Frequency-stepping interferometry for accurate metrology of rough components and assemblies

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ABSTRACT

We describe a distance-measuring interferometer based on a novel frequency-stepping laser that is tunable over 30 nm. Conventional tunable lasers provide continuous tuning over a range of wavelengths without any mode transitions. The new frequency-stepping laser was designed to maximize frequency repeatability by exploiting the mode-hopping behavior to achieve equal frequency increments. An interferometric image is collected at consecutive laser mode frequencies making it very easy to perform Fourier transforms. The modulation frequency of the interference on each pixel is directly proportional to the optical path difference between the reference and test arms of the interferometer as well as the laser mode spacing. The inherent stability of the frequency-stepping laser results in a very accurate conversion from the modulation frequency of the pixel to its OPD. A Fourier transform is performed on each pixel to determine the height difference between the reference and measurement arms independent of its neighboring pixels.

Our laser mode spacing of 36 GHz results in an unambiguous measurement range of 2.1 mm. Prior knowledge about the features of the part being measured allows us to measure over 300 mm of range with 10 nm resolution. This can be combined with conventional PMI techniques to achieve sub-nanometer resolution. This technique is applicable to both rough and smooth parts making it possible to perform metrology on individual components as well as partial assemblies that require tight tolerances.

Keyword List: tunable laser, interferometry, Fourier transform, mode-hopping, external-cavity tunable laser, white light interferometry, coordinate measuring machine, distance measuring interferometry

1.0 INTRODUCTION

We present a new frequency-stepping technology that can measure discontinuous regions such as recessed surfaces. Advances in tunable laser technology, image sensing detectors and computer processing have enabled a new class of interferometer based on frequency-scanned laser illumination. This new technology offers the ability to make precise measurements of both diffuse and specular objects. This paper describes the principles behind the new frequency-stepping technology, provides some details on the system design, and presents two examples of applications with measurement results.

2.0 FREQUENCY-STEPPING INTERFEROMETRY

Conventional, single-wavelength interferometers offer excellent height resolution over a continuous, smooth surface; however, there are two major drawbacks for these systems: they cannot measure diffuse or rough surfaces, and they cannot measure step heights between discontinuous regions [1]. For diffuse surfaces, the height variation within a pixel and between pixels often is substantially greater than the measurement wavelength, resulting in interferograms that look like speckle patterns. In these cases, conventional single-wavelength interferometry employing standard phase-unwrapping algorithms does not work because there is no fringe pattern.

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White-light interferometers overcome both of these limitations [2]. Their optical arrangement is similar to the single-wavelength setup, but a short temporal-coherence source replaces the laser. The surface under measurement is simultaneously illuminated with a range of source frequencies. White-light fringes are localized and are only visible when the optical paths for the reference and test arms are very well matched. A measurement requires that the reference mirror or test object be scanned precisely in the direction of the illumination to locate the interference fringes. Although white-light interferometry is very capable, the requirement of a moving reference can make it impractical for the measurement of deep or large objects. Furthermore, the measurement time increases directly with the measured range.

Unlike white-light interferometry, the measurement time is independent of range in frequency-stepping interferometry. A tunable laser source is used that can step to discrete wavelengths over a broad range of frequencies. In a manner similar to single-wavelength interferometry, multiple interferometric images of the part under measurement are collected. For each image or frame of data, the laser frequency is changed by an equal increment. The intensity of each pixel will vary by a frequency that is determined by the mismatch in the distance between the reference and test arms [3].

For conventional phase measuring interferometers (PMI), the modulation frequency for all the pixels is constant as shown in Figure 1, and the phase is measured to determine the changes in relative distance across the test surface. For frequency-stepping interferometry (FSI), however, the modulation frequency for all the pixels is not constant, and the modulation frequency is measured directly to obtain the absolute distance between the reference and test surfaces.

