# A laser speckle reduction system

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## ABSTRACT

Speckle degrades the contrast of the fringe patterns in laser interferometers that measure rough objects. In this paper, we describe a speckle reduction system that can be used with high speed cameras to increase the frame rates of the interferometer and creates less vibration in the system.

**Keywords:** Speckle reduction, Frequency stepping interferometry, MEMS

## 1. INTRODUCTION

Interferometers use coherent light to compare a reference wavefront to an altered wavefront. This altered wavefront carries measurement information that is decoded by evaluating an interference fringe pattern. The coherent light creates high contrast fringes between the reference and the test wavefronts, but this comes at the expense of speckle[1]. This is especially the case for interferometers that measure rough parts that scatter the light in the return wavefront. The speckle creates an objectionable noise signal, and so it is desirable to reduce the speckle contrast.

Many interferometers have effectively dealt with this problem by focusing the laser source onto a spinning diffuser disk. As the focus spot travels across the spinning diffuser, different speckle patterns are generated. If enough uncorrelated speckle is averaged into a single capture frame of the camera, then the contrast of the speckle is significantly reduced. Fleischlad was able to replace the rotating diffuser with a rotating wedge plate with the speckle and tilt term, which are both removed by averaging[2]. This method only works for an interferometer that can determine the wavefront shape, or phase, nearly instantaneously.

Frequency stepping interferometers monitor the variation of fringes as a function of wavelength from a tunable laser source. This allows for multiple surfaces to be measured simultaneously, but it can take a significant amount of time to capture all of the data. Using a faster frame rate camera can reduce the measurement time, but this requires a faster speckle busting solution. One solution is to increase the rotation speed or the diameter of the diffuser disk, but this comes with increase vibration that degrades the interferometric measurement. We have developed an alternative method that scans the beam on a diffuser rather than scanning a diffuser on a beam.

## 2. FREQUENCY STEPPING INTERFEROMETRY

Figure 1 illustrates the optical design for a frequency stepping interferometer described by Dunn[3]. A frequency tunable laser source is delivered to the optical head by an optical fiber. The fiber output is imaged onto a spinning diffuser disk. The diffuser disc is positioned at the focal point of a collimator lens. The collimated laser light is then reflected from a Fizeau surface and an object to be measured placed on top of the Fizeau. The reflected light is redirected to a CCD camera system by a beam splitter where the interference fringes can be viewed.

As the wavelength of the laser is varied, the interference fringes also vary. The fringe variation frequency depends on the distance from the object to the Fizeau. A depth map of the object can be calculated from the fringe variation frequency as compared to the wavelength variation.

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A unique speckle pattern is generated by each simultaneous position of the diffuser disk. As the disk is spun, these speckle patterns are averaged onto a single capture frame of the CCD and the speckle contrast is reduced.

This type of normal incidence interferometer can produce very high contrast fringes even when the object surface and the Fizeau surface are far apart. It is sometimes required to reduce the range of depths to be measured for certain objects. This can be done by defocusing the image of the fiber output at the diffuser disk surface, which creates effectively a larger diameter secondary source and a larger angular distribution incident on the object, thus reducing the depth of the spatial coherence at the object.

A full measurement, for an interferometer of this type, requires the tuning of the laser over some spectral region. The speed of this system is limited by the frame rate of the CCD. As the CCD frame rate is increased there is less averaging of speckle in each frame, and thus the speckle contrast increases.

We have been investigating options for increasing the frequency of uncorrelated speckle that we can illuminate the system with. We could use a faster motor or a larger diffuser disk, but this can create balancing issues causing unwanted vibration in the system.

