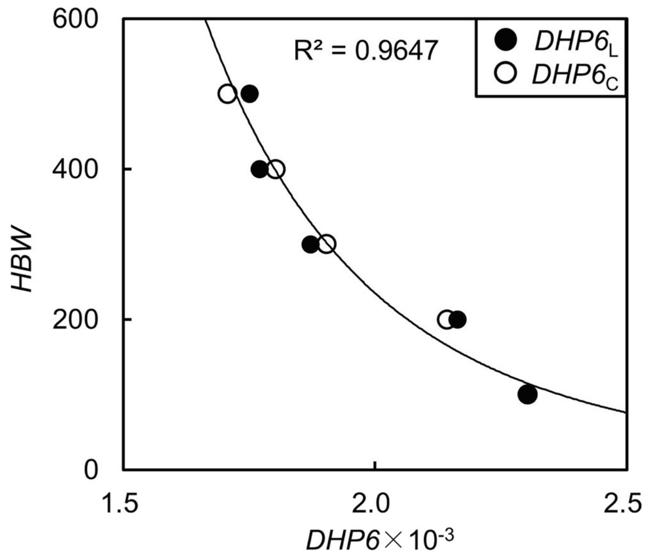

Fig. 9 Correlation between *DHP6* and *HBW*

The present study contributes to improving the portability and convenience of the Herbert hardness tester and to reducing the manufacturing cost of the tester without decreasing its accuracy. The measurement accuracy of the Herbert pendulum swing angle can be further improved by using a gyro sensor [14].

Conclusions

In this study, a new Herbert hardness tester with mounted microcomputer and accelerometer sensor was developed to improve portability. Herbert hardness testing was carried out to investigate the accuracy of the new tester. As a result of this study, the following conclusions were obtained.

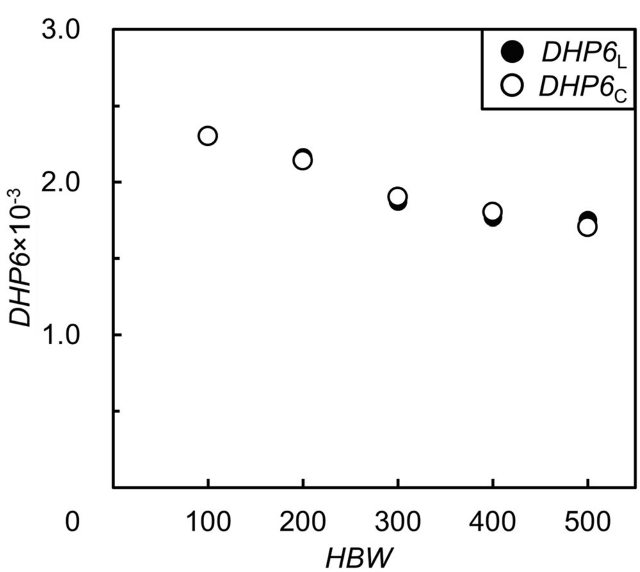

Fig. 8 $DHP6_C$ and $DHP6_L$ plotted against Brinell hardness

1) The new Raspberry Pi-based Herbert hardness tester is equipped with all the devices needed to perform a hardness test. A smooth free decay curve was obtained using the acceleration sensor installed on the pendulum.
2) For all specimens, the damping hardness measured by the acceleration sensor was smaller than that measured by the two laser displacement sensors. This was caused by the noise of the acceleration sensor. The corrected damping hardness obtained with the acceleration sensor showed good agreement with that obtained with the two laser displacement sensors.
3) The new Herbert hardness tester is superior to the conventional one in terms of size, weight, cost, and convenience without decreased accuracy.

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