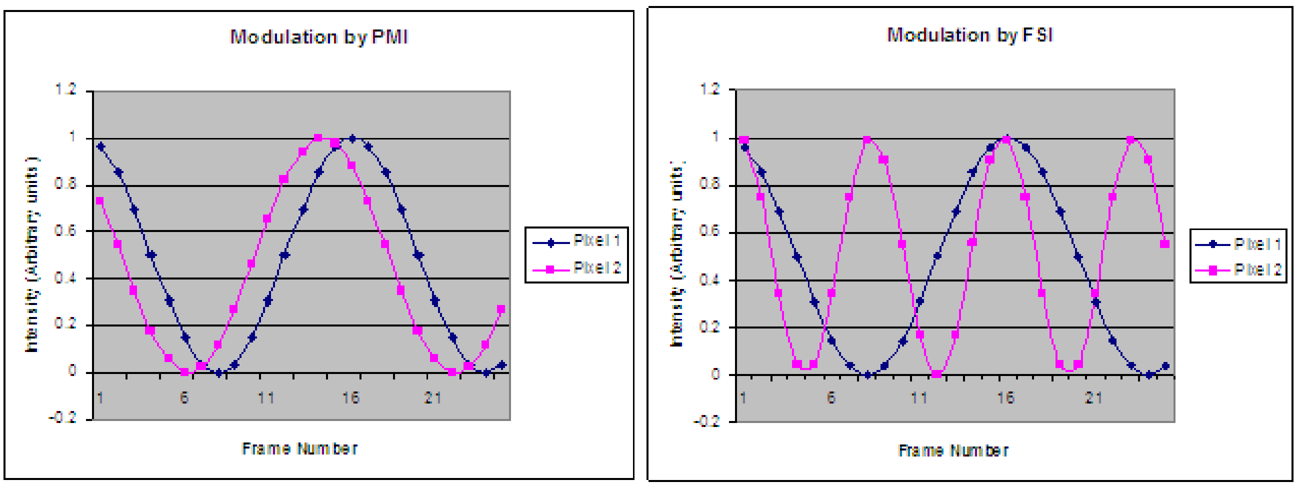

Figure 1. In conventional PMI systems all the pixel modulate at the same frequency and the phase difference is used to create the surface profile. For our FSI system, the modulation frequency is a direct measure of the OPD and is different for each pixel.

One advantage of frequency-stepping interferometry is that the height of each pixel is obtained independently of its neighboring pixels by using Fourier transform algorithms to determine the modulation frequency. No phase-unwrapping algorithms are utilized. As a result, it is possible to measure rough and diffuse surfaces in which there can be very large differences in height from pixel to pixel. Similarly, this enables the measurement of discontinuous regions separated by distances greater than 100 mm.

The technique also enables a variety of unique instrument design forms. By eliminating any precision motion requirements, the interferometer becomes very compact and modular with few, if any, moving parts. Measurements are performed in seconds, independent of the measuring range.

Another feature is that the interferometer can be located remotely from the laser source. A single-mode optical fiber transmits the variable-frequency illumination to the instrument, which incorporates the reference arm and high-resolution camera. This design enables new applications for interferometry, such as the in-line measurement of precision components or assemblies.

3.0 SYSTEM DESIGN

3.1 Laser sub-system

The frequency-stepping interferometer is comprised of two subsystems: the tunable laser source and the interferometer head. The tunable laser source is the core of the frequency-stepping technology since it must generate a broad illumination bandwidth at constant frequency intervals. This was accomplished through a tunable external cavity laser (ECL) of our own design shown in Figure 2. We integrate a semi-conductor laser diode which is commercially available in a 5.6 mm can package. Unlike continuously tunable ECL's, these diodes are not AR coated. This requires us to mode-match the length of the external cavity so that it is an integer multiple of the optical length of the fundamental laser diode. The laser diode is mounted in a flexure (not shown) so that we can translate the diode along the cavity axis to mode match to the external cavity length. The external cavity consists of a collimating lens and a high-pitched grating. The collimating lens is also mounted on a flexure to allow independent adjustment. The grating serves as a dispersive element and is used in the Littrow configuration so that the first order diffracted beam from the grating is aligned with the axis of the external cavity. As the grating is tuned over small angles, the wavelength of the first order diffracted beam that is directed back into the laser diode is changed. The laser output can be tuned over a range of up to 30 nm by changing the angle of the grating over 2.4 degrees. The zero order beam is used to couple light out of the cavity. The grating is mounted in a barrel such that the grating face is aligned with the barrel's rotation axis [4]. The barrel also carries a fold mirror which directs the zero order beam from the grating parallel to the ECL axis. As the grating is tuned through the range of wavelengths, the zero order beam sees small translations but it is always parallel to the laser axis.

