Ultra-high-resolution optical monitoring system using a noise cancellation technique

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Abstract. The feasibility of using bi-detectors or quad-detectors for ultra-high-resolution position-monitoring systems is explored. Factors that can affect the resolution of this kind of detection system are examined. We find that one of the major limiting factors is the shifting of the laser beam. A noise cancellation technique is developed successfully to suppress this noise. Using this noise cancellation system together with a thermally compensated laser and a pinhole spatial filter in a temperature- and vibration-controlled environment, the feasibility of ultrahigh resolution ($<20 \text{ \AA}$) for displacement monitoring is demonstrated using off-the-shelf components. © 1997 Society of Photo-Optical Instrumentation Engineers. [S0091-3286(97)00712-5]

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1 Introduction

There are many applications in which very precise noncontact displacement measurements are needed. Traditionally, noncontact techniques such as an optical interferometer are used^{1,2} for such purposes. The resolution of optical interferometers is determined by how well one can interpolate between the fringes, and 1/10 to 1/20 of a wavelength of resolution can be achieved by this kind of device. One characteristic of optical interferometers is that they measure the displacement in the direction of the optical axis of the system.

To measure lateral displacements perpendicular to the beam axis, position-sensitive detectors (PSDs) such as four-quadrant detectors and lateral effect photodiodes^{3,4} (LEPs) are commonly used. For example, high-resolution lateral-displacement-sensing methods were reported by Makynen et al.⁵ and by Takamasu et al.⁶ Besides the capability of measuring the lateral displacement, there are some interesting characteristics of monitoring systems using PSDs. Instead of monitoring different optical fringes, as with optical interferometers, PSDs are relatively simple and easy to use. Furthermore, instead of depending on counting fringes that are related to the wavelength of the optical source, PSDs rely on the change of location of the image on the detector. The resolution depends on the sensitivity of the movement of the image on the detector and the level of the noise in the system. Therefore there is a possibility that position-sensing systems using PSDs can achieve higher resolution than the optical interferometer technique. In fact, Takamasu et al. have reported system resolution as high as 10 nm using a spherical reflector as a target.

Both the systems by Makynen et al.⁵ and by Takamasu et al.⁶ measured only the two lateral displacements perpendicular to the beam axis. Recently, another position-monitoring using PSDs was proposed by Lee et al.⁷ that can simultaneously monitor not only the lateral displacement perpendicular to beam axis but also the displacement

along the beam axis. Furthermore it can measure all three rotational displacements. This system has been used successfully for the study of alignment precision of a mechanical alignment system.⁸ The preliminary setup of this system⁷ has a resolution better than 50 nm and angular resolution better than $0.25 \mu\text{rad}$. While this level of resolution is adequate for many applications, for example, it can be used to calibrate submicrometer-level instruments, nevertheless it is interesting to explore and to improve the resolution of this system. That is the objective of this paper.

In our investigation, we have found that the effects of background electronics noise and the background room lighting noise can be readily kept below the equivalent of the 1- to 2- $\text{\AA}$ level. However, there are many factors that can affect the resolution of the system. In Sec. 2, we discuss how various factors such as optical design, vibrations, detector saturation effects, and geometry of the quad-detectors can affect the resolution of the system. After we optimized our system, we established that one of the major limiting factors that determine the resolution of the system was the shifting of the laser beam. To solve this noise problem, a new noise cancellation system has been successfully developed, and the principle of this noise cancellation system is discussed in Sec. 3. In Sec. 4, results of the noise cancellation system are presented. Based on our data, we demonstrate that it is possible to achieve resolution below 20 $\text{\AA}$ using off-the-shelf components.