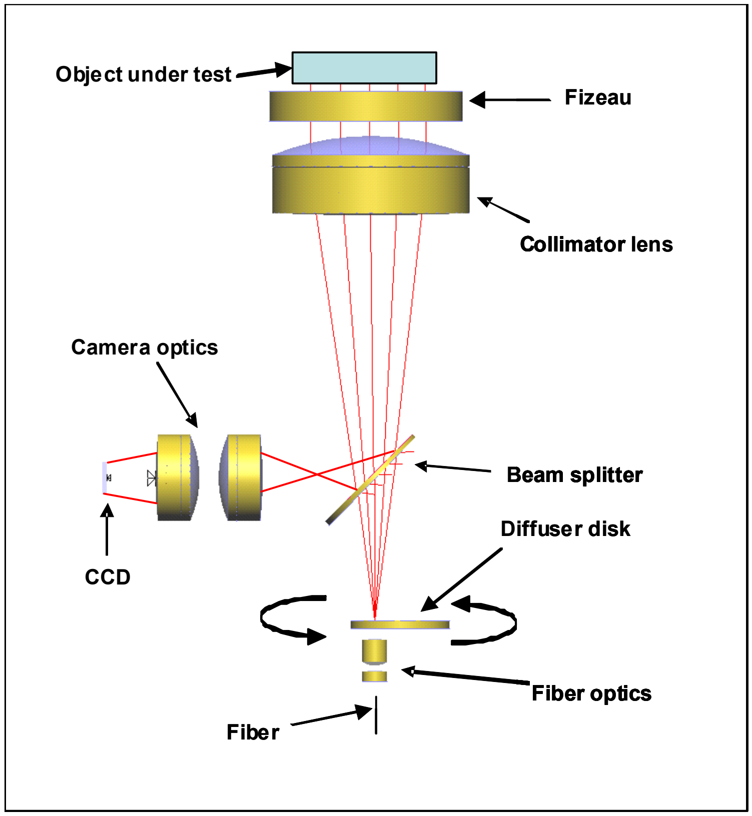


**Figure 1: Optical head for a frequency stepping interferometer**

## 3. SPECKLE BACKGROUND

Speckle is observed when coherent light is transmitted or reflected by surfaces with roughness on the scale of the wavelength. Many interferometers can avoid significant speckle by avoiding rough surfaces, unless the purpose of the interferometer is to measure rough surfaces such as unpolished IC wafers or mechanical parts.

Speckle contrast is reduced by averaging uncorrelated speckle patterns. The speckle contrast is defined by the ratio of the standard deviation over the mean of the speckle pattern's intensity distribution[4]. For commonly obtained, fully developed speckle, the contrast is 1 and the intensity follows the negative exponential probability distribution. The speckle contrast is reduced by the factor of inverse square root of the number of discrete uncorrelated speckle patterns being averaged. As an example, in the case with a polarization maintaining optical system, speckle created by two orthogonal polarizations will average and reduce the speckle contrast by $1/\mathrm{sqrt}(2) \approx 0.71$. Though this is not a significant improvement, it does have the advantage of not increasing the étendue. If a polarized beam is split, the polarization rotated in one segment and then recombined, the étendue is effectively not increased. All other methods increase the étendue with some more than others, with the exception of source spectrum manipulations. Another method, for laser beams of shorter coherence lengths, is to split the beam with beamsplitters and recombine the beam after being delayed by a loop of mirrors or prisms. If multiple delay loops are placed in series, then thousands of beams can be generated. Each of these beams needs to have a different wavefront shape in order to produce an uncorrelated speckle pattern[5]. To generated different wavefront shapes, the beams are aberrated differently in each delay line. This increases the divergence a small amount, and thus the étendue. This method does not work well for highly temporal coherent beams as used for interferometry, but is useful as an instructive example of a method speckle reduction.