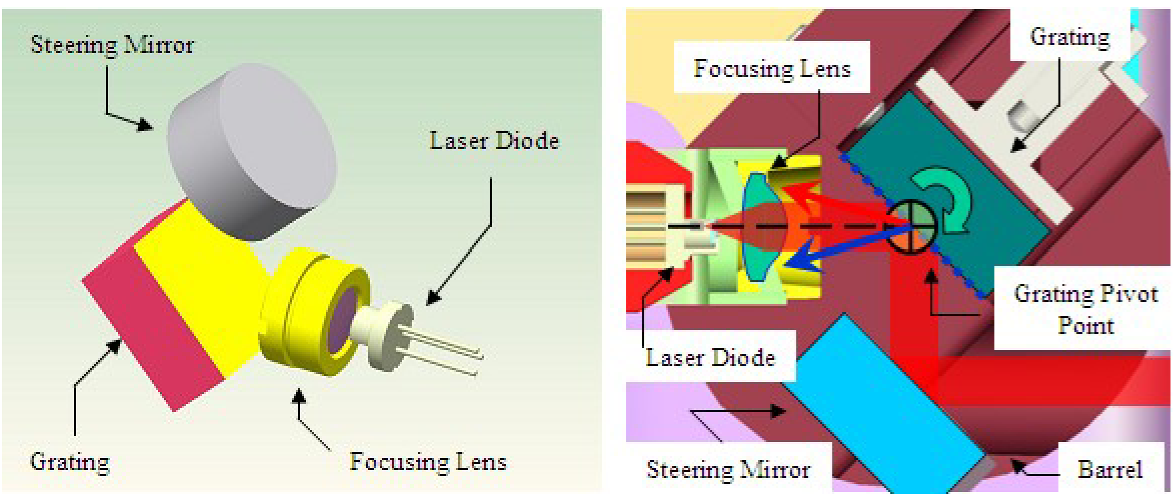

Figure 2. The design of our tunable external cavity laser (ECL) uses a commercially available laser diode in 5.6 mm can which is not AR-coated. The grating is used in the Littrow configuration and is mounted in a barrel that rotates on an axis that is co-planar with the grating face.

The length of the tunable cavity is optimized so that the longitudinal mode spacing of the external cavity is a multiple of the longitudinal modes of the fundamental laser diode. This minimizes mode competition, and frequency-pulling effects. It also makes it possible to tune the laser in equal frequency intervals by stepping from one longitudinal mode to another. There are a number of key advantages that this laser design has over conventional continuously tunable ECL's. Continuously tunable ECL's require a pivot axis for the grating such that the cavity length changes to allow the longitudinal mode to track the peak wavelength as it tunes [5]. This enables mode-hop free tuning. In our design, the pivot axis is chosen to be on the face of the grating so that the cavity length remains fixed as the wavelength changes. This forces the laser to hop from one longitudinal mode to the next and provides us a stable comb of frequencies ideal for interferometry applications.

Another advantage is that the tunable ECL of our design does not require an AR-coated laser diode. This eliminates the development of expensive coatings as well as the lifetime issues associated with these coatings. We have built a number of systems operating at central wavelengths of 785, 808, and 830 nm using different commercially available laser diodes.

We show in Figure 3 the tuning range and characteristics of one of our 830 nm frequency-stepping lasers. The laser can tune over a range of wavelengths from 850 nm to 820 nm. If we look at the tuning curve on a finer scale, we see that the laser changes in discrete 36.1 GHz steps. This step-like tuning behavior is ideal for interferometry applications since small angular errors of the grating during the scan do not translate into laser frequency errors.

