# Frequency-Scanning Interferometry

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## 1.0 Introduction

A growing number of precision component manufacturers are machining objects that have micron- or submicron-level tolerances on parameters such as flatness, thickness and parallelism. They are discovering that subcomponents that each are within tolerance nevertheless can result in an assembly that does not function properly because of tolerance stack-up. This problem requires more frequent metrology during the assembly process so that the subcomponents can be properly matched. Consequently, there is an increased emphasis both on accurate subcomponent metrology and on assembly metrology.


Figure 1. The frequency scanning interferometer's head is mounted on a small stand. A small part is shown placed on the measurement window at the top of the interferometer

We present a new frequency scanning 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-scanning technology, provides some details on the system design, and presents an example of an application with measurement results.

## 2.0 Frequency Scanning 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. 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 good fringe pattern.

White-light interferometers overcome both of these limitations. Their optical arrangement is similar to the single-wavelength setup, but a white-light source that emits radiation over a broad range of frequencies 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-scanning interferometry. The technique uses the same optical arrangement as the Michelson interferometer, but it incorporates a laser source that is tunable over a range of laser frequencies (bandwidth >10 nm). 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.

For conventional single wavelength interferometers, the modulation frequency for all the pixels is constant, and the phase is measured to determine the changes in relative distance across the test surface. For frequency-scanning interferometry, 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.

One advantage of frequency-scanning interferometry is that the height of each pixel is obtained independently of its neighboring pixels using fast 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 20 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

The frequency scanning interferometer is comprised of two subsystems: the tunable laser source and the interferometer head. The tunable laser source is the core of the frequency scanning technology since it must generate a broad illumination bandwidth at constant frequency intervals. This was accomplished through a tunable external laser cavity design shown in Figure 2. A multiple quantum well AlGaAs semiconductor laser diode is utilized that operates in CW mode at 785 nm. This is placed in an external cavity that consists of a collimating lens and a high-pitched grating. 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 10 nm by changing the angle of the grating over approximately one degree. The zero order beam is used to couple light out of the cavity.

The length of the tunable cavity is designed 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.

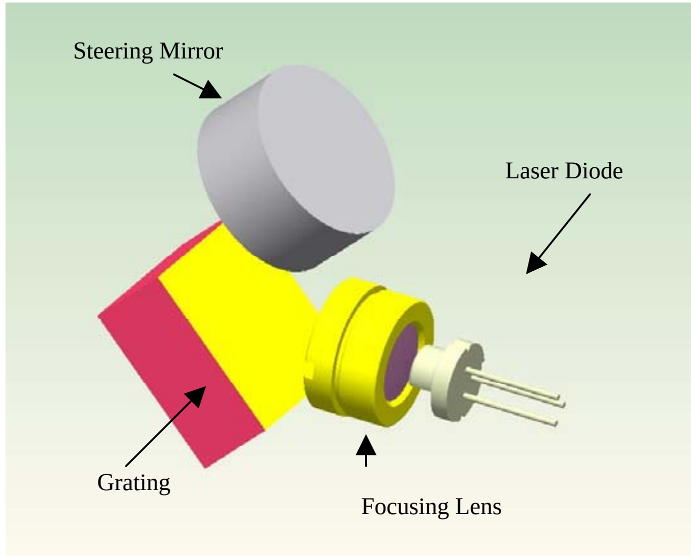



Figure 2. The tunable laser system consists of a 785 nm laser diode that is coupled into an external cavity consisting of a focusing lens and a grating. The first diffraction order of the grating is directed back into the laser diode while the zero order is directed to a steering mirror.

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. The interferometer head is already shown in Figure 1. 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.

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.

## 4.0 Sample application and measurement results

Frequency scanning interferometry offers many advantages over conventional approaches: fast measurement times, a scaleable field of view for the measurement of various part sizes, a dynamic range of tens 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.

Figure 3 displays the parameters that can be measured easily for individual component or assembly applications. Different surfaces are labeled A, B or C. The flatness of any surface – as well as the parallelism and height separation between surfaces – can be measured with submicron accuracy and repeatability. With two sensors, data may be collected simultaneously on both end faces of an object so that part thickness also can be measured.

