Errors Caused by Nearly Parallel Optical Elements in a Laser Fizeau Interferometer Utilizing Strictly Coherent Imaging

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ABSTRACT

Most commercial laser Fizeau interferometers employ a rotating diffuser on an intermediate image plane. The image formed on this plane is relayed to the detector using incoherent imaging, eliminating potential interference effects from elements after the diffuser. Systems requiring high spatial frequency resolution cannot employ the diffuser or incoherent relay system to the degradation they cause to the system transfer function. With strictly coherent imaging, however, nearly parallel optical elements such as the CCD cover glass will produce interference fringes. Though these elements are common path, fringes will be visible in the phase measurement unless one of several specific conditions are met.

This paper explores the theory behind the formation of these fringes and examines cases where this error may be eliminated. Theoretical calculations are compared with actual measurements taken on a laser Fizeau interferometer. The errors evident in the final phase measurement may be minimized with proper coating of the system optics, sufficient wedge in the elements, or removal of the nearly parallel elements from the system.

Keywords: Interferometry, Coherent Imaging, Fixed Pattern Effects

1. INTRODUCTION

Conventional laser Fizeau interferometers are used primarily for low frequency surface figure measurements. Typically, Zernike coefficients or other figures of merit are used for evaluating the optics, since such errors are most crucial the geometric performance of the system. In these systems, a rotating diffuser in an intermediate image plane is usually employed. The image formed on the diffuser is then relayed incoherently to the CCD array, often by a commercial zoom lens that allows parts of varying sizes to be tested. While the incoherent relay system eliminates potential interference effects from both the zoom lens and elements within the CCD camera, the combination of the rotating diffuser and zoom lens drastically reduce the system transfer function.

For some systems this reduction in the system transfer function is unacceptable. For instance, the optics for use in the high powered National Ignition Facility laser must be free of surface errors with periods from 33mm down to .12 mm. The large size of many of the optics (600 mm clear aperture) and the desire to measure larger areas of the parts at one time necessitate an interferometer with high system transfer function. The interferometer specifications require greater than a 60% transfer function at half the Nyquist frequency. In order to achieve this requirement, the rotating diffuser and zoom system must be eliminated and strictly coherent imaging employed.

Without the rotating diffuser, a nearly parallel optical element inserted into the beam path may cause the detector to see light from multiple beams. Most CCD cameras contain a protective outer cover glass, which could cause such multiple beams. Figure 1 demonstrates how four different beams originating from the object could be incident on the final CCD plane. Similarly, four additional beams are possible from the reference surface. It is important for accurate measurements that the combination of these multiple beams not introduce artifacts into the calculated surface height of the test object. This paper will explore the formation of such artifacts and will suggest ways of reducing or eliminating them from the final measurement.

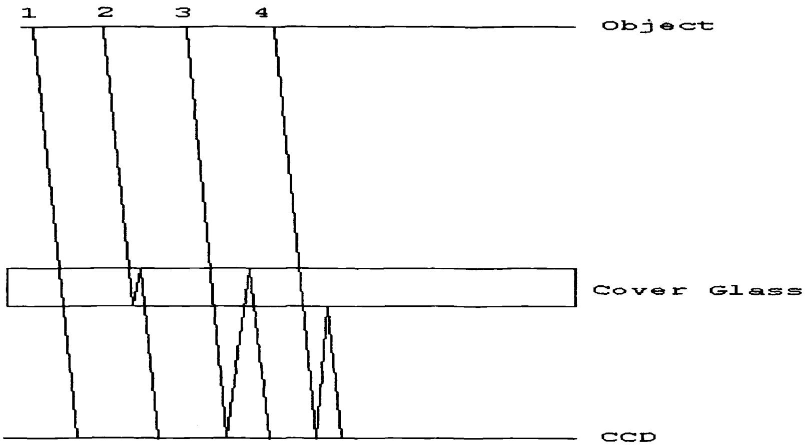

Figure 1: Four possible beams incident on the final image plane due to reflections off the cover glass. Generally very little light is reflected from the CCD array so only beams 1 and 2 are significant.

2. FORMATION OF FIXED PATTERN ERRORS

Typically very little light is reflected off of the CCD array of a commercial camera back into the system. This is due both to AR coating of the array and grating effects from the array. Thus beams 1 and 2 from Figure 1 are typically much stronger than beams 3 and 4. Therefore, beams 3 and 4 will be ignored in this analysis. For modeling purposes, one may therefore consider only two beams from the reference surface and two beams from the test surface.