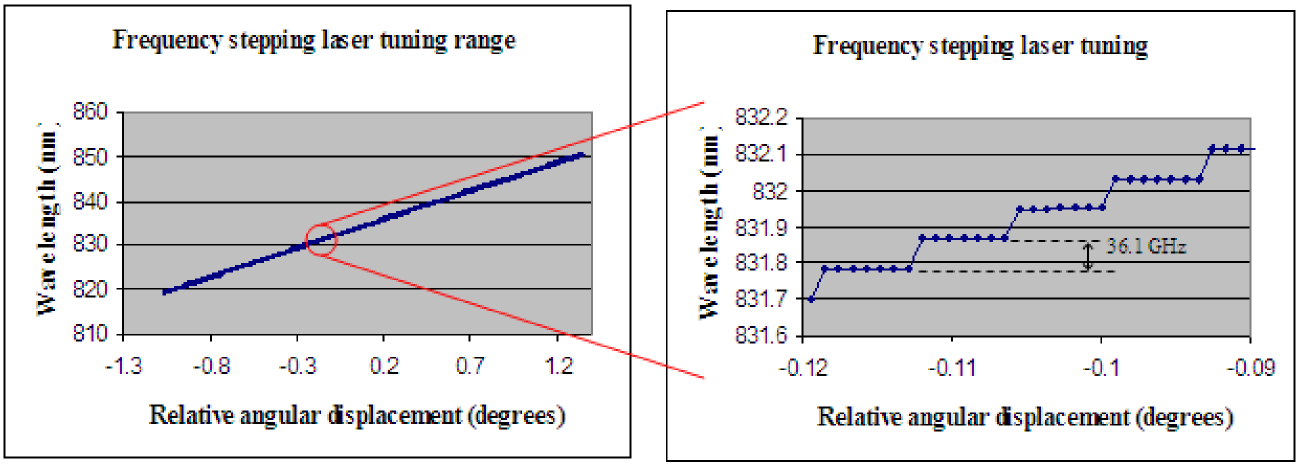

Figure 3. The frequency-stepping laser covers more than 30 nm and provides a comb of frequencies ideal for interferometry measurements.

When performing interferometric measurements, the grating steps are chosen so that each longitudinal laser mode is sampled once. We typically collect 128 frames so we only use ~ 10 nm of the available bandwidth. The laser frequency is tracked by using an uncoated fused silica window as an etalon. A small portion of the laser beam is split off and is focused before the etalon to generate a pair of sheared spherical wavefronts that illuminate a linear CCD array. The phase of the interfering waves is monitored to measure the frequency errors during the scan [6]. The etalon thickness (~ 3.2 mm) is chosen to give us a high-resolution measurement of the laser frequency. We show in Figure 4a the phase data from the monitoring etalon during an interferometric measurement. Since the free spectral range (FSR) of the etalon at 31 GHz is less than that of the ECL at 36.1 GHz, the fringe pattern shifts by 1.16 FSR's giving us a phase change of ~ 420 degrees (aliased to 60 degrees) for each laser step. If we compare the phase difference between adjacent steps of the interferometric scan as shown in Figure 4b, we obtain a measure of the repeatability of the frequency. The standard deviation of the phase differences in Figure 4b is 1.4 degrees which translates to a frequency repeatability of 120 MHz.

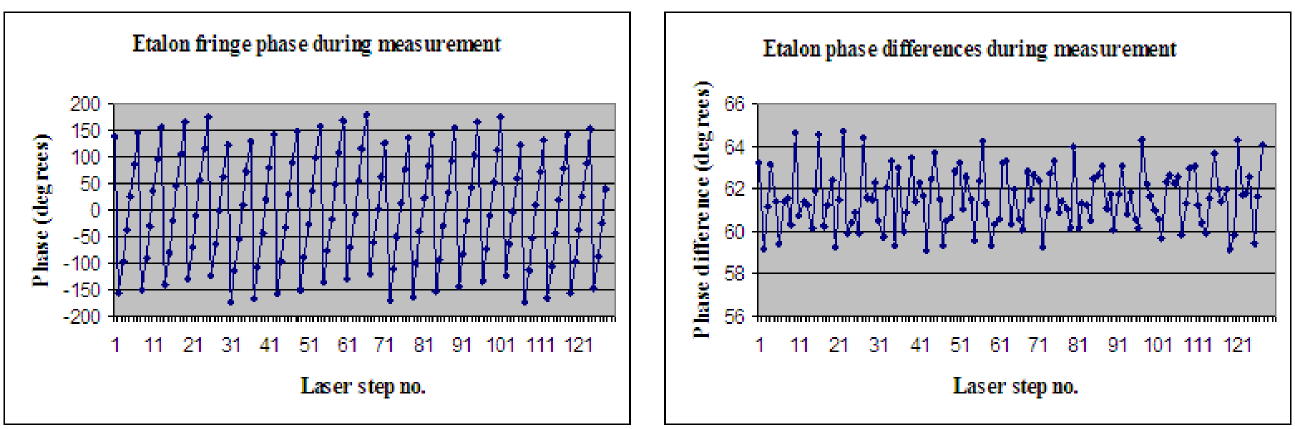

Figure 4. The plot on the left shows the change in phase (~ 420 or 60 degrees) for each of the 128 frames during an interferometric measurement. The plot on the right shows the phase difference between successive frames. The standard deviation of 1.4 degrees corresponds to a frequency repeatability of 120 MHz.

