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Non-contact precision profile measurement to rough-surface objects with optical frequency combs

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Abstract

In this research, we developed a new method for the high precision and contactless profile measurement of rough-surfaced objects using optical frequency combs. The uncertainty of the frequency beats of an optical frequency comb is very small (relative uncertainty is 10^{-10} in our laboratory). In addition, the wavelengths corresponding to these frequency beats are long enough to measure rough-surfaced objects. We can conduct high-precision measurement because several GHz frequency beats can be used if the capability of the detector permits. Moreover, two optical frequency combs with Rb-stabilized repetition frequencies are used for the measurement instead of an RF frequency oscillator; thus, we can avoid the cyclic error caused by the RF frequency oscillator. We measured the profile of a wood cylinder with a rough surface (diameter is approximately 113.2 mm) and compared the result with that of coordinate measuring machine (CMM).

Keywords: profile measurement, optical frequency comb, non-contact measurement, rough surface measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

Machining accuracy is ensured by measurement accuracy, thus high-precision measurement method is necessary for improvement of manufacturing. Since 2009, optical frequency combs have become the national standard for the measurement of length in Japan because of its high precision interval of pulses (relative uncertainty is 10^{-14}). Until now, many measurement methods with optical frequency combs such as interferometer are realized. One of them is realized by changing the optical path length with linear stage [1] and another interferometer is realized by shifting the repetition frequency of optical frequency comb [1–3]. Two wavelength interferometer stabilized with optical frequency comb is also used [4, 5]. Time of flight is also applied with optical frequency comb [6]. The beat signals are obtained when the beam of the optical frequency comb is detected. This kind of signal is also used for measurement [7–10].

Recently, a high-precision non-contact measurement method for rough surface objects became more important in factories. For example, in factories which produce airplanes, we usually measure the whole surface of airplanes with a large CMM. However, it takes a long time to measure whole surface. Thus, a non-contact measurement method to rough surface is necessary to decrease the time cost of the measurement. The aim of this research is to develop a non-contact precision absolute measurement system that can also measure the profile of rough-surfaced objects without cyclic error.

So far, many kinds of distance measurement methods for this purpose have been invented in previous investigations. Fujima's group invented a distance measurement system with He–Ne laser modulated by 28 GHz and the standard deviation was 1 μm [11]. However, this measurement system needs correction of the cyclic error to the measured distance. An ordinary electronic distance meter also has cyclic error [12]. Minoshima's group developed a distance measurement

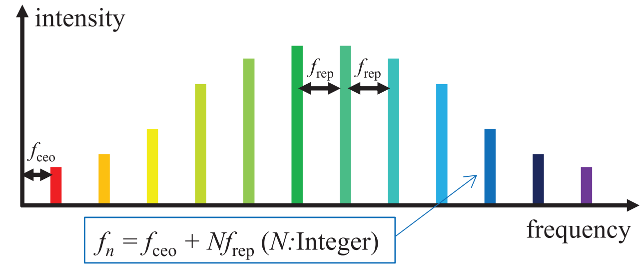


Figure 1. Spectrum of optical frequency comb. The interval of each frequency is called repetition frequency.

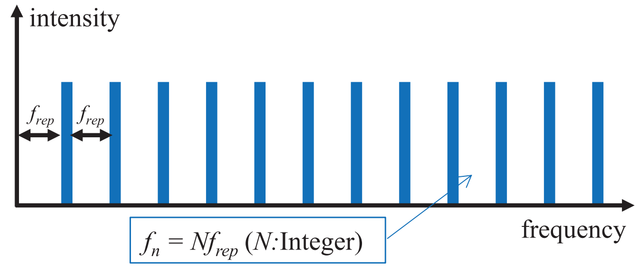


Figure 2. Spectrum of self-beat signals which are obtained when the beam is detected.