A diffuser increases the étendue by the convolution of the diffusion angular distribution and the incident angular distribution. Focusing the beam on the diffuser limits the total increase to the étendue, since the spatial distribution is minimized. A diffuser made by grinding a single surface of a glass plate and followed by an acid or ion beam etching, produces effectively millions of micro-lenses of a random size, shape, focal lengths and thus NA's. It is highly efficient, maintains polarization and, as expected by the central limit theorem, will produce a Gaussian angular diffusivity distribution. When illuminated by coherent beam, the thousands of micro-lenses form foci with random NA's and positions, producing a speckle pattern in the far field. As the diffuser moves across the beam, or vice-versa, the micro-lenses on the trailing edge fall out of the illumination and new micro-lenses fall in on the leading edge, and thus altering the far field speckle pattern. How far does the beam or diffuser need to shift to produce a speckle pattern that is uncorrelated? We know that when the shift is greater than beam width, the pattern is completely uncorrelated. Goodman derives the integrals for determining the contrast as a function of shift, diffuser parameters, and following imaging relays[6, 7]. In the case of the interferometer described, the rough object under test is in the far field of the diffuser. The object is imaged to the CCD camera by the viewing arm at a higher NA than the illumination arm of the interferometer, so effectively the speckle at the object is not modified at the camera. As the diffuser and beam shifts, the phase of the speckle on the rough object surface varies, and the resultant contrast of the speckle is reduced by the averaging over the integration time of the camera. In this case, speckle is used to fight speckle. The speckle generated by the diffuser is used to vary the phase of the illumination of the rough object.

# 4. SCANNING SPECKLE REDUCERS

One method to reduce speckle involves scanning a beam on a diffuser rather than scanning the diffuser on the beam. This has been suggested by Peled[8], and Figure 2 illustrates one way to incorporate a Micro Electro-Mechanical System (MEMS) mirror into such a design. The incoming, collimated laser beam passes through a beam splitter and then through a hole in a reflective diffuser. The reflective diffuser is positioned at the front focal point of a focusing lens, and a MEMS tilting mirror is placed at the rear focal point of the focusing lens. The beam is focused onto the 2-axis tilting MEMS mirror and each axis is driven by a sine wave signal. A $\pi$ phase shift between the signals produces a circular scanning pattern. The reflected beam is then re-collimated by the focusing lens and strikes the reflective diffuser surface. The diffuse light then passes back through the lens and the resultant focus on the MEMS mirror is now blurred by the diffuser. The MEMS mirror re-directs the light back through the center of the focusing lens and through the central hole in the diffuser. The beam splitter folds the beam towards a second lens which creates an image of the light on the MEMS mirror. This image is then placed at the focal point of the collimator for the interferometer and it becomes the feed beam for the interferometer.