3.2. Interferometer sub-system

The output of the laser system is directed to a fiber coupler so that it can be coupled through a single mode fiber to the interferometer head. A schematic of the interferometer head is shown in Figure 5. The output of the optical fiber is focused to a diffuser system inside of the head that allows adjustment of the spatial coherence and optimizes the illumination uniformity. The beam expanding from the diffuser passes through a beamsplitter and is collimated so that a planar beam is incident on the Fizeau reference surface. The Fizeau surface reflects some of the light (reference beam) back through the beam splitter. The light that is transmitted through the Fizeau surface is the measurement beam that illuminates the part at normal incidence.

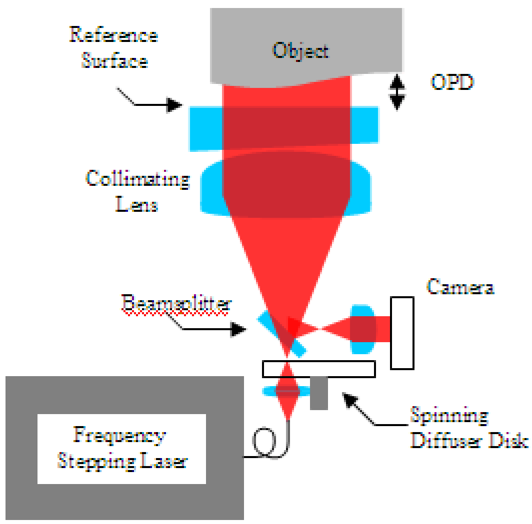

Figure 5. The interferometer is based on a Fizeau design. The new frequency-stepping technology measures the absolute distance between the Fizeau reference surface and the measurement object for each pixel on the camera independently of the adjacent pixels.

The light that reflects from the part surface is also passed through the beamsplitter and is combined with the reference arm to produce an interferogram. An optical system after the beamsplitter directs the interferometric image onto a camera that feeds frames into the computer.

We have built several systems with different fields of view (FOV): 25 mm, 40 mm, and 150 mm. The lateral resolution depends on the camera format. The selection of a 1MegaPixel camera with a 40 mm FOV gives ~ 40 micron pixels. The range of heights that can be measured is limited by the depth of focus of the imaging system which depends on the FOV. For the 40 mm system, we can measure a height range of 40 mm, but the 150 mm system can measure up to a 300 mm height range from the Fizeau surface.

4.0 DATA PROCESSING AND ANALYSIS

The interference at each pixel between the reflected light from the measurement object and the reference beam from the Fizeau surface can be described by the following expression,

$$I = |U_1|^2 + |U_2|^2 + 2|U_1||U_2|\cos(f_n(x_1 - x_2)) \tag{1}$$

where U_1 and U_2 are the amplitudes of the object and reference beams, f_n describes the successive frequencies from the stepping laser, and $(x_1$-$x_2)$ is the optical path difference for the particular pixel. The amount of phase change for each successive frequency step is directly proportional to the change in frequency and to the optical path difference. The change in laser frequency is governed by the fundamental diode cavity free spectral range, which is fixed; therefore, this term can be treated as a constant. This means that the rate of phase change measured on each individual pixel of the array is a direct measurement of the optical path distance between the part surface and the reference surface. This rate of phase change can also be expressed as the modulation frequency output of a given pixel over the course of all of the laser frequency steps. This modulation frequency can be conveniently calculated with a discrete Fourier transform (DFT).

With a calculated modulation frequency for every pixel in the field of view, and knowledge about the mode spacing, it is a straightforward relationship to convert the modulation frequency for each pixel into a surface height map. A part measurement typically involves collecting 1 frame for each laser frequency as we scan through 128 successive laser steps separated by 36 GHz. We then perform a DFT on each pixel to generate the frequency map. The range of possible frequencies is determined by the Nyquist limit (N) of the DFT. The smallest possible frequency step sets the unambiguous range of height measurement. This unambiguous height range is 2.1 mm and is given by the following expression:

$$\Delta Z = \frac{c}{4\Delta \nu} \tag{2}$$

where c is the speed of light and $\Delta\nu$ is the laser frequency step size. It is still very straightforward to measure beyond the unambiguous height range of 2.1 mm since the DFT will simply detect the frequency as an aliased frequency in a very predictable pattern. For frequencies between 0 and the Nyquist limit, the measured or detected frequency is equal to the actual frequency, and we will consider this range of frequencies to be a single "ambiguity interval". In the second ambiguity interval containing modulation frequencies from the Nyquist limit (N) to 2 times the Nyquist limit (2N), the measured or detected frequency from the DFT will decrease from N to 0. For actual modulation frequencies from 2N to 3N, the sampling condition is such that our frames are spaced in a way that an entire period of the sine wave is skipped in the processing. The result is that for actual modulation frequencies from 2N to 3N, the measured or detected frequency varies from 0 to N. This pattern continues indefinitely as shown in Figure 6.

