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A High Speed and Compact System for Profile Measurement of Scroll Compressors

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Profile measurement of a scroll compressor is important for improving compression efficiency. This paper describes the height profile measurement of a scroll compressor in the manufacturing line using a prototype measurement system. A commercial CMM is also employed for comparison. The measurement repeatability of the height profile by the prototype measurement system is approximately ±1 μm, which satisfies the requirements from the manufacturing line. Through compensation of the tilt component, result of the prototype measurement system is in good agreement with that of the commercial CMM.

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1. Introduction

Scroll was invented at the beginning of the 19th century by Creux.[1] Scroll compressors are air compressors made by scrolls. A picture of the scroll compressor is shown in Figure 1. A scroll compressor is composed of two scrolls with identical involute profiles. One of the scrolls is kept fixed, which is called the fixed scroll, and the other scroll, which is called the orbiting scroll, orbits around the fixed scroll. The working principle of air compression is shown in Figure 2. The combination of the two scrolls generates a number of crescent-shaped compressed rooms. When the orbiting scroll orbits around the fixed scroll, the compressed room moves to the center of the fixed scroll so that the volume of the compressed room can be reduced to increase the air-pressure. At last, the air with a high pressure is taken out from a discharged port. The advantages of the scroll compressor include small variations of torque, low vibrations and noises. The efficiency can be also made high because there is no direct fluid path between the suction port and the discharged port. Because of these reasons, scroll compressors are widely used recently.[2-4]

To further improve the efficiency of the scroll compressor, it is necessary to reduce the leakage. The two kinds of leakages are shown in Figure 3. One reason of the leakage is the facial leakage caused by a gap between the flanks of the two scrolls. The other is the radial leakage caused by a gap between the bottom and the top plates of the scrolls.[5] These leakages are influenced by the manufacturing errors. Measurements of the height profile of the

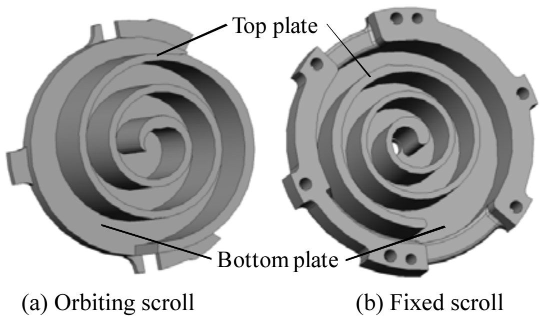


Fig. 1 Sample of the orbiting scroll and fixed scroll

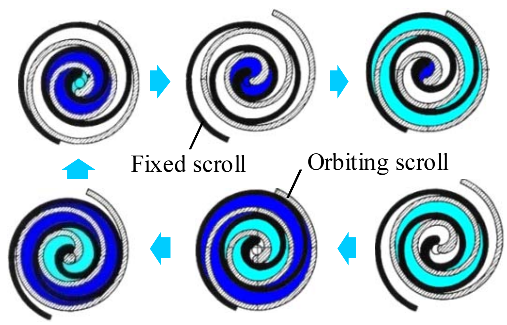


Fig. 2 Working principle of a scroll compressor

scroll along the radial direction and the involute profile along the flank direction are thus important. Conventionally, profiles are measured by coordinate measuring machines (CMMs), which is very time-consuming and expensive. The purpose of this research is to develop a high-speed profile measurement system for the scrolls that can use it in manufacturing line of the factory. The required measuring accuracy is ±1 μm or less. This paper presents the design and the construction of the height profile measurement system of the scrolls and the experimental results as well as their comparison with the results measured by a commercial CMM.