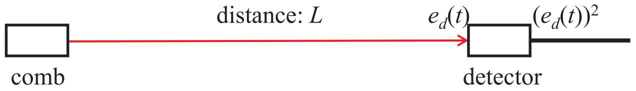


Figure 3. Beam from the comb enters the detector. L is the distance and $e_{\mathrm{d}}(t)$ represents the electrical field of the incident beam.

system with frequency beats of the optical frequency comb and the measured distance was up to 240 m [7]. The relative uncertainty was about 8 ppm. In this system, the frequency used for measurement was 1 GHz and the component of the measurement system was made to be simple. Thus, in this measurement system, no cyclic error was observed. In our past research, we used an optical frequency comb and RF oscillator to apply frequency beats of higher frequencies than 1 GHz. However, cyclic error was observed because of using the RF oscillator. Thus, we used the beat signals of two optical frequency combs instead of using the signal of RF oscillator [13]. However, the measurement accuracy is poor because of the use of the signal of frequency synthesizer as the reference signal directly. In this paper, optical frequency combs and AOM are used to improve the signal processing, and we utilize the characteristics of the optical frequency combs to achieve our objective, and we explain the principle of the proposed measurement system with optical frequency combs and an experiment of measuring the profile of a cylinder with a rough surface (Ra $> 10\ \mu$m).

2. Measurement principle with an optical frequency comb

An optical frequency comb is a pulse laser, and the relative uncertainty of the pulse interval is very small (the relative uncertainty of the comb used in our lab is 10^{-10}). Because the pulse envelop is periodic, many frequency modes are observed in the frequency domain. The frequency difference between each mode corresponds to the pulse interval. This frequency difference is called the repetition frequency (f_{rep}). In our lab, the relative uncertainty of the repetition frequency is also 10^{-10}. The frequency of nth mode signal is represented as $f_{\mathrm{ceo}} + nf_{\mathrm{rep}}$ (figure 1). f_{ceo} is called carrier envelop offset whose relative uncertainty is the same as the frequency of laser diode. When a beam of an optical frequency comb is detected by a detector, the beat signals between each frequency are obtained. Thus, the frequency of the detected signal is represented as Nf_{rep} where N is an integer (figure 2). The frequencies of these signals are in the range of several tens of GHz and are limited by the detector. Hereafter, we refer these signals as self-beat signals.

In the time domain, the electrical field of the beam of an optical frequency comb $e(t)$ is represented as

$$\begin{gathered} e(t) = \sum_i \cos(2\pi f_i t + \theta_i) \\ \theta_i - \theta_{i-1} = \mathrm{const} \end{gathered} \tag{1}$$

Here, f_i and θ_i are the frequency and the phase of the ith mode signal, respectively and n is refractive index. In figure 3, the beam from the comb enters the detector. The distance between the comb and the detector is L. The detected beam $e_{\mathrm{d}}(t)$ is represented as

$$e_{\mathrm{d}}(t) = \sum_i \cos\left(2\pi f_i t + \theta_i + \frac{2\pi f_i nL}{c}\right) \tag{2}$$

Here, c is the velocity of light. The detected signal is represented as $(e_{\mathrm{d}}(t))^2$. Thus, the jth mode of a self-beat signal ($s_j(t)$) is represented as

$$\begin{aligned} & s_j(t) \\ & = \sum_i \frac{1}{2} \sin\left(2\pi(f_{i+j} - f_i)t + \theta_{i+j} - \theta_i + \frac{2\pi(f_{i+j} - f_i)nL}{c}\right) \end{aligned} \tag{3}$$

In the proposed method, the phases of the self-beat signals are used for distance measurement. If the optical path length to the detector is changed by ΔL, the phase change of the jth mode of the self-beat signal ($\Delta\varphi_j$) can be represented by

$$\Delta\varphi_j = \frac{2\pi(f_{i+j} - f_i)n\Delta L}{c} = \frac{2\pi j f_{\mathrm{rep}} n\Delta L}{c} \tag{4}$$

Thus, if $\Delta\varphi_j$ is measured, the change in the optical path length ΔL can be calculated.

$$\Delta L = \frac{c\Delta\varphi_j}{2\pi j f_{\mathrm{rep}} n} + \frac{mc}{j f_{\mathrm{rep}} n} \tag{5}$$

Here, m is an integer. The wavelengths of the self-beat signals range from several tens of millimeters up to several meters. Thus, we can measure rough-surfaced objects because the wavelength is longer than the roughness. In equation (5), if ΔL is longer than the wavelength, m is not zero and is determined using a coincidence method with some other frequencies of the self-beat signals.