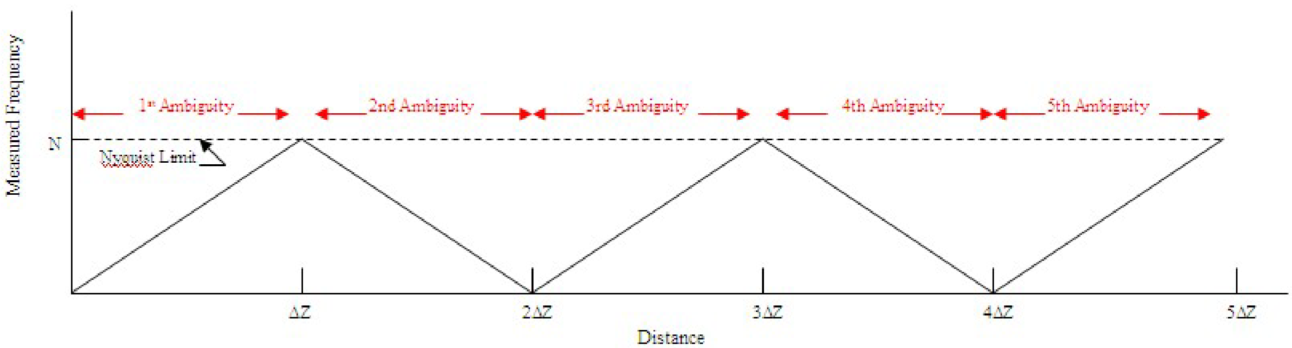

Figure 6. The 36 GHz laser steps creates an unambiguous height range (ΔZ) of 2.1 mm. We can still measure components at much higher ambiguity intervals because the comb of laser frequencies is so stable that the modulation frequency can be aliased allowing measurements of heights > 300 mm.

The result of this relationship between measured modulation frequency and the absolute optical path difference is that with a small amount of prior knowledge of the expected surface geometry it is possible to identify which interval the actual surfaces are in, and therefore measure true height differences of hundreds of millimeters with nanometer scale resolution. This eliminates the need for phase unwrapping and also eliminates the need for accurate stages as in the case of a white light interferometer.

In principle, the limit on the maximum height that can be measured with the frequency-stepping technology is determined by the repeatability of the laser spacing. At larger heights, small variations in the frequency steps cause larger errors in the measured modulation frequency. In practice, the main limitation for distance measurement is the depth of focus of the imaging system, since the contrast between pixels becomes too low when the image is out of focus. For a 40 mm field of view, this interferometer configuration can measure surface height variations over 40 mm, which corresponds to over 19*N. With a larger field of view, the depth of focus becomes larger, increasing the depth of focus dramatically. On the 150mm field of view configuration, parts with depths in excess of 300 mm were measured with very good results, and this corresponds to over 142*N.

With this ability to measure components over a very large variation of heights, it becomes more critical that surface features are identified in order to report meaningful measurement parameters. A variety of image processing macro tools have been built into our post-processing to quickly and easily identify discrete surfaces by grouping pixels with similar modulation frequencies. This allows the user to preconfigure an analysis to find the measured surfaces of interest, and calculate the appropriate GD&T measurement parameters such as flatness, parallelism, depth, or height. The ability to generate surface datums allows a much more accurate height or parallelism than can be calculated than from a few samples of points.

We show in Figure 7 one of the frames from the data collection (left picture) of a scroll compressor component as viewed by our system with 150 mm FOV. The part has a rough surface with a range of surface heights covering 25 mm. This speckle pattern cannot be interpreted by conventional interferometers. After the frequency map is generated (middle picture), our image-processing tools allow us to identify one surface (right picture) and ignore the rest (shown in gray in right picture). We can then perform measurements on just the surface of interest such as flatness, parallelism, etc.