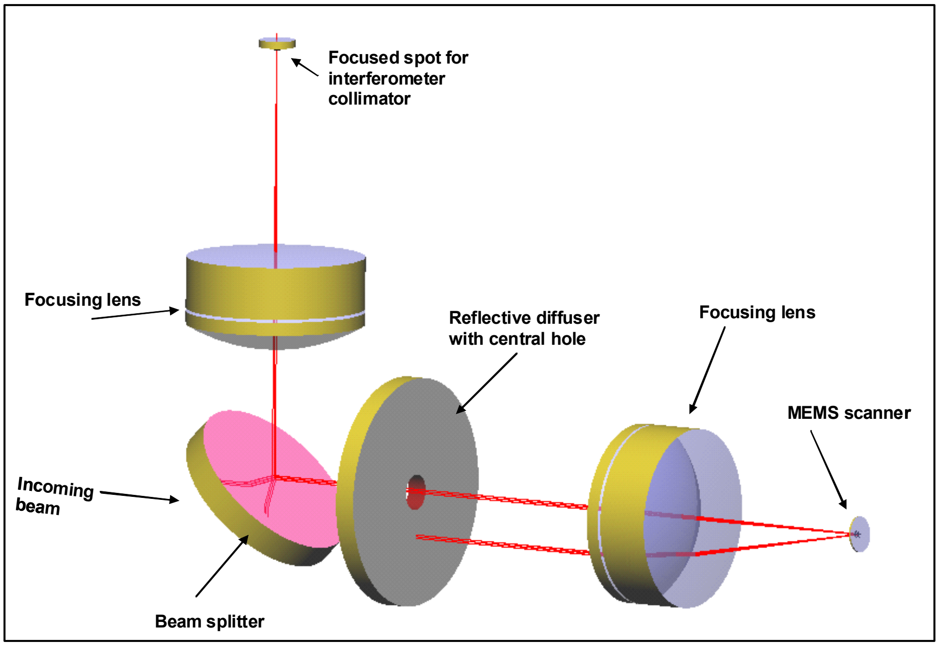


**Figure 2: MEMS speckle buster system**

As the MEMS mirror scans across the reflective diffuser, the feed beam does not change in position or average angle. The 2nd reflection off the MEMS sends the light back along the optical axis since the mirror movement is inconsequential to the speed of the light. However, the speckle pattern is varied as the beam travels over the diffuser. The étendue of the beam is increased by the diffuser and limited by the size of the MEMS mirror diameter. The size of the fill of the MEMS mirror at the 2nd reflection is the convolution of the fill at the 1st pass and the diffuser's angular distribution transformed by the focal length of the focusing lens. Focusing the beam onto the mirror at the first pass allows a larger NA from the diffuser get through the system, and thus effectively smaller features on the diffuser are working to alter the speckle pattern.

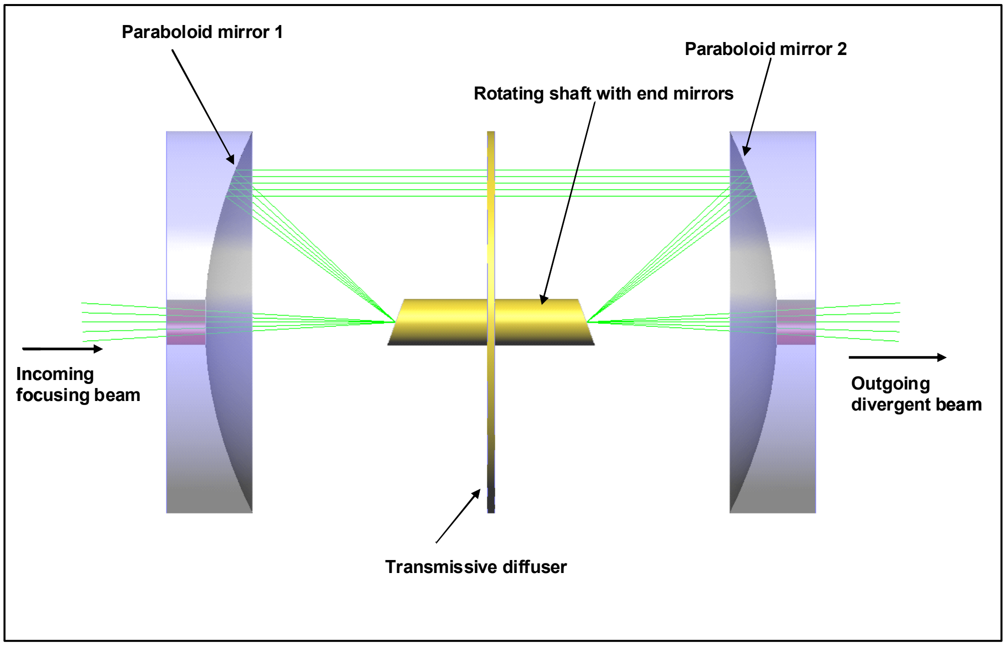


**Figure 3: Dual paraboloid system with focus at mirror face**

It should be noted that the system described has the beam focused on the mirror, and not the diffuser as shown in Figure 1. The tilting mirror and diffuser are at opposite conjugates. In either case, the spatial coherence can be adjusted with an iris at the focus of the focusing lens.

We have built a laboratory prototype using a MEMS mirror from Texas Instruments (TALP1000B). This 2 axis gimbaled mirror has a ±5 degree mechanical rotation and a mirror size of 9 $mm^2$. The typical resonance frequency of the mirror is about 130 Hz. The drive signal was supplied by an iPod through an application call IFunGen which is a stereo frequency generator. Although the idea worked well and our speckle was reduced, our calculations predicted that 130 Hz would not rotate the beam fast enough to reduce the speckle in the frame rates we were targeting. The MEMS could be replaced with a rotating shaft with a tilted end mirror. The size, shape and weight of a shaft is much less