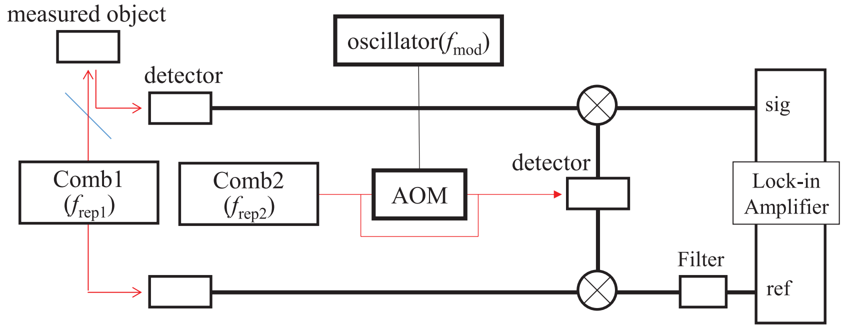
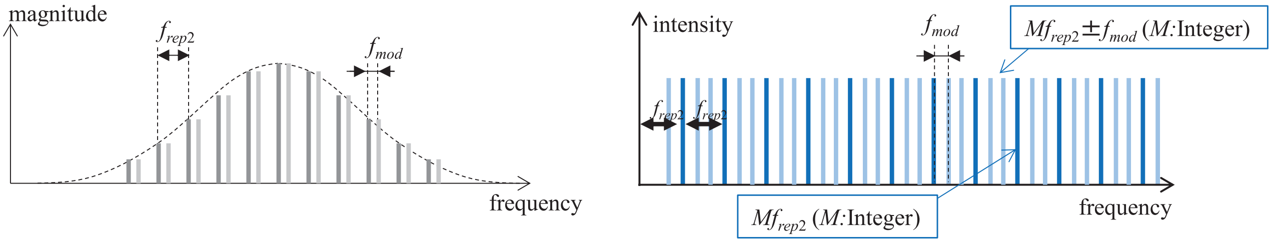


Figure 4. Signal processing of the proposed measurement system. We compare the phase of the beam from the measured object with that of the reference beam by using a lock-in amplifier (0.5 Hz–200 kHz, 5610B, NF-corporation).



(a)

(b)

Figure 5. Frequency of the beam which goes through the AOM is shifted by f_{mod} and the spectrum of the beam at the detector is as the left side of the figure (a). Thus, the frequencies of detected self-beat signals are shifted by $\pm f_{\text{mod}}$ (b).

3. Measurement of the phase change of self-beat signals

If the frequency of the self-beat signal is very low, it is easy to detect the change in phase. However, the frequencies of self-beat signals are high (radio frequency (RF)). Hence, we cannot use a phase comparator and lock-in amplifier, and the detection of the phase change becomes difficult.

In the proposed measurement system, we used two optical frequency combs (f_{rep1} is 100 MHz and f_{rep2} is 58.417 MHz), an acoustic optical modulator (AOM (30–70 MHz)), and a frequency mixer are used to reduce the frequency without a phase change. The signal processing of the proposed measurement system is shown in figure 4. The beam of comb2 is split before the AOM. One of the beams goes through the AOM and the other doesn't pass the AOM. These two beams are gathered and go into the detector. The detected self-beat signal of comb2 in frequency domain is shown in figure 5. The frequency of the beam which goes through the AOM is shifted by f_{mod}. Thus, the frequencies of detected self-beat signals are shifted by $\pm f_{\text{mod}}$.

In order to obtain the phase change, we compare the phase of the beam from the measured object with that of the reference beam by using a lock-in amplifier (0.5 Hz–200 kHz, 5610B, NF-corporation). In addition, we use a frequency mixer to minimize the frequency without a phase change. Moreover, we have to remove the unnecessary signals, which are obtained after mixing. In order to do that, we used an AOM for changing the frequency of the self-beat signal by $\pm f_{\text{mod}}$, and the frequency of the signal after mixing is set to a frequency which is same as that of the filter (10 kHz). Thus, only the necessary signals can be used. In the case of measurement with the frequency of 3.6 GHz, the modulate frequency is set to 36.553 MHz. In our research, we used the self-beat signals of another optical frequency comb instead of an RF oscillator and the modulate frequency is low (about 50 MHz) so that the phase noise of the signal from the oscillator does not cause cyclic error. Thus, we can decrease the effect of the cyclic error caused by the RF oscillator as reported in previous research.