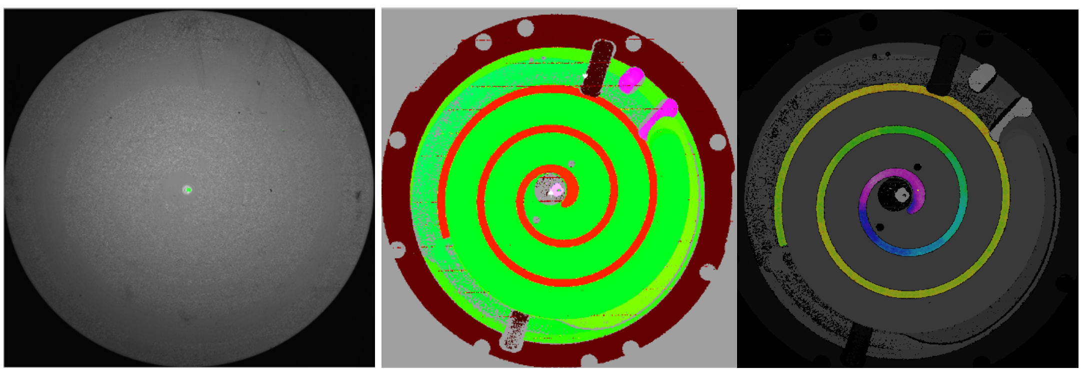

Figure 7. One of the frames from the data collection of a scroll compressor is shown on the left, and it is apparent that the rough surface results in a speckle pattern that would not work for conventional PMI interferometry. The frequency map is generated for all the pixels in the middle picture. On the right, one surface from the scroll compressor component is extracted and isolated from all the other surfaces allowing GDT analysis.

5.0 SAMPLE APPLICATION AND MEASUREMENT RESULTS

Frequency-stepping interferometry offers many advantages over conventional approaches: fast measurement times, a scalable field of view for the measurement of various part sizes, a dynamic range of hundreds of millimeters, submicron precision, compatibility with surface finishes from cast to polished, and compatibility with a wide range of materials, including metals, ceramics, glass and plastics.

Two example applications that take full advantage of the benefits of frequency-stepping interferometry are demonstrated below. In the first case there are dozens of surfaces at varying heights, and the second is a large part with large height variation between the surfaces.

5.1. Watch Assemblies and Components

The mechanical watch has long been a symbol of precision and accuracy. There are dozens of mechanical parts assembled into a very small package. The size and complexity of the designs require very sophisticated mechanical tolerances on components that could have dozens of critical surfaces to prevent interference between the different moving parts while minimizing the overall package size.

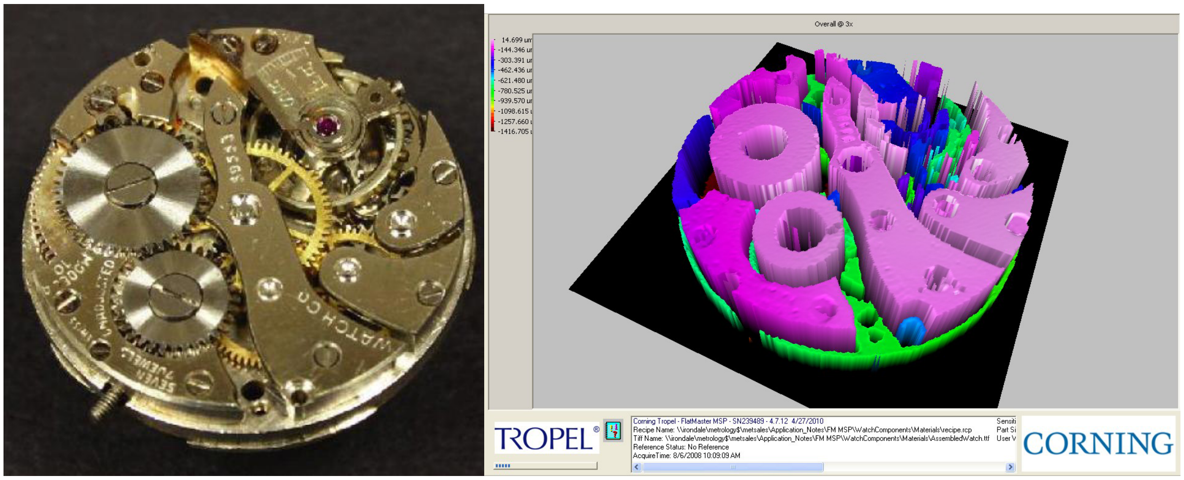

Figure 8. Example of a mechanical watch assembly (left) and a 3D plot of the measurement (right).

Traditional characterization and control of such complex components and assemblies can take a prohibitively long time to perform. Measurement of all these surfaces using a small coordinate measuring machine takes more than 30 minutes and provides only a sampling of points on each surface. Measuring such a small number of points per surface does not provide the true form of that surface making it very difficult to detect process related problems. With full surface measurements from a frequency stepping interferometer it is possible to fully characterize all of the surfaces simultaneously with hundreds of thousands of data points in 30 seconds.