2 Factors Affecting the Resolution of the System

Multiple prisms with different orientation were used for our multidimensional displacement-monitoring system.⁷ The system was somewhat involved, but it can be broken into its simplest building blocks, as shown in Fig. 1. In this arrangement, a prism p is attached to a workpiece. A collimated laser beam going through a lens is reflected by prism p . The reflected beam is then incident on a quad-

Fig. 1 Original optical monitoring system.

detector, which is at the focal point of the lens. Any displacement of the workpiece will change the orientation and/or the lateral position of the prism that reflected the laser beam. This will cause the laser beam to move across the quad-detector. The principle of position detection by laser beam movements across a quad-detector is well known.⁹ For example, if the laser beam moves from the left to right across the center of the quad-detector, the output signal of the right-side detectors will increase while, the output from the left side of the quad-detectors will decrease. The differential output of the left-side detectors minus the right-side detectors will decrease as the laser beam moves across the detector from left to right.

There are many factors that can affect the resolution of the displacement of the workpiece based on this type of optical arrangement. These are discussed later. A few of the factors have already been discussed,⁷ however, for the completeness of this paper, we update and include them in our discussion.

2.1 Background Electrical and Lighting Noise

To achieve very high levels of resolution, we first must ensure that the background noise levels can be supported by such a system. Our optical system is setup inside a class 1000 clean room. The walls of our class 1000 clean room are made of sheet metal, which may act as a shield for electrical noises. The electrical noise is calculated from the detector readings with the quad-detectors blocked off to disallow any light entering it. The readings are composed of the dead current and the electrical noise, respectively, the mean and the standard deviation. The electrical noise was of the order of 50 μV .

Another potential source of noise is due to fluctuations in ambient lighting. We measured noise level under no light (setup was enclosed in a black box), dim (clean room light-

Fig. 2 Sensitivities and measured beam sizes with different focal lengths.

ing switched off, but ambient light present), and bright room light conditions. Under each of these conditions, the noise level remained insignificant.

Therefore the total background noise, including the electrical and lighting noise, contributed to the position sensing uncertainty of our detector by about 50 μV . This noise level, as we discuss below, corresponds roughly to about 1 to 2 $\text{\AA}$.

2.2 Laser Beam Spot Size on the Detector

From a simple geometric consideration, the sensitivity of our system should be roughly inversely proportional to the laser beam spot size on the detector, because, for a given displacement of the laser beam, a smaller laser beam will generate a larger signal (since a proportionally larger portion of the beam will move from one side of the detector to other side).

As shown in Table 1 and Fig. 2, the sensitivity curve and measured beam size curve correlated well with each other. As the laser spot size on the quad-detector depends on the numerical aperture (NA) of the focusing lens, the sensitivity increases as the focal length of the lens decreases. This is the case for focal lengths ranging from 40 to 15 cm. For a less than 15-cm-focal-length lens, another factor, saturation of the detector, dominates, and the sensitivity no longer improves.

2.3 Power Saturation Effect on the Detector

At low power levels, the differential output signal of the detector increases with the laser power. However, when the laser power is increased beyond a certain level, the detector signal plateaus due to saturation. Since the laser beam has a

Table 1 Effect of focal length on beam size, sensitivity, noise, and resolution.

Lens	40 cm	30 cm	25 cm	15 cm	10 cm
Theoretical beam size (μm)	17.2	12.9	10.74	6.46	4.3
Experimental beam size (μm)	24.5	22	20.2	16.1	18.9
Sensitivity ($\text{V}/\mu\text{m}$)	0.335	0.344	0.366	0.464	0.448
Noise (V)	0.036	0.032	0.027	0.022	0.009
Resolution (μm)	0.108	0.092	0.072	0.048	0.021

Fig. 3 Relationship between sensitivity and laser power level.

Gaussian intensity distribution, the central portion of beam causes saturation first, and thus the laser beam is effectively broadened. Therefore, as shown in Fig. 3, the sensitivity first increases with the input power of the laser until it reaches a plateau, then the sensitivity begins to decrease due to the saturation of the detector. Note that this nonlinear effect depends on intensity and not the total power of the laser beam. For a small focus spot, the detector will be saturated at a lower power.

