Implement of Digital Moiré technique on DSP for alignment of partial compensation interferometer

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Abstract. Digital Moiré technique is adopted in partial compensation interferometer (PCI) for high-precision testing of figure error of the aspheric surfaces. The figure error of the measured aspheric is obtained by a series of calculation with the real interferogram and ideal interferograms generated by computer. The dense interference fringes at the exit pupil make it difficult to align the PCI. On the contrary, digital Moiré fringes composed from real and ideal interferograms are sparse and corresponding to the figure error of the measured aspheric, making it easier to align the PCI. Generally, digital Moiré technique is processed on the computer, resulting in slow processing speed and difficult display in real time. Digital Signal Processor (DSP) can be used to implement digital Moiré technique and display digital Moiré fringes in real time with its powerful processing capacity. In this paper, digital Moiré technique is implemented on the TMS320C6455 DSP. The hardware system consists of a DSP module, a CCD camera and a monitor. Finally we experimentally obtain the digital Moiré image, and further analyze how to align the PCI theoretically.

1. Introduction

Digital Moiré technique is used in partial compensation interferometer (PCI) for the testing of aspheric surfaces\textsuperscript{[1,2]}. The figure error of the measured aspheric surface is obtained by a series of calculation with the real interferogram and ideal interferograms generated by computer. Usually, we monitor the interference fringes to align the PCI. However, PCI is in non-null configuration, generating dense interference fringes at the exit pupil. It’s hard to align the PCI. Digital Moiré fringes composed of real and ideal interferograms are sparse and corresponding to the figure error of the measured aspheric surface, making it easier to align the PCI. Thus, real-time composition and display of the digital Moiré image is of great significance for interferometer alignment and high-precision measurement. The process of obtaining the digital Moiré image is called digital Moiré composition.

Generally, digital Moiré composition is processed on computer. It will take up the operation capacity of the CPU, resulting in slow processing speed. In order to realize display in real time, Digital Signal Processor (DSP) can be used to implement digital Moiré composition and display in high speed with its powerful processing capacity. The TMS320C6455 DSPs developed by Texas Instrument are the highest-performance fixed-point DSP generation in the C6000 DSP platform. With performance of up to 9600 million instructions per second(MIPS) at a 1.2GHz clock rate, the C6455 offers cost-
effective solutions to high-performance DSP programming\textsuperscript{[3]}. It is an excellent choice for digital Moiré composition algorithm which includes large amount of multiplication and addition operations.

In this paper, we implement digital Moiré technique on TMS320C6455 DSP, experimentally obtain the digital Moiré image, and further analyze how to align the PCI according to the digital Moiré image theoretically.

2. Principle

2.1. Principle of PCI

A partial compensation lens of PCI partially compensates the large spherical aberration yield by the measured aspheric surface. Unlike null compensation interferometer, PCI transforms the aspheric wavefront into residual wavefront, not planar nor spherical wavefront. The magnitude of residual wavefront is limited by the spatial resolution of the camera used for capturing the interference fringes\textsuperscript{[4]}.

Figure 1 shows the principle of PCI. We have two sets of interferometers. Set1 is the computer-simulated virtual PCI consisting of a virtual Fizeau-type interferometer, a partial compensator(PC)\textsuperscript{[5]} and an aspheric surface, the parameters of which are all nominal. We can get virtual interferograms with intensity distribution $I_V$ corresponding to residual wavefront of $W_V$ from Set1. Set2 is the real experimental PCI, which has the same structure with Set1 except that all elements are with errors. We can get real interferograms with intensity distribution $I_R$.

![Figure 1. Principle of partial compensation interferometry](image)

2.2. Principle of Digital Moiré technique

Two frames of interferograms are obtained with PCI. The real interferogram contains the information of real measured aspheric surface and the virtual interferogram generated by computer contains the information of virtual measured aspheric surface. Digital Moiré technique provides a way calculating the deviation between the standard aspheric surface and measured aspheric surface. The figure error of the measured aspheric surface can be calculated by digital phase-shifting of the Moiré image which is discussed in Refs. \textsuperscript{[6]} and \textsuperscript{[7]}. The principle of digital Moiré technique is as follows.

\begin{align}
I_V &= I_1(x, y)\{1 + \cos[2\pi f_V x + \delta_V(x, y)]\} \\
I_R &= I_2(x, y)\{1 + \cos[2\pi f_R x + \delta_R(x, y)]\}
\end{align}

Equation (1) describes the ideal interferogram with intensity distribution $I_V$. $I_1$ is the direct current component of intensity distribution. $\delta_V(x, y)$ is the residual wavefront after partially compensating. Spatial carrier frequency $f_V$ is added in simulation software for frequency filtering. Equation (2) is similar to equation (1). $I_R$ is the light intensity distribution of the real interferogram. $I_2$ is the direct...
current component and $\delta R(x,y)$ is the real residual wavefront in the real PCI after partially compensating. $f_R$ is real spatial frequency controlled by the tilt of the mirror.