4. Measurement uncertainty of the proposed measurement system

In figure 2, if the optical path length changes by ΔL and the detected phase changes by $\Delta\varphi$, the measured distance can be represented as follows.

$$\Delta L = \frac{mc}{fn} + \frac{c\Delta\varphi}{2\pi fn} \tag{6}$$

Here, m is an integer, c is the speed of light, f is the frequency of the ith mode self-beat signal, and n is the refractive index of air. The measurement uncertainty of the proposed measurement system is represented as follows.

$$\sigma_{\Delta L} = \sqrt{\left(\frac{c}{nf}\right)^2\left(\frac{\sigma_{\Delta\varphi}}{2\pi}\right)^2 + \Delta L^2\left(\frac{\sigma_f}{f}\right)^2 + \Delta L^2\left(\frac{\sigma_n}{n}\right)^2} \tag{7}$$

Here, $\sigma_{\Delta L}$ is the uncertainty of ΔL, $\sigma_{\Delta\varphi}$ is the uncertainty of $\Delta\varphi$, σ_f is the uncertainty of f, and σ_n is the uncertainty of n. The relative uncertainty of f is the same as the repetition frequency of the optical frequency comb, which is approximately 10^{-10} in this research, and the relative uncertainty of n is approximately 10^{-6} for a 1 °C change in temperature. ΔL is about several meters to several tens of meters. Thus, the

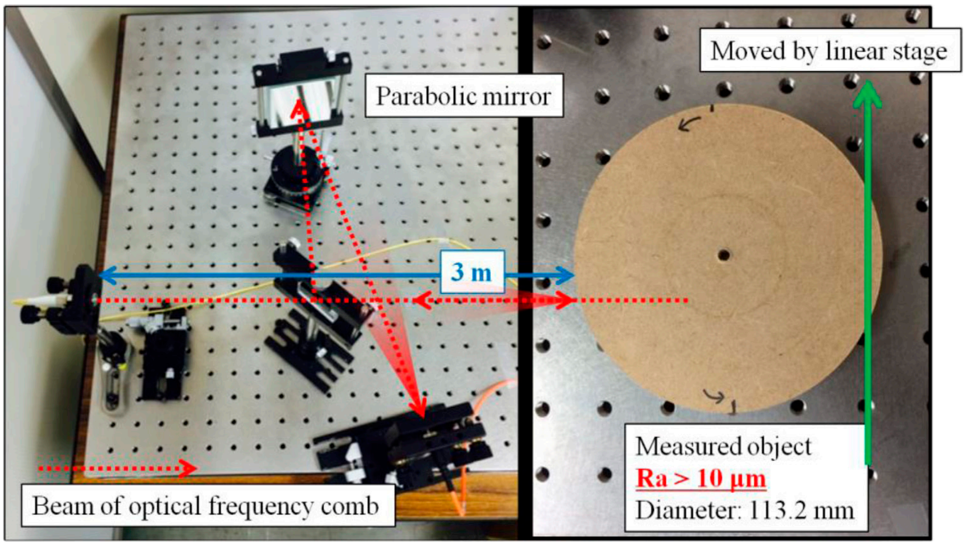


Figure 6. Setup of the proposed measurement system. The size of the cylinder is 113.2 mm, and it is moved by 120 mm. Surface profile is measured by a change in the optical path length.