We may model the system using the following four beams:

$$\begin{aligned}\vec{R} &= R\cdot\exp[i(k_1x+\eta)]\\ \vec{r} &= r\cdot\exp[i(k_2x+\phi_c+\eta)]\\ \vec{T} &= T\cdot\exp[i(k_3x+\phi)]\\ \vec{t} &= t\cdot\exp[i(k_4x+\phi+\phi_c+\Delta)]\end{aligned} \tag{1}$$

In the above equation, the first terms on the right are the amplitudes of the reference, reflected reference, test, and reflected test beams, and k_i the propagation constants of the beams. Also, η is the phase shift introduced by the interferometer PZT, ϕ_c the phase introduced in the reference beam by the differences in the cover glass surface from a plane, ϕ the phase delay between the test and reference beams, and Δ the difference in additional phase between test and reference beams due to tilt between the two. If the reference and test beams are parallel, Δ is zero.

The four terms above may be added together and this sum multiplied by its complex conjugate to get the final intensity in the image plane.[1] The term containing rt is ignored due to its low amplitude. In addition, terms with coefficients r^2, t^2, tT, and rR, which do not contain η, and thus do not change with phase shift of the interferometer, may combined into a single constant term. This leads to the following equation.

$$\begin{aligned}I &= C+2RT\cos[(k_3-k_1)x+\phi-\eta]\\ &+2rT\cos[(k_3-k_2)x+\phi-\phi_c-\eta]\\ &+2Rt\cos[(k_4-k_1)x+\phi+\phi_c+\Delta-\eta]\end{aligned} \tag{2}$$

In general, the last two terms above may cause fixed pattern effects to occur in the final phase measurement. The calculated phase at each point will contain spatially dependent contributions due to the different factors in front of the x terms. The final calculated phase of the surface will in general reflect these phase variations and fixed pattern fringes will be observed in the measurement.

Figure 2 below shows a measurement with fixed pattern effects due to a cover glass located in front of the CCD array. Although the measured part was a high quality flat, it appears that it has an approximately 15nm sinusoidal error across the surface. This sinusoidal error will be different for different amounts of tilt between the test and reference beams, and in certain situations may be eliminated from the measurement.

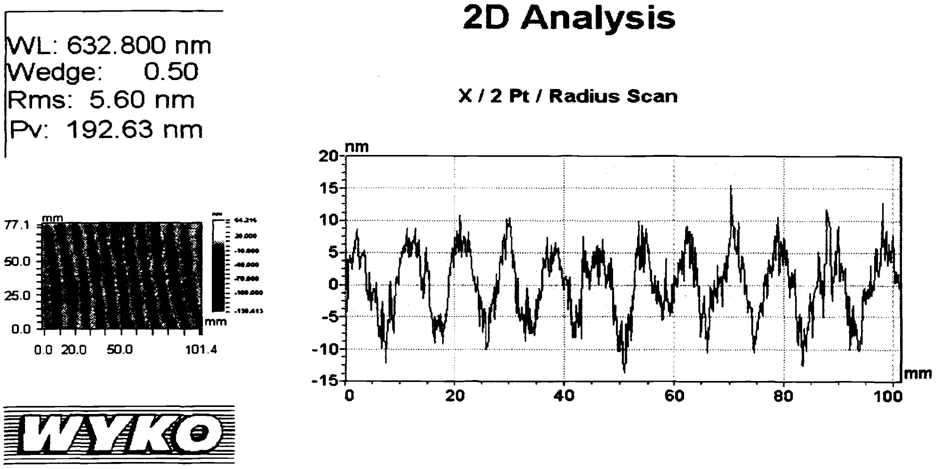
WL: 632.800 nm
Wedge: 0.50
Rms: 5.60 nm
Pv: 192.63 nm

Figure 2: Measurement of a high quality flat where fixed pattern effects due to camera cover glass are evident. For this case, the surface appears to have a 15nm peak to valley sinusoidal variation across it.

Several special cases of the above equation 2 may be studied to lend insight into when these errors may be eliminated. The first situation studied is that in which the cover glass has no wedge, such that $k_1=k_2$ and $k_3=k_4$. For this case, the above equation becomes:

$$\begin{aligned} I &= C + 2RT\cos[(k_3-k_1)x+\phi-\eta] \\ &+ 2rT\cos[(k_3-k_1)x+\phi-\phi_c-\eta] \\ &+ 2Rt\cos[(k_3-k_1)x+\phi+\phi_c+\Delta-\eta] \end{aligned} \tag{3}$$

In this expression, each of the terms merely has a constant phase added to the phase shifting term, with a constant tilt in the contribution of each term with respect to x. Although the base phase of the measurement will be different than if the cover glass were not present, this only adds a piston term to the phase calculation. No fixed pattern fringes will be observed for this case.