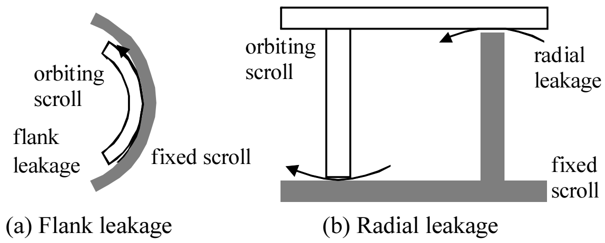


Fig. 3 Two kinds of leakages

2. Prototype measurement system

Figure 4 shows a schematic of the prototype measurement system. Scroll profiles are conventionally measured by CMMs, which can be employed for measurement of workpieces with various shapes. The scanning mechanisms of most CMMs are composed of X-, Y- and Z-directional linear stages. The spiral scanning path for measurement of the scroll profile is generated by combining the linear motions of the X- and Y-stages, which are associated with frequent acceleration and decelerations. The heavy masses of the moving elements are also factors to limit the speed of the spiral scanning. On the other hand, the measurement system developed by the authors is specially designed for scroll profiles and has the following specifications that are different from a CMM. An X-axis linear stage and a theta-axis rotary stage are employed to construct the spiral scanning mechanism, which makes the scanning faster and the configuration of the scanning stage controller simpler.[6] The mass as well as the inertial of the moving elements are also much lighter than those of the CMM. As the measurement system to be used in the manufacturing line must be small in size and fast in measurement speed, an X-Z-θ scanning unit controlled

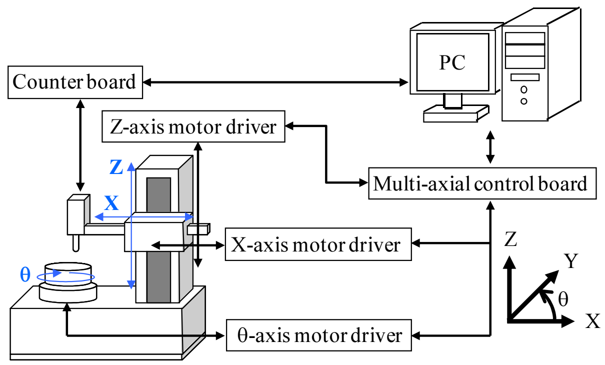


Fig. 4 Measurement system

by PID control is employed. Table 1 shows the specifications of the prototype measurement system.[7] The size of the system is 475 mm×667 mm×900 mm and the weight is 180 kg. Because of the high precision encoder in each axis, the measurement system can realize precise positioning. The positioning error is small enough to be ignored. The positions of each stage are measured by each encoder and taken into a personal computer via multi axis control board. Taking into consideration the influence of cutting oil and chips, a contact-type probe is employed in the measurement system.

Table 1 Specifications of the prototype measurement system

Rotational accuracy	Radial	(0.5+6H/1000) μm
	Axial	(0.5+6X/1000) μm
X straightness		5 μm/150 mm
Z straightness		1 μm/280 mm

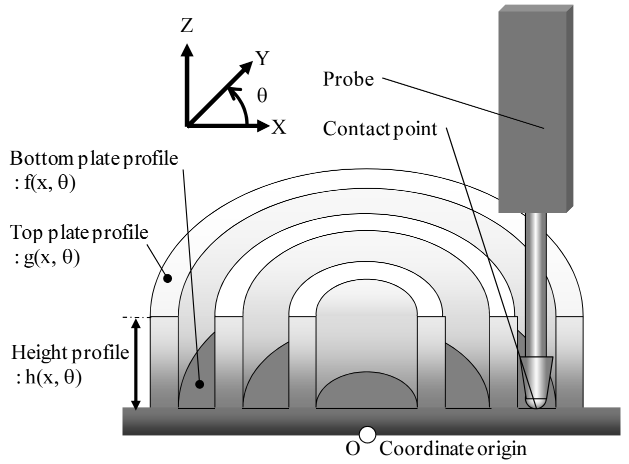


Fig. 5 Principle of measuring the height profile

Figure 5 shows principle of measuring the height profile. It is assumed that the Z-directional position of the bottom surface of the scroll is expressed by f(θ) and the Z-directional position of the top surface is expressed by g(θ), and the height profile of the scroll is expressed by h(θ). The height profile h(θ) can thus be obtained as:

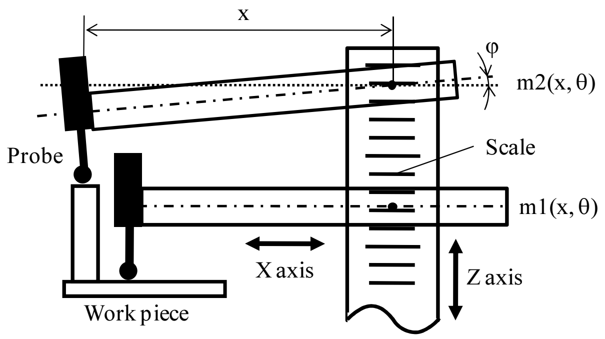
$$h(x, \theta) = f(x, \theta) - g(x, \theta) \tag{1}$$

Height profile of scroll is several tens of millimeters. Therefore, long movement range in the Z-direction is necessary to measure the bottom and top plate. As can be seen in Figure 6(a), Z-axis stage of the scanning unit has a large Abbe offset.[8] Differential output of the scale m1and m2 can be expressed by:

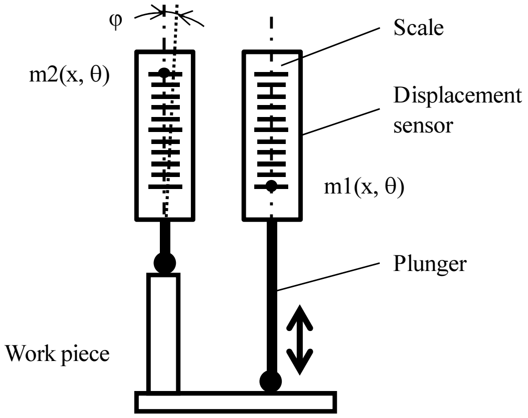
$$m1 - m2 = f(x, \theta) - (g(x, \theta) - x\tan\varphi) \approx h(x, \theta) + x\varphi \tag{2}$$

where, x is the length between contact point and scale point along the X-direction and φ is the tilt motion of Z-stage. In this prototype measurement system, x is about 300 millimeters. When assuming that tilt motion φ is 1 arc-second,[9-18] Abbe error is about 1.5 μm. Therefore, this offset causes large measurement error.

A possible measurement model for solving this problem is shown in Figure 6(b). The displacement sensor is fixed on the end of X stage. In order to reduce the measurement error, a displacement sensor which has measurement range larger than the height of the scroll is employed. The plunger of the displacement



(a) Measurement system that used Z axis stage



(b) Measurement system that used plunger of displacement sensor

Fig. 6 Schematic of Abbe error

sensor can be moved along the measuring axis by a motor equipped in the displacement sensor.[19] The displacement of the plunger is measured by a linear encoder[20] in the displacement sensor. The output of the linear encoder was taken into a personal computer via a counter board. The Differential output in this system can be expressed by:

$$m1 - m2 = f(x, \theta) - g(x, \theta)\cos\varphi \approx f(x, \theta) - g(x, \theta)(1 - \varphi^2/2)$$
$$= h(x, \theta) + g(x, \theta)\varphi^2/2 \qquad (3)$$

As φ is very small value, measurement free from the Abbe error can be achieved. This displacement sensor has 60 mm measuring range. The resolution and accuracy of the displacement sensor are about 0.1 μm and ± 0.5 μm, respectively and the measuring force is about 1 N. The Z-axis stage of the measurement system is only used to set the initial position of the displacement sensor and kept stationary during scanning of the scroll.

The prototype measurement system is installed in the manufacturing line of scrolls for measurement experiment. In the experiment, the total number of measured points is determined before the measurement. The displacement sensor is moved to each of the measured points by the X-axis and θ-axis stages of the scanning unit. After measuring f(θ) at the bottom surface and g(θ) at the top surface of the scroll, the height profile of the scroll is calculated by Eq. (1).

The same scroll sample is also measured for comparison by a commercial orthogonal type CMM,[21] which is installed in a temperature-controlled metrology room. The volumetric accuracy and probing accuracy of the CMM are 0.6+L/600 μm and 0.6 μm, respectively. The size of the CMM is 2795 mm×2013 mm×3240 mm and the weight is 7700 kg.