The intensity distribution of Moiré image calculated by multiplication of $I_R$ and $I_V$ is shown in equation (3).

$$I_{mw}(x, y) = I_R(x, y) I_V(x, y)$$

$$= I_R I_I(x, y) + I_R I_v(x, y) \cos[2\pi f_R x + \delta s(x, y)]$$

$$+ I_I I_I(x, y) \cos[2\pi f_V x + \delta v(x, y)]$$

$$+ \frac{1}{2} I_I I_I(x, y) \cos[2\pi (f_R + f_V)x + \delta s(x, y) + \delta v(x, y)]$$

$$+ \frac{1}{2} I_R I_I(x, y) \cos[2\pi (f_R - f_V)x + \delta s(x, y) - \delta v(x, y)]$$

Equation (3) shows that the light intensity distribution of digital Moiré image generates two new frequencies. $f_R + f_V$ is the sum frequency and $f_R - f_V$ is the difference frequency. The difference between real and ideal residual wavefront $\delta R(x,y)$- $\delta V(x,y)$ is related to the figure error of the measured surface, so the item with difference frequency is the target of the measurement. Because sum frequency leads to dense fringes which is difficult to observe while difference frequency leads to sparse fringes, we need to use low-pass filter to remove the sum frequency and obtain the difference frequency at the same time. We get the final intensity distribution of digital Moiré image shown as in equation (4).

$$I_{mw}(x, y) = I_R I_I(x, y)$$

$$+ \frac{1}{2} I_R I_I(x, y) \cos[2\pi (f_R - f_V)x + \delta s(x, y) - \delta v(x, y)]$$

$$= a(x, y) + b(x, y) \cos[2\pi (f_R - f_V)x + \delta s(x, y) - \delta v(x, y)]$$

Equation (4) shows that the light intensity distribution of digital Moiré image only contains difference frequency component, also making it an easier way to monitor and align the PCI.

3. Implement of digital Moiré technique on DSP

According to the principle of digital Moiré technique, we can get the algorithm flow chart on DSP as shown in figure 2.

**Figure 2.** Flow chart of the digital Moiré technique on DSP

All the PCI sets are simulated in Zemax, including the real set2. We transmit the residual wavefront data on the exit pupil of the interferometer from Zemax to DSP to generate two interferograms: one is ideal, and the other is with figure error. The image resolution is 256 pixel × 256 pixel. We set the carrier frequency $f_V=0.35\lambda$/pixel to guarantee that there are 90 fringes in the field of view. $f_R$ is set the same as $f_V$. Figure 3(a) shows the ideal interferogram and figure 3(b) shows the real interferogram with figure error. We multiplied the intensity of each corresponding pixel in these two interferograms to
obtain an new image called point multiplication image shown as in figure 3(c). The light intensity distribution of point multiplication image is showed in equation (3).

\[ H(u,v) = \frac{1}{1+[D(u,v)/D_0]^{2n}} \]

where \( D(u,v) \) is the distance from point \((u,v)\) to the center of the frequency rectangle. It should be noted that the carrier frequency controlled by tilt should be suitable to separate the fundamental frequency and difference frequency. After low-pass filtering in frequency domain we need to transform the image from the frequency domain back to the spatial domain. Inverse Fast Fourier Transform(IFFT) is implemented and we extend it to two-dimensional IFFT(IFFT2) on DSP. Figure 5 shows the result of applying the BLPF of equation (5) with \( n=3 \) and \( D_0=15 \) and IFFT2 method.
4. The result of experiment and analysis of PCI alignment

4.1. The result of simulation experiment
With various figure error added to the measured surface, such as spherical, defocus, coma, astigmatism, we obtain different kinds of digital Moiré images by implementing digital Moiré technique on DSP. The digital Moiré technique efficiently transforms dense interference fringes into sparse digital Moiré fringes. Along with some surface figure errors changing, digital Moiré images also make the corresponding changes as shown in figure 6. Figure 6(a) is with spherical and defocus. Figure 6(b) is with 0º and 90º astigmatism. Figure 6(c) is with -45º and 45º astigmatism and figure 6(d) is with coma.

![Figure 6](image)

**Figure 6.** Digital Moiré images with corresponding surface figure error

4.2. Analysis of PCI alignment
Figure 7 is the hardware system chart of a PCI system adopting digital Moiré technique for alignment. It includes a real experimental PCI, an image transmission and processing system and a monitor. The system captures real interferograms generated by PCI by the CCD camera and transmits them to the DSP first. Then DSP receives the ideal interferogram image from the PC and implements digital Moiré technique. Finally digital Moiré images are sent to the monitor for observing.
It is difficult to calculate the surface figure error directly from the original dense interference fringes even if the interferometer is in good alignment. However, digital Moiré fringes are sparse enough to calculate the figure error of the measured aspheric surface, and make it easier to align the PCI. In the process of alignment of the PCI, defocus and coaxiality are the key influencing factors. We simulate these two factors in Zemax and obtain the digital Moiré images by implementing digital Moiré technique on DSP. Figure 8(a) shows that defocus introduces defocus and spherical aberration and figure 8(b) shows that coaxiality introduces asymmetric aberration in the digital Moiré images.

![Digital Moiré images with defocus and coaxiality](image.png)

**Figure.8** Digital Moiré images with defocus and coaxiality

We turn the screw in the optical mount of PCI to adjust defocus and coaxiality of the measured surface by monitoring the change of digital Moiré fringes to align the PCI. The aberration introduced by the misalignment will gradually change when defocus and misalignment are introduced to the PCI. In the process of alignment, when the digital Moiré fringes on the monitor become the sparsest which indicates that the spherical and asymmetric aberrations are the smallest, the PCI is set to the optimal measurement position.

5. Conclusions

We implement digital Moiré technique on the TMS320C6455 DSP in high speed, and finally we experimentally obtain different kinds of digital Moiré images with corresponding surface figure error, and further analyze how to align the PCI theoretically. It is of great significance for the interferometer alignment and high-precision measurement and lays the foundation for the system of real-time composition and display of the digital Moiré image.

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