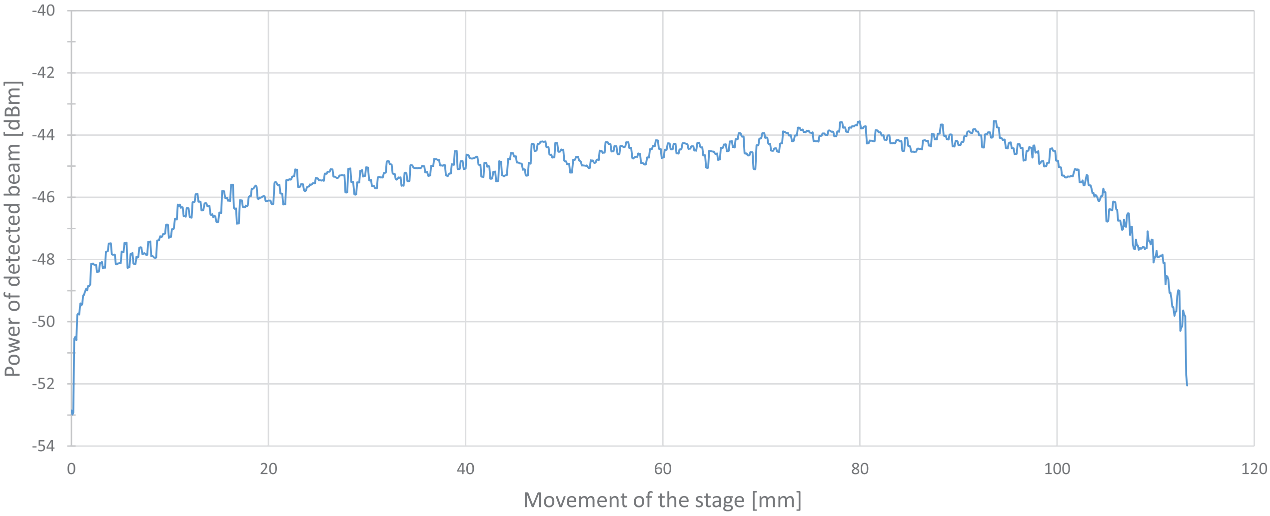


Figure 7. Power of the detected beam from measured object. In a wide range, the power is lower than −44 dBm (approximately 30 nW).

uncertainty of f and n does not have much effect on $\sigma_{\Delta L}$ if the measurement distance and the time of measurement are short. In this case, $\sigma_{\Delta L}$ is represented as

$$\sigma_{\Delta l} = \frac{c}{nf}\left(\frac{\sigma_{\Delta\varphi}}{2\pi}\right) \tag{8}$$

Thus, the uncertainty of the measurement is obtained by f and $\sigma_{\Delta\varphi}$. $\sigma_{\Delta\varphi}$ depends on the quality of the detected signal. $\sigma_{\Delta\varphi}$ is represented as follows.

$$\sigma_{\Delta\varphi} = \frac{kv_{\rm n}}{v_{\rm s}} \tag{9}$$

Here, k is a constant value of the measurement system determined by the equipment used in our system, $v_{\rm n}$ is the amplitude of noise in our measurement system, and $v_{\rm s}$ is the amplitude of the signal used to measurement. Thus, this value k does not change if the equipment used in the research is the same. Also, the main source of $v_{\rm n}$ is thermal noise in the circuit. If the temperature (300 K) is changed by 1 °C, the amplitude of $v_{\rm n}$ is changed by 0.3%. Thus, measurement uncertainty can be calculated with the amplitude of the signal if $kv_{\rm n}$ is already known. $kv_{\rm n}$ can be calculated with value of $\sigma_{\Delta\varphi}$ and $v_{\rm s}$ which are experimentally obtained by a lock-in amplifier.

5. Measurement of the cylinder with a rough surface

As we explained, the wavelength of the self-beat signals of an optical frequency comb is longer than the roughness of the surface. Thus, the profile of rough-surfaced objects can be measured. In this paper, we measured a cylinder which has a rough surface (Ra $>$ 10 μm). The experimental system is shown in figure 6. The beam of the optical frequency comb comes from the collimator and hits on the measured surface. The reflected beam is concentrated by a parabolic mirror. The measured cylinder is placed on the linear stage and is moved