3. Measurement results

Figure 7 shows a photograph of the developed prototype measurement system. Figure 8 shows the results of the stability test, in which the stage was kept stationary. The horizontal axis indicates measurement time and the vertical axis shows output of the displacement sensor. The test duration was 10 second, and the

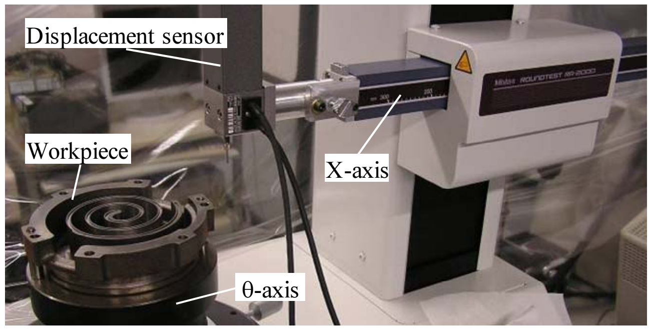


Fig. 7 Photograph of the prototype measurement system

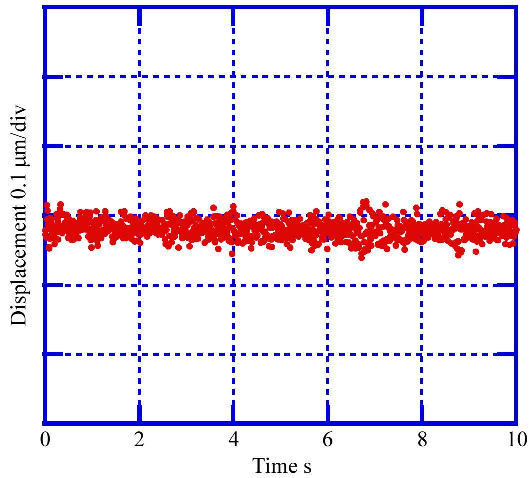


Fig. 8 Stability of displacement sensor

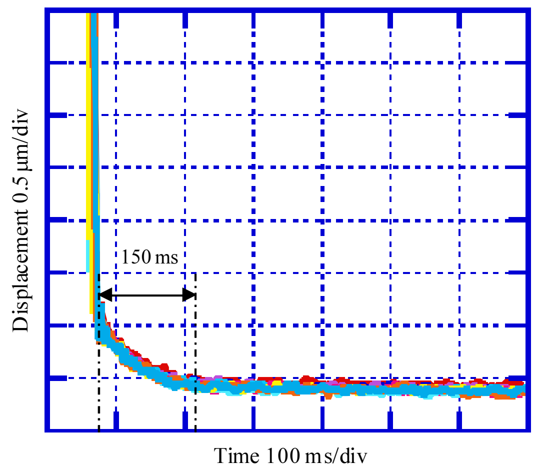


Fig. 9 Settling time of displacement sensor

sampling interval was 50 milliseconds. As can be seen in this figure, the output of the displacement sensor varied within a range of approximately 0.1 µm. Figure 9 shows five experimental results of settling time. From this figure, the displacement sensor stops 150 milliseconds at each measured point for a stable measurement. To reduce the influence of random errors, the measurement value at each measuring point is obtained by averaging 100 data.

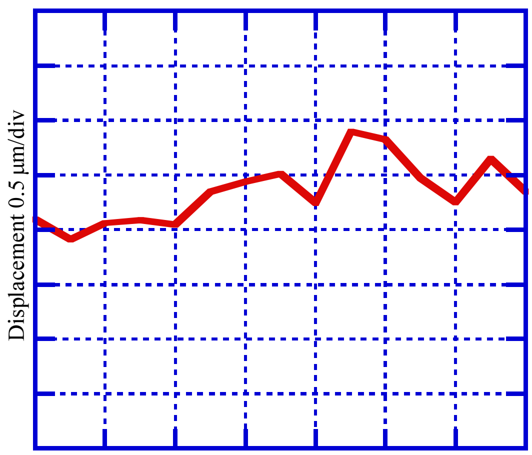
Scanning motion error of prototype measurement system was measured by using optical flat. Flatness of the optical flat was ±50 nm. Figure 10(a) shows scanning error motion of the X-stage. The horizontal axis indicates the position in the X-direction and the vertical axis shows the displacement in the Z-direction. Travel range was 70 mm. Figure 10(b) shows scanning motion error of θ-stage. The horizontal axis indicates rotation angle and the vertical axis shows the displacement in the Z-direction. As can be seen in these figures, the displacement varied within a range of approximately ±0.5 µm.