5.2. Scroll Compressor

The scroll compressor efficiency is related to the distribution of the clearance between the two halves of the scroll. Each has a spiral-shaped nominally flat fin. The two fins are oscillated relative to each other creating a pocket of fluid which move along the spiral from the larger diameter inlet to the smaller diameter outlet. As the pocket moves along the spiral the volume of the pocket becomes smaller thereby compressing the fluid. This compression process leads to a non-uniform distribution of heat along the compressor scroll. Since the material of the scroll has a non-zero coefficient of thermal expansion, in order to improve the sealing of the scroll faces to each other, it is desirable to have a specifically varying height as a function of the position along the spiral.

This requires the scroll face to have a specific shape target which must be controlled to micron-level tolerances. Similarly, the base of the scroll has a flatness target on the order of microns, and the two surfaces separated by tens of millimeters need to be both parallel and controlled for absolute height on the same micron-level scale.

These components are shown in Figure 9, and were measured on a system with a 150 mm field of view. The surfaces of these precision controlled surfaces are not polished so they are not measurable using traditional phase measuring techniques. Contact-based systems such as coordinate measuring machines tend to be slow for characterizing a full surface, and the accuracy of such systems tends to be low relative to these tolerances.

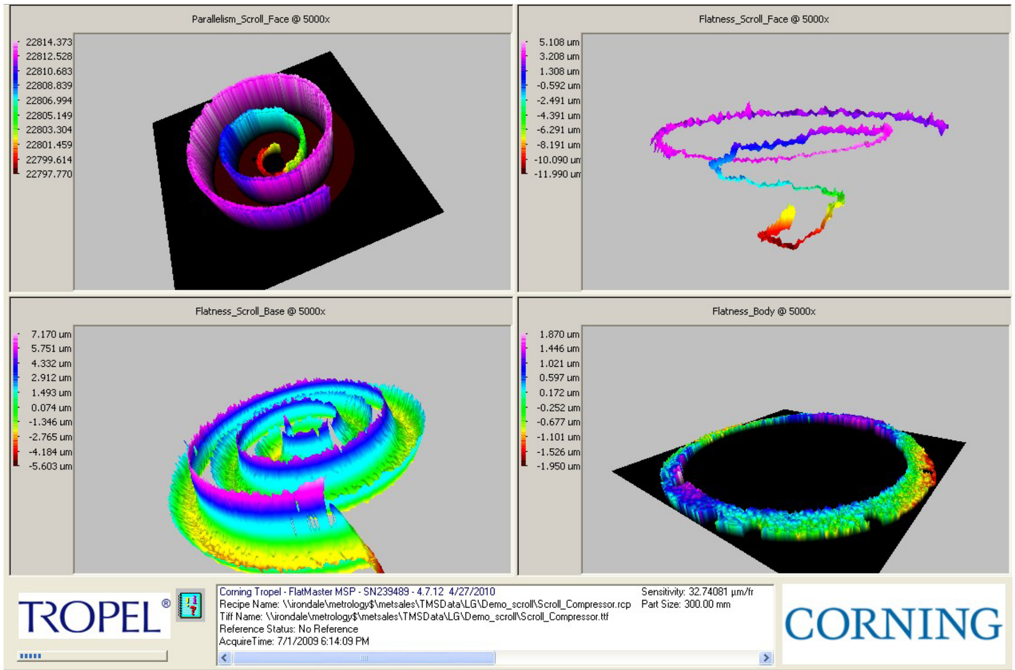

Figure 9. High-resolution, high-dynamic range measurement of a scroll compressor component is shown. From the face to the base of the scroll is approximately 25 mm, and the flatness of the scroll body is 3.8 microns.

Frequency-stepping interferometry lends itself perfectly to this application providing a 10 nanometer resolution map of hundreds of thousands of data points on the entire part in 30 seconds. This makes it not only perfect for process development, but with such high speed, it can also be used for process control in production.

6.0 CONCLUSION

Frequency-stepping interferometry enables a new class of metrology instrument which will greatly expand the role of optical metrology in precision manufacturing. Frequency-stepping interferometry incorporates the capabilities of single-wavelength interferometry and, thanks to the digital signal processing, also includes the capabilities of white-light interferometry without the need for moving optics. We envision many applications for this technology including the measurement of precision machined parts and complex assemblies of components.

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