It is interesting to note that while saturation has a negative effect on the sensitivity, it also helps to suppress the noise level of the system. We have found that the optimum level of operation is when the detector is slightly saturated. As seen in Table 1, the best sensitivity was achieved using a 15-cm-focal-length lens. However, the best resolution was achieved using an even shorter focal length lens.

2.4 Effect of Vibrations

At very high levels of resolution, vibration can be an important source of noise. Our experiment was set up on a vibration-isolated air cushion table. Furthermore, since the setup is inside a clean room, there is a considerable air current flowing across our instruments. We found that the air currents can affect the performance of the system. To minimize the effect of such mechanical vibrations, all the components of the instruments should be firmly secured. In particular, the wiring leading to the quad-detector, which was suspended in the air, was very susceptible to the disturbance due to air currents and vibrations. It is interesting to note that one simple way to suppress this air current was to drape a curtain around the table. As shown in Table 2, we achieved approximately a 4× improvement on the average noise levels in our system by using the curtain. This experiment was performed with a 25-cm-focal-length lens.

2.5 Thermal Effects

Our clean room is temperature controlled to within $\pm 0.4^\circ\text{C}$. As discussed in our previous work,⁷ we saw some thermal drift in our optical system. The drifting matched well with the fluctuations in the room temperature, which was periodic in nature. In general, the thermal drift is relatively slow. Furthermore, thermal drift can be extrapolated. For our application, we took thermal drift data in between

Table 2 Effect of curtain on the noise level.

Time	Signal (V)	Noise (V)	Average Noise (V)
Without curtain	1.7638	0.0421	0.0338
	1.7740	0.0276	
	1.7540	0.0317	
	2.0360	0.0738	0.0462
	2.0920	0.0434	
With curtain	2.1040	0.0215	0.0094
	1.5303	0.0085	
	1.5380	0.0141	
	1.6428	0.0057	0.0100
	1.6503	0.0093	
After 10 min	1.6545	0.0131	0.0100
	1.6800	0.0075	

each displacement measurement. In this way we substantially reduced the effect due to thermal drift. For the development of a more practical system, one may consider a somewhat tighter temperature control and the use of low-thermal-expansion material such as invar for the experimental setup. However, this is outside of the scope of this paper, as the purpose here is to investigate the level of resolution achievable by this kind of optical system.

Besides thermal drift, another important effect is caused by the thermal fluctuation of the environment. As discussed later, the power level and the stability of beam propagation direction of the laser can be adversely affected by temperature fluctuation.

2.6 Laser Noise

The laser can contribute two kinds of noise to our optical position-monitoring system. One problem is that the power of the laser beam can fluctuate with time. This fluctuation causes uncertainty in the output signal. This problem can be minimized by the following approaches. First, we used a special thermally compensated laser (Spectra-Physics He-Ne laser: Model 117A). The stability of laser power improved considerably using this thermally compensated laser (as compared to our original laser, a Newport He-Ne laser Model U-1335). Less than $\pm 0.1\%$ fluctuation in laser power has been achieved by this laser.⁶ The noise due to laser power fluctuations can further be suppressed using a normalization method. Suppose the output signals of the left and right sides of the detector are A and B , respectively. We can use $(A-B)/(A+B)$ as differential output signal instead of $A-B$ to normalize the signal. With these two kinds of measures, we find the noise due to laser power fluctuation can be kept very small.

A more problematic noise source is due to the shifting of laser beam in propagation direction. When the laser beam shifts from one side of the detector to the other side of the quad- or bi-detector, it affects the differential output of the detector. The laser beam shift may result from mode hopping,¹⁰ which can be very fast in switching time and can cause a substantial amount of noise. We monitored both the sum and the differential output of our detectors and found

that the fluctuations of the total signal due to the change in laser power is much less than the change in differential output due to the laser beam shift.

To suppress the noise caused by laser beam shift due to mode hopping, we used a pinhole spatial filter. The collimated laser beam was focused onto a pinhole filter before being recollimated. The pinhole spatial filter was used to eliminate, as much as possible, the parasitic higher order mode laser energy, which is more susceptible to mode hopping and redistributing energy between the higher order modes. While this spatial filter appears helpful, the noise due to mode hopping was not totally eliminated by this method.