The measuring time of height profile is shown Table 2. It can be seen that the measuring time of the prototype measurement system is shorter than that of the CMM. Table 2 also shows the repeatability of measurement by the two systems. It can be seen that although the repeatability of the prototype system is worse than that of the CMM, which is approximately ±1 µm, the prototype system satisfies the requirement from the manufacturing line.

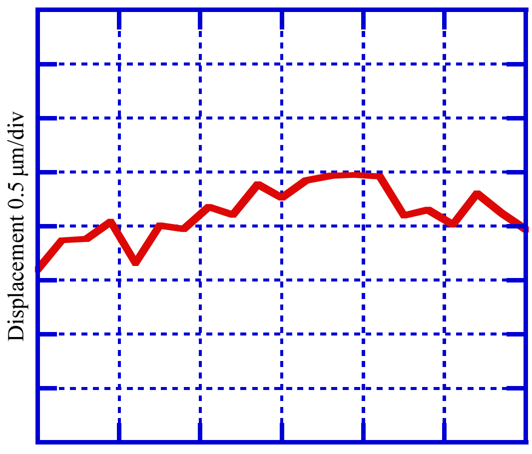
Table 2 Measurement result of the height profile

Instrument	Measuring time	Repeatability
Prototype	432 s	±1 µm
CMM	1047 s	±0.2 µm

Figure 11(a) shows the measurement result of the height profile by the prototype measurement system, and (b) shows that by the CMM. In Figure 11(b), work piece was kept stationary. The horizontal axis indicates rotational angle of work piece and the vertical axis shows variation of the height profile. It can be seen from these figures that the two results are different. Compared with the CMM, the result by the prototype measurement system has remarkable cyclic error component with a period of 360 degrees. Figure 12 shows top and bottom plate profiles. From this figure, this cyclic error component is considered to be caused by the inclination of the scroll, which is compensated by the least square method. If the scroll inclines in the case that the scroll is kept

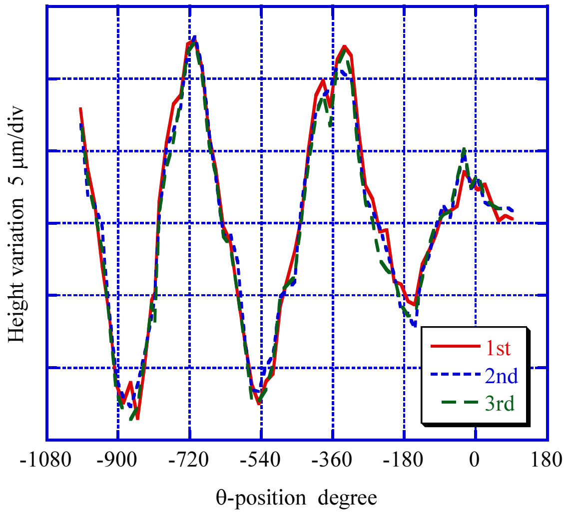


(a) Linear stage (X-axis)

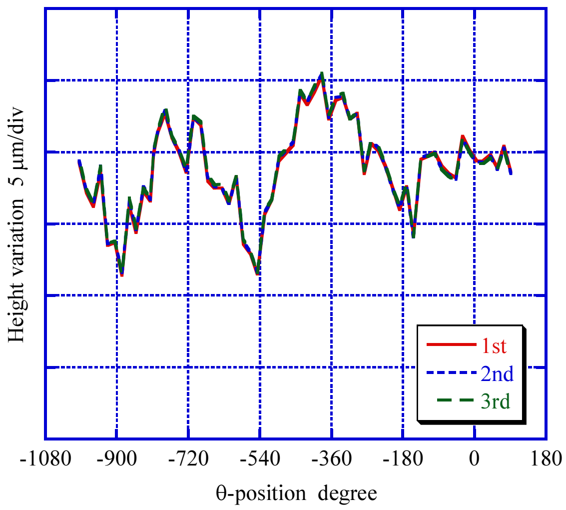


(b) Spindle (θ-axis)