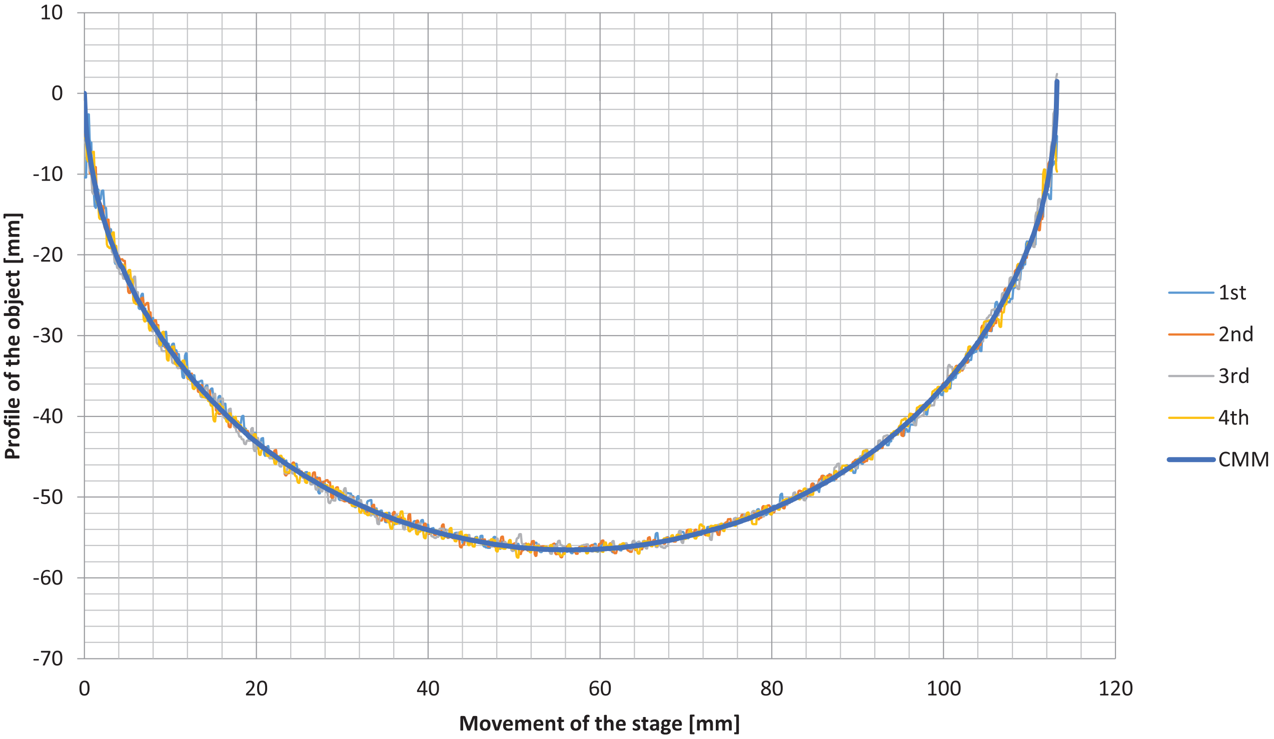


Figure 8. Profile of the measured object. The profile can be measured from one side to the other side. The result of the proposed system and that of the CMM is almost the same.

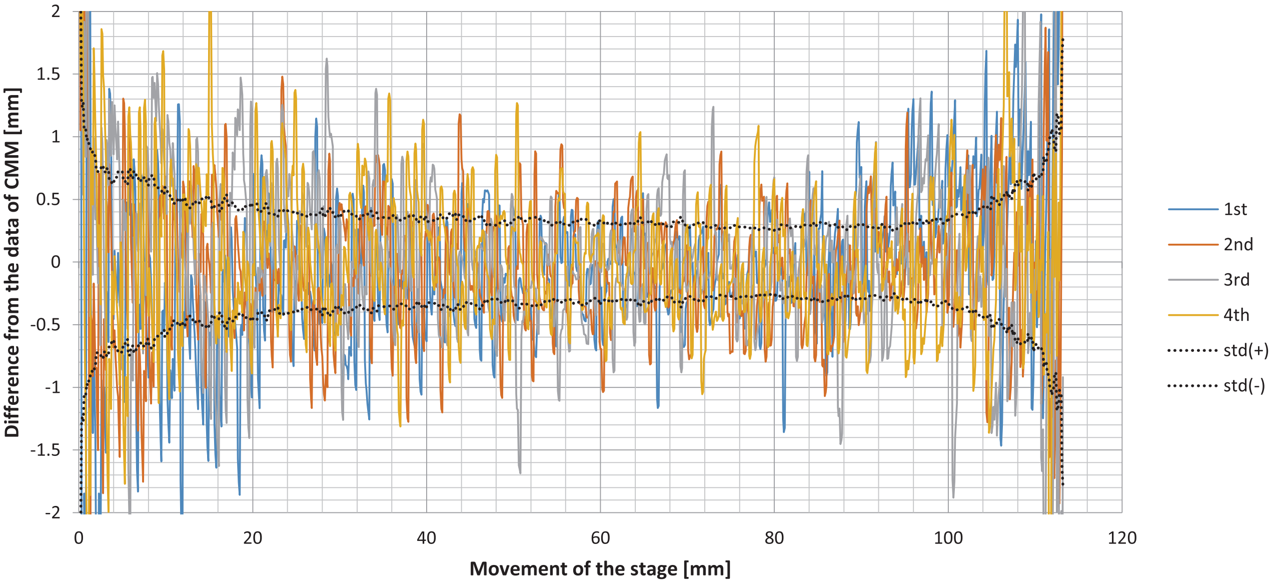


Figure 9. Difference between the result of the proposed measurement system and that of the CMM. The black dotted line represents the uncertainty predicted using (8) and (9). In a wide range, the measurement uncertainty is approximately 400 μm.