The second case occurs when the reference and test beams are perfectly parallel. For this case, k_1=k_3, k_2=k_4, and Δ is zero. The intensity equation becomes:

$$\begin{aligned} I &= C + 2RT\cos(\phi - \eta) + 2rT\cos((k_1 - k_2)x + \phi - \phi_c - \eta) + 2Rt\cos((k_2 - k_1)x + \phi + \phi_c - \eta) \\ &= C + 2RT\cos(\phi - \eta) + 2rT\cos(\phi - \eta + \xi(x)) + 2Rt\cos(\phi - \eta - \xi(x)) \end{aligned} \tag{4}$$

In this situation, the final two terms will introduce equal and opposite contributions to the phase of the final beam. Whether or not the cover glass has wedge, no fixed pattern fringes will occur in the final phase calculation. Measurements taken on a coherent laser Fizeau system with a high quality return and test flat confirm that when tilt between the beams is eliminated, no fixed pattern effects are observed.

The final case where fixed pattern effects become negligible occurs for k_3-k_2=k_4-k_1;, and Δ=mπ-2ϕ_c, where m is any odd integer. Unfortunately, this condition will not necessarily occur over the entire field since ϕ_c may vary with x. However, if ϕ_c is sufficiently small or is slowly varying it may be neglected or the above condition assumed to hold across the entire field. The intensity is now:

$$\begin{aligned} I &= C + 2RT\cos[(k_3 - k_1)x + \phi - \eta] \\ &+ 2rT\cos[(k_3 - k_2)x + \phi - \phi_c - \eta] \\ &+ 2Rt\cos[(k_3 - k_2)x + \phi - \phi_c + \pi - \eta] \\ I &= C + 2RT\cos[(k_3 - k_1)x + \phi - \eta] + 2rT\cos(\delta) - 2Rt\cos(\delta) \\ I &= C + 2RT\cos[(k_3 - k_1)x + \phi - \eta] \end{aligned} \tag{5}$$

This is just the basic phase shifting equation[2] and once again no fixed pattern effects should appear in the measurement. System measurements again confirm this result, although if a poor quality test flat is used the required matching conditions do not hold over the field. Certain areas of the measurement will therefore exhibit fixed pattern effects.

3. ELIMINATION OF FIXED PATTERN ERRORS

Unfortunately, there is no guarantee that any of the above three cases may be met for a given measurement. Some wedge in the camera cover glass is mostly unavoidable. In addition, unless one is testing a perfect flat there is no way that the object and test beams will be perfectly parallel or angled such that the third condition above is met over the entire field. Fixed pattern errors will therefore almost certainly appear in the measurement unless steps are taken to eliminate them.

There are only a few viable solutions to eliminate such errors from the measurements. The first would be to coat the camera cover glass with a high quality AR coating. For high quality phase measurements, however, the potential phase error should not exceed a tenth of a nanometer. Computer simulations of fixed pattern effects show that in order for this error level to be achieved, the cover glass would have to be coated to .05% reflectance. While such a coating may be obtained, the added cost of obtaining such a coating may make this option undesirable for certain situations.

Another solution to the problem would involve introducing wedge into the cover glass. With enough wedge, any potential phase variations will be of too high a frequency to be detected by the measurement. The camera used for the NIF project has approximately 1000 pixels and is 10mm square. Assume at least 5 fringes across each pixel are desired to avoid any possibility of detecting fixed pattern effects. Each pixel is only 10μm in size, and to have five fringes across the pixel would require a wedge angle of roughly 10 degrees assuming 632.8nm light. This angle is too large to be practical for most situations. Therefore, this solution is unacceptable.

An obvious solution is to merely remove the cover glass from the camera. While this may not be possible for systems where the cover glass is required for protection, systems utilizing strictly coherent imaging are generally sealed from the environment. Since dust on any of the system optics including the camera cover glass may cause diffraction effects in the measurement, the systems must be kept free from any contamination. Thus, the sealed system itself should protect the camera and removing the camera cover glass will generally not result in any risk of damage to the array. Without the cover glass in place, there is no chance that poor coatings or insufficient wedge angle will allow residual fixed pattern effects into the measurement.

4. CONCLUSIONS

For systems employing strictly coherent imaging, fixed pattern effects due to the protective cover glass used with most CCD cameras may introduce phase errors into the measurement. Keeping the reference and test beams parallel, eliminating any wedge in the cover glass, or certain angles between the test and reference beams will eliminate this error. However, if the part being measured is not perfectly flat, these fixed pattern errors will occur across certain portions of the field. Using a highly wedged cover glass will eliminate these errors. However, the wedge required is impractical. Properly AR coating the cover glass will also reduce these errors to below the noise level of the system. The AR coating must be quite good, but can be obtained and allows further protection of the CCD array from its environment. Since the system of interest will be sealed from the outside environment to prevent dust from contaminating the optics, elimination of the cover glass remains an option as well. This prevents any possibility of fixed pattern errors from that element causing measurement errors through the simple expedient of removing the problem element.

5. REFERENCES

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