Fig. 10 Scanning error motions

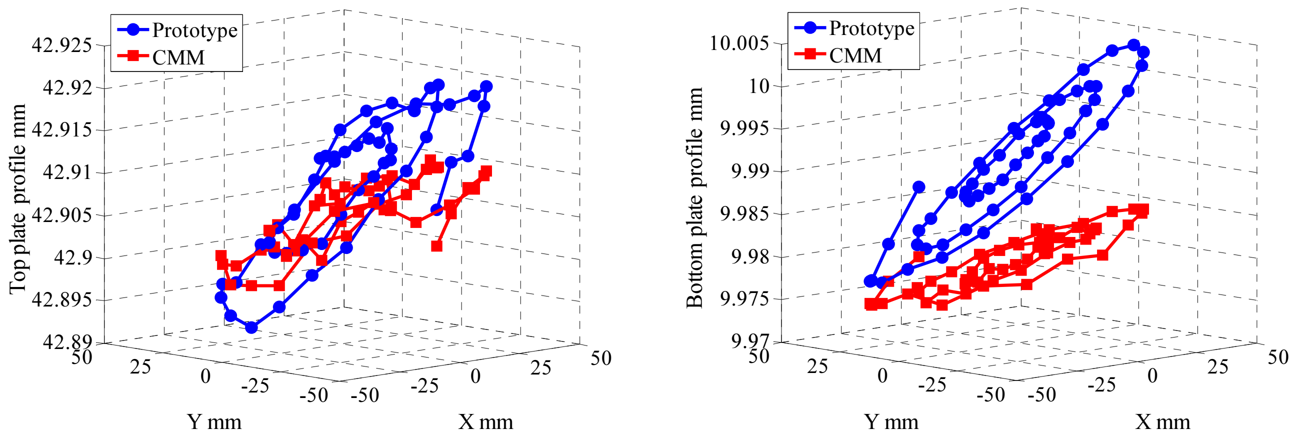


(a) Result of the prototype system



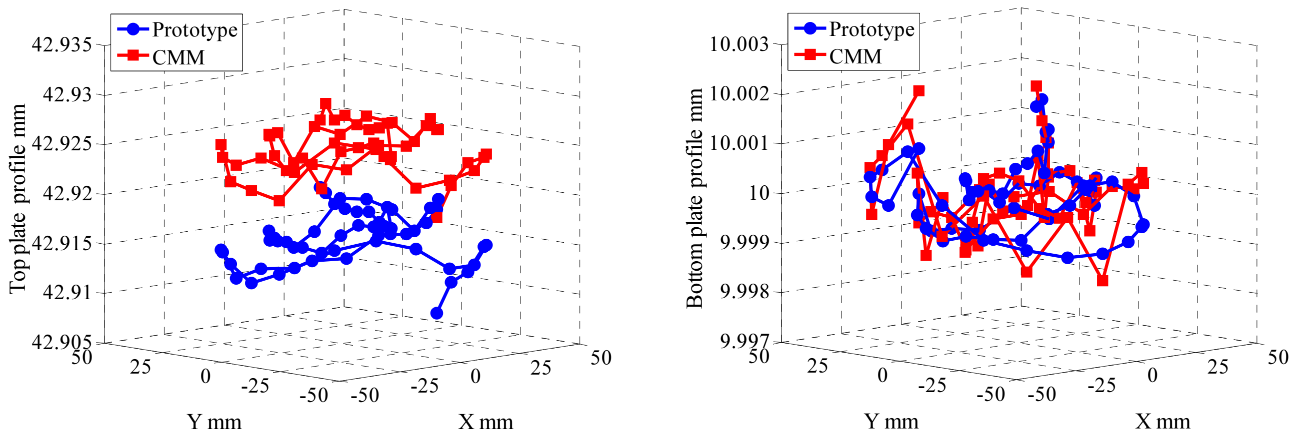
(b) Result of the CMM

Fig. 11 Height profile of orbiting scroll



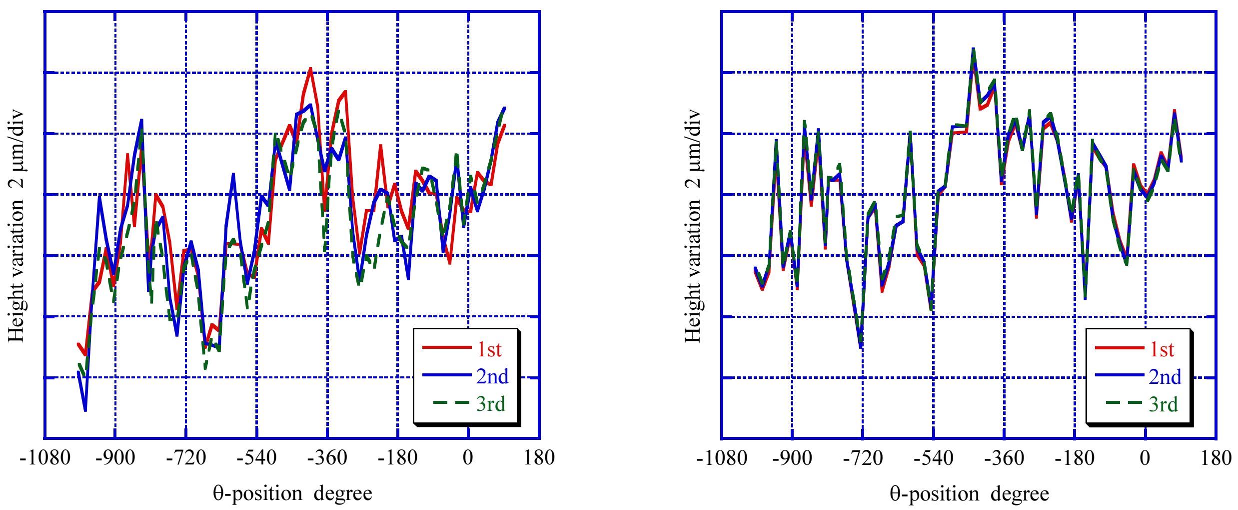
(a) Top plate profile (b) Bottom plate profile

Fig. 12 Plate profiles of orbiting scroll without tilt compensation



(a) Top plate profile (b) Bottom plate profile

Fig. 13 Plate profiles of orbiting scroll with tilt compensation



(a) Result of the prototype system (b) Result of the CMM

Fig. 14 Height profile with tilt compensation

stationary, it is necessary to consider not only the inclination of the scroll but also the tilt of the coordinate system. It is assumed that the tilt angle of the coordinate system about Y-axis is α and that about the X-axis is β. α and β can be obtained by the least square method. The least square method is carried out based on the measured data by the prototype measurement system. The coordinate without tilt error z can be expressed by:

$$z = \frac{\cos\alpha\cos\beta\left(z' - x\sin\alpha\right) + y\sin\beta\cos\beta\left(1-\sin^2\alpha\right)}{1-\sin^2\beta-\sin^2\alpha\cos^2\beta} \quad (4)$$

where, x and y are the coordinates of the measurement points and z' is the value of measurement result. As x, y and z' are known, z can be calculated.

Figure 13 shows the results of compensation using the least-square fitting and tilt conversion. It can be seen from this figure, the tilt error component is removed. Figure 14 shows the measurement results of height profile by the prototype measurement system and the CMM. The results by the prototype measurement system and the commercial CMM have consistent results.

4. Conclusion

A prototype measurement system for scroll compressor has been developed for measurement of height profiles of scrolls in the manufacturing line. The measuring time by the prototype system is half of that by a commercial CMM. The measurement repeatability by the prototype system is approximately ±1 μm. Compensation of the inclination of the scroll has also been carried out.

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