2.7 Geometric Effect of the Quad-Detector

In the course of our investigations into improving the resolution of the system, we found that the resolution of the system was strongly dependent on the location of the detector with respect to the beam. In the construction of the quad-detector, there is a cross gap between the four cells of the detector (Fig. 5 in Sec. 4). Also, the response of the detector at the edge is most likely somewhat less uniform than that of the rest of the detector. As discussed in Sec. 2.2, a smaller (focused) beam spot on the quad-detector provides better sensitivity. However, a tighter or smaller focusing spot implies that a larger central portion of the laser beam falls into the gap between the different detector cells. This obviously has an effect on the sensitivity. But as shown in the experimental results in Sec. 4, this gap also affects the noise level. This leads us to believe that while laser mode hopping redistributes some of the laser energy from one side to the other side of the quad-detector, mode hopping also redistributes the energy between the central portion and the outer portion of beam. If the central portion of the beam is in the gap, while the outer portion of the beam is on the detector cells, the redistribution of the laser energy from the center to the outside portions of the beam will contribute a substantial amount of noise.

3 Principle of Noise Cancellation

As discussed in the noise analysis of our system, we were able to suppress most of the noise sources quite effectively, and the major remaining source of the noise is due to laser beam shifting. In this section, we discuss a new approach to how to effectively cancel the effect of this noise.

The principle of our noise cancellation system is simple. In our original system shown in Fig. 1, we cannot distinguish whether the movement of the laser beam on the detector is due to shifting of the laser beam or results from the actual displacement of the target or sample. This difficulty can be resolved by a dedicated position detector monitoring the beam shifting of the laser beam. Using this information, we can separate the contribution of laser beam shift from the true signal due to movement of the workpiece. One of a simple arrangement of our concepts is shown in Fig. 4. Here, in addition to the original reflecting prism p and position-sensing quad-detector D , a partial reflection prism p' and quad-detector D' were used to monitor the laser beam motion due to laser beam shift.

Fig. 4 Noise cancellation system structure.

4 System Performance Using Noise Cancellation Techniques

To demonstrate the principle of the noise cancellation effect, we try to keep the conditions of both detectors D and D' as close to each other as possible. For example, we try to keep the spot size, laser power, and the location of laser spot with respect to the two quad-detectors as much the same as possible. We monitored the differential output of D and D' and noise cancellation output $D - D'$. Ideally, the output signal of the monitoring detector D' should remain constant. If the workpiece has not been displaced, then both D and $D - D'$ should also be constant. However, if noise cancellation techniques work, the noise level of $D - D'$ should be smaller than D . As shown in Table 3, this is indeed the case, and $D - D'$ is about $5 \times$ better than D and D' .

The experiment in Table 3 was performed with the laser spot center of the detector as shown in Fig. 5(a). As already discussed, there is a cross gap⁵ between the detecting cells (A , B , C , and D) of the quad-detector. Because of this gap, the system may not perform optimally, so we move the laser spots of both detectors to a new location, as shown in Fig. 5(b). In this way, we can eliminate part of the gap between the top and bottom halves of the detector. The result is shown in Table 4, and we found that the noise level was three times lower. It is also interesting to note that the result of the noise cancellation technique appears to work even better in this configuration.

Figure 6 shows the output signal of detector D as well as noise cancellation system $D - D'$ as functions of displacement of the workpiece. The two curves matched reasonably. The difference may be due to a change of the impedance of the electronics due to the direct wiring of $D - D'$.

Figure 7 shows the noise level of D and the noise cancellation $D - D'$ as functions of the displacement of the workpiece. As seen in the figure, the noise cancellation system $D - D'$ performs better than the original simple position-monitoring detector D in general. However, the maximum benefits occur in the region where both detectors D and D' are at nearly equivalent states with respect to the laser beam. As the laser beam moves away from this position on detector D , the noise cancellation method begins to deteriorate since the laser shift has different effects on the

Table 3 Noise of single detector and noise cancellation system when the beam is in the detector center.