by 120 mm. As the measured cylinder moves, the optical path length to the measured surface changes. Thus, the profile of the cylinder can be measured by measuring the change in the optical path length. Even if the phase difference exceeds 2π, phase-unwrapping process can be applied because the measured surface is continuous. The experimental conditions are as following. The experimental conditions are as following. The distance from the collimator to the rough surface is approximately 3 m. The frequency of the self-beat signal is 3.6 GHz (wavelength is 83.275 68 mm). The time constant of the lock-in amplifier is 100 ms. We measure the profile of the surface four times. The power of the detected beam is shown in figure 7. The experimental results are shown in figures 8 and 9. We measure the profile of the surface four times. The profile is laso measured with a CMM (uncertainty is 2 μm).

As shown in figure 7, the power of the detected beam is lower than -44 dBm in a wide range. However, we could measure the surface from one side to the other side (figure 8). The measurement result obtained by using the proposed system is almost the same as that of the CMM, and the standard

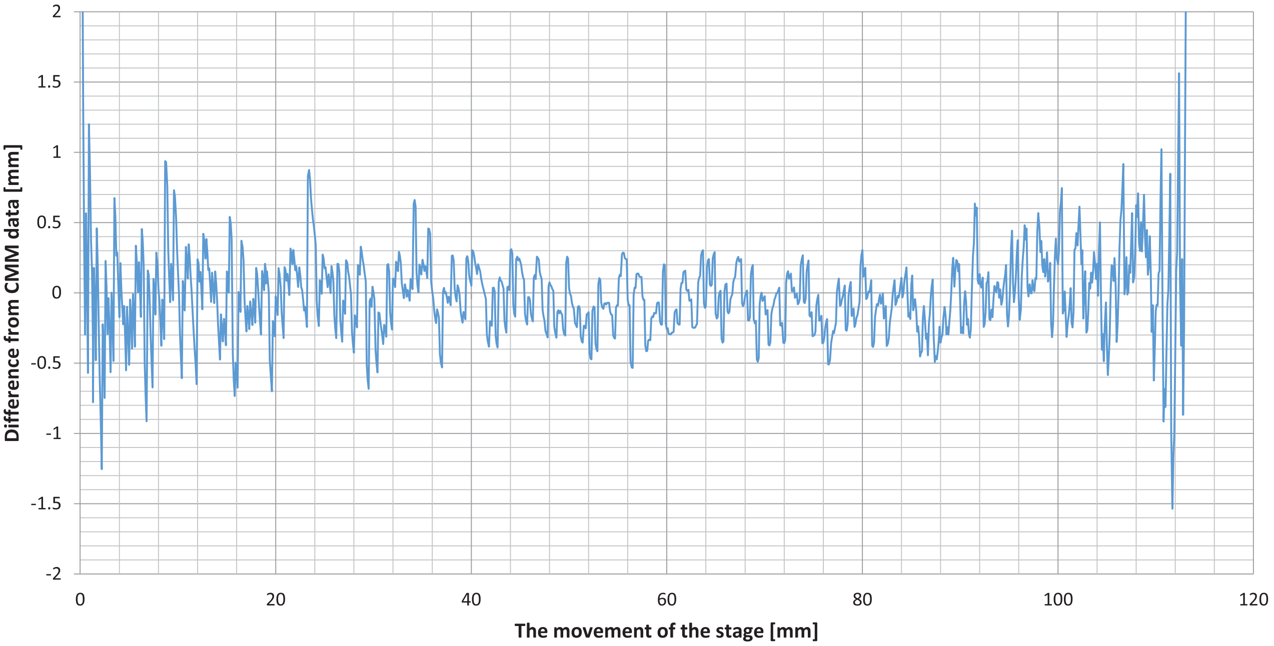


Figure 10. Difference between the averages of four measurement results obtained by the proposed measurement system and that of the CMM. In a wide range, the measurement uncertainty approximately 200 μm.