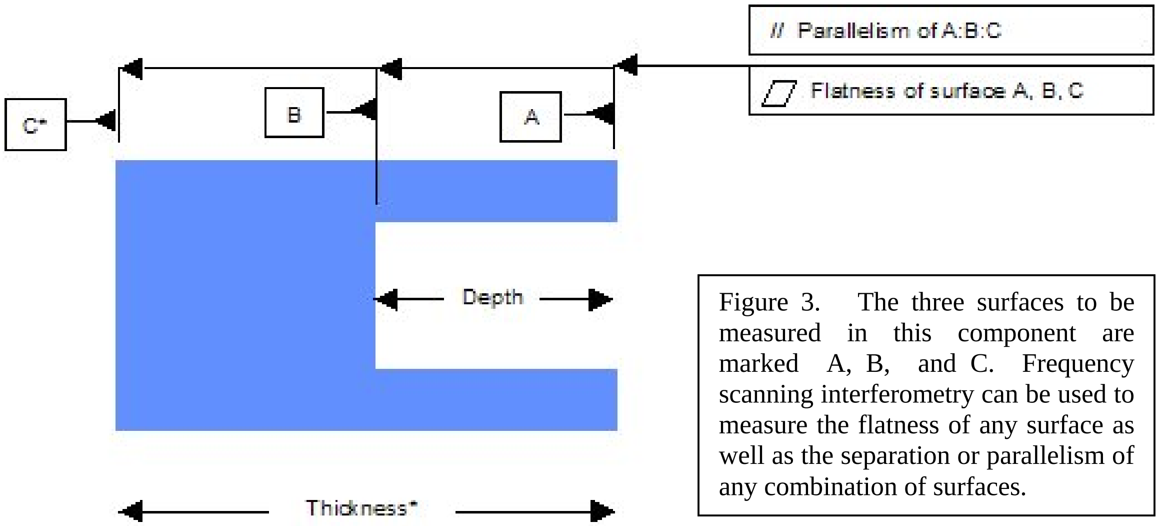
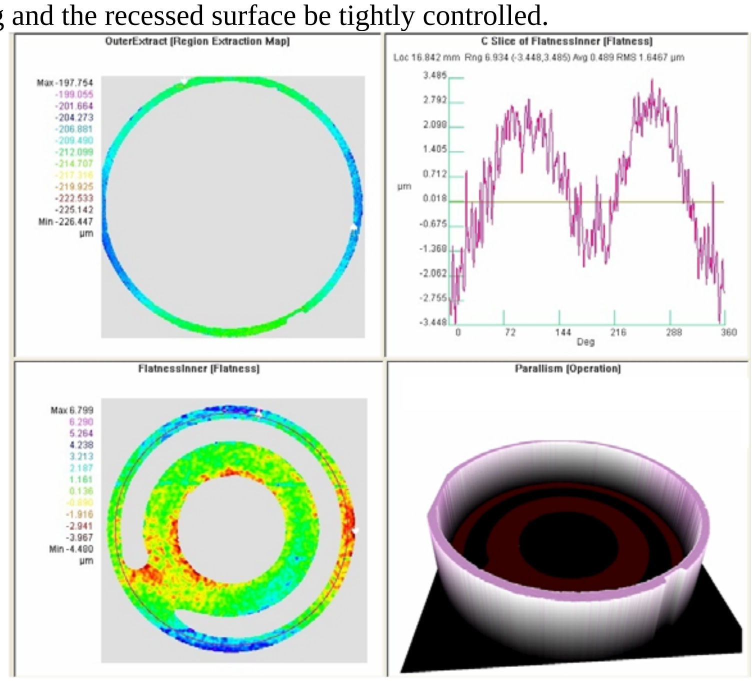



Figure 3. The three surfaces to be measured in this component are marked A, B, and C. Frequency scanning interferometry can be used to measure the flatness of any surface as well as the separation or parallelism of any combination of surfaces.

As one example of an application with this technology, Figure 4 illustrates the measurement of an automotive fuel pump component. A typical design uses an impeller to pump fuel through a cavity formed by two housing halves, one of which features a groove in the bottom to provide the fluid flow to the impeller's teeth or vanes. Proper operation requires that the flatness, parallelism and height between the outer ring and the recessed surface be tightly controlled.

Figure 4. This impeller housing (below) is a component in an automotive fuel pump. Proper operation requires accurate metrology (right) of the flatness, parallelism, and height between the outer ring and the recessed surface.




## 5.0 Conclusion

In conclusion, frequency-scanning interferometry enables a new class of metrology instrument which will greatly expand the role of optical metrology in precision manufacturing. Frequency-scanning interferometry includes the capabilities of single-wavelength interferometry and, thanks to the digital signal processing, 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.