	D'		D		$D - D'$	
1	0.0450	0.0623	0.0781	0.0621	0.1254	0.1262
2	0.0625	0.0746	0.0927	0.0836	0.1262	0.1285
3	0.0447	0.0663	0.1146	0.0813	0.1275	0.1320
4	0.0839	0.0582	0.1181	0.0916	0.1320	0.1301
5	0.0567	0.0561	0.1138	0.1009	0.1313	0.1323
6	0.0511	0.0530	0.0852	0.1003	0.1277	0.1326
7	0.0319	0.0565	0.1063	0.0767	0.1261	0.1301
8	0.0597	0.0863	0.1054	0.0602	0.1260	0.1330
9	0.0614	0.0518	0.1147	0.0716	0.1261	0.1319
10	0.0777	0.0683	0.1233	0.1075	0.1264	0.1375
Noise	0.0155	0.0108	0.0150	0.0164	0.0023	0.0030
Ave. Noise	0.0132		0.0157		0.0027

Fig. 5 Laser beam (a) in and (b) out of the center of the detector.**Table 4** Noise of single detector and noise cancellation system when the beam is out of the detector center.

	D'		D		$D - D'$	
Reading No.	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
1	0.0188	0.0235	0.0345	0.0251	0.1230	0.1183
2	0.0225	0.0244	0.0352	0.0366	0.1216	0.1181
3	0.0253	0.0241	0.0315	0.0232	0.1227	0.1183
4	0.0174	0.0231	0.0313	0.0293	0.1228	0.1172
5	0.0217	0.0287	0.0251	0.0246	0.1230	0.1176
6	0.0200	0.0219	0.0460	0.0352	0.1227	0.1170
7	0.0259	0.0207	0.0451	0.0412	0.1234	0.1170
8	0.0263	0.0205	0.0346	0.0424	0.1234	0.1181
9	0.0147	0.0186	0.0411	0.0479	0.1234	0.1183
10	0.0225	0.0183	0.0370	0.0400	0.1229	0.1174
Noise	0.0038	0.0031	0.0065	0.0086	0.0005	0.0005
Ave. Noise	0.0035		0.0075		0.0005

Fig. 6 Calibration curves of D and $D-D'$.

two detectors. Figure 8 shows the resolution of our noise cancellation system. For the $\pm 1\text{-}\mu\text{m}$ range at the equivalent point, the system resolution is about $20\text{ \AA}$ or better.

5 Discussion and Conclusions

Various factors that can affect the resolution of the position-monitoring system using a PSD were analyzed. Most of the noise can be suppressed readily. One important source of the remaining noise of the system was identified as being caused by laser beam shift. To eliminate this, a noise cancellation technique was developed. Using this noise cancellation technique, the SNR of our position-monitoring system could be greatly enhanced, and a resolution of $20\text{ \AA}$ was demonstrated using standard off-the-shelf components.

Several interesting questions remain. Can the resolution of the position-monitoring system using a PSD be further improved? And if so, how? In the course of our investigation, we found that gaps between the four quadrants of the quad-detectors can affect the both the sensitivity and the noise of the system. Although the system performance was improved significantly by moving away from the cross center of the detector, a gap still remains between the two halves of the detector. Elimination of this gap (or its effect) may further improve the performance of the system.

Fig. 7 Noise level of D and $D-D'$ along the stage.

System resolution after noise cancellation

Fig. 8 System resolution of $D-D'$ after noise cancellation.

Another limiting factor we encountered was the intensity saturation of the detector. If the intensity saturation problem can be solved, one can further reduce the size of the focused laser spot on the detector by using shorter wavelength lasers and/or a shorter focal length lens in our system. This would help to improve the sensitivity of the system further. Thus, we believe it is possible to achieve further improvements in the resolution of our system and this will be the subject of future investigations.

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