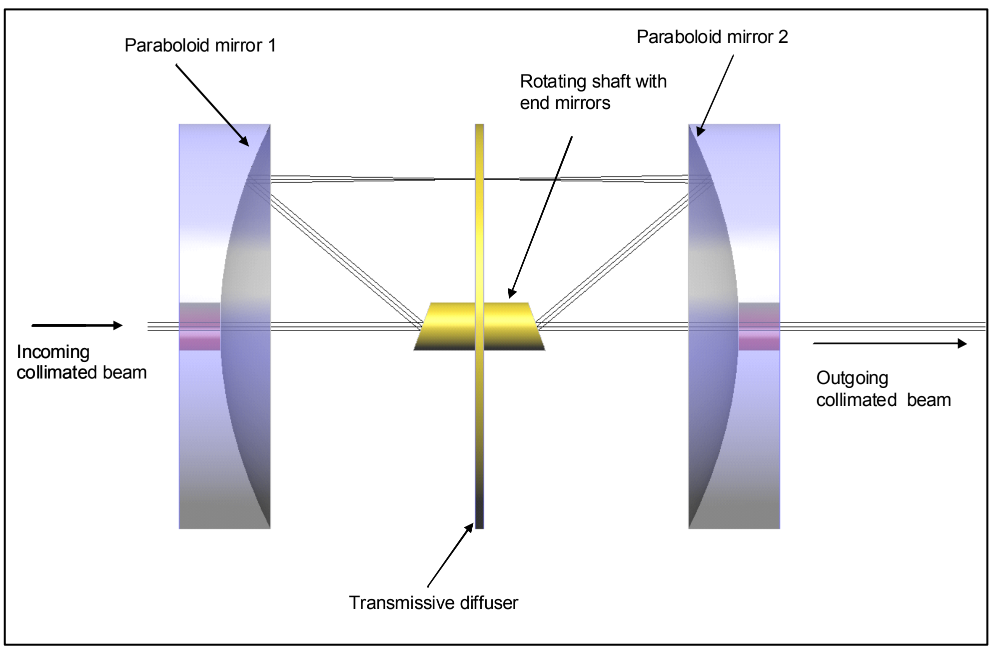


**Figure 4: Dual paraboloid system with focus at diffuser surface**

susceptible to vibration than a rotating diffuser.

Figure 3 shows another design which will allow for faster speeds of the mirror while also allows for recombining the beam without losing energy through a beam splitter. The incoming beam is focused onto the surface of a tilted mirror on a motor shaft. The mirror sits at the focal point of a paraboloid mirror. The tilted mirror reflects the beam towards the paraboloid mirror which collimates the beam. The collimated beam strikes a transmissive diffuser and is re-focused by a second paraboloid mirror onto a second tilted mirror that is on the same shaft as the first tilted mirror. The outgoing divergent beam exits the system through a hole in the second paraboloid mirror. The shaft rotates, but the diffuser is stationary. One advantage to this system is that the shaft can be rotated at a higher speed than a MEMS mirror, and is also less susceptible to vibration than a rotating diffuser.

In Figure 3, the beam is focused on the rotating mirror and the diffuser is at the opposite conjugate of the focus. Figure 4 is a variant of this system where the beam is focused onto the diffuser and collimated at the mirror. In this case, the collimated output beam would be focused to the focal point of the interferometer collimator. Figure's 3 and 4 are analogous to the system of Figure 1, where the beam can be focused on the tilting mirror, or at the opposite conjugate – the diffuser.

## 5. SUMMARY

By moving the beam across the diffuser, as opposed to rotating the diffuser, faster rates of speckle generation can be achieved with little vibration. These rates and low vibrations allow faster camera frame rates and thus faster measurements for frequency stepping interferometers. The methods presented require that the beam reflect off two synchronized mirrors or the same mirror twice. These systems can work with the beam focusing on the diffusers or the mirror, which are at opposite conjugates. One system using a tilting MEMS mirror was built and performed as predicted. Other designs using faster rotating shafts were presented.

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