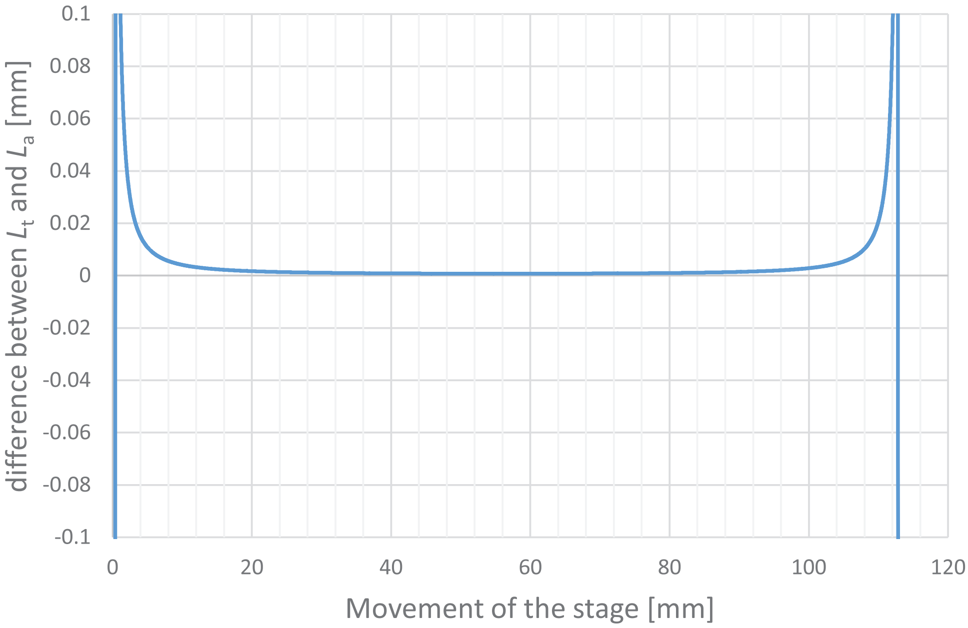


Figure 11. We have simulated the difference of the measurement with beam diameter of 1 mm (L_a) and with that of infinitesimal (L_t). In wide range, the difference from actual value (L_t) is smaller than 0.02 mm.

deviation of the difference is approximately 0.4 mm in a wide range (figure 9). The uncertainty in the measurement is due to the weak power of the reflected beam (< -44 dBm) which is scattered by rough surface. Thus, in order to improve the accuracy of the measurement, we need to increase the power of the detected signal or improve the signal processing. As shown in figure 9, almost all the errors are random errors. If we use the average of the four data, the difference between the result of the proposed method and that of the CMM becomes smaller (figure 10).

6. Discussion

In our experiment, we measured the curved surface and beam diameter is about 1 mm on the measured surface. Thus, the result of the measurement is the average distance on the beam spot. We have simulated the difference of the measurement with beam diameter of 1 mm (L_a) and with that of infinitesimal (L_t) as shown in figure 11. The diameter of measured cylinder is set to 113.2 mm. At the side of the measured object, the difference from actual value (L_t) is larger than 0.02 mm.

However, in wide range, the difference from actual value (L_t) is smaller than 0.02 mm. Thus, in our measurement of the cylinder with the diameter of 113.2 mm, the beam diameter has not much effect in wide range of the cylinder.

In the research done by Minoshima's group, just up to 1 GHz signal can be used because mixing to decrease the frequency of signal is not applied [7]. In our method, many self-beat signals can be used because the frequency of each signal is decreased by mixing (less than 30 MHz). If we process more of the self-beat signals simultaneously, the measurement uncertainty becomes much better. For example, we have simulated using 25 signals simultaneously and the measurement uncertainty will be about 40 μm to the rough surface of Ra $>$ 10 μm. Also, absolute measurement can be conducted with this method.

7. Summary

In this paper, we explained the measurement principle of optical frequency combs with the self-beat signals. The wavelengths corresponding to these self-beat signals are long enough to measure rough-surfaced objects. In addition, we can conduct high-precision measurements because several tens of GHz frequency beats can be used depending on the capability of the detector. Moreover, two optical frequency combs with Rb-stabilized repetition frequencies are used for the measurement instead of an RF frequency oscillator, thus, we can avoid the cyclic error caused by the RF frequency oscillator.

We measured the profile of a rough-surfaced cylinder four times, and we confirmed that the result of the proposed measurement system and that of the CMM is almost the same. The difference between the average data of the proposed system and that of the CMM is approximately 200 μm. However, the power of the beam reflected from the measured surface is very weak, and that becomes the main reason for uncertainty in the measurement. If we process all of the self-beat signals simultaneously, the measurement uncertainty becomes much better. For example, if we use 25 signals simultaneously, the measurement uncertainty will be about 40 μm to the rough surface of Ra $>$ 10 μm. Also, absolute measurement can be conducted with this method.

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