A novel vibration sensor based on the near-field Talbot effect

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Abstract. A novel technique for vibration measurement is proposed using the near-field Talbot effect. The sensor is based on monitoring intensity modulation of interference patterns deviated from that at the Talbot distance. To achieve high sensitivity to mechanical vibrations, an asymmetric grating is employed to provide a small grating open fraction. Our theoretical outcomes show that the sensor resolution can be at micro and even nano scales. This practical vibration sensor can be useful in metrology and many industrial applications.

1. Introduction
Vibrations can be typically generated by various sources ranging from some human activities to certain natural events. They are usually undesirable since they can cause machinery and electronic equipment to fail to function properly or even to break down. On the other hand, vibrations originated from operation of a machine itself can be exploited as an indicator of machinery condition. For instance, an unexpected increase in vibration level could signify problems such as untightened, misaligned, or deteriorated machine parts. Hence, precise vibration measurement and analysis have been essential in maintenance, monitoring, as well as developing of machinery.

A wide variety of high-sensitivity vibration detectors have been developed and used in industries including piezoelectric accelerometers, strain gauges, and optical accelerometers which are relied upon a leaf spring and a fiber Bragg grating (FBG) \cite{1,2}. Some drawbacks of the accelerometers such as their required installation on a vibrating element make the accelerometers not appropriate for a target object with a mass comparable to those of the accelerometers. There are capacitive and eddy-current displacement sensors which can be utilized for vibration measurement without contacting the measured target \cite{3}. However, these displacement probes are susceptible to environmental factors including temperature. Whereas noncontact interferometric techniques such as laser doppler vibrometer are also achieved for measuring vibrations of the object of interest with the sensitivity in the order of laser wavelength, one of their disadvantages is their installation complexity \cite{4}. Low-frequency vibration sensing probes have been proposed using the Talbot effect, a near-field diffraction phenomenon which produces repeated images of a diffraction grating at certain propagation lengths. A Talbot interferometer associated with variation in a Moiré pattern was used for measuring and monitoring of speaker membrane vibration \cite{5}. A method of using the Talbot effect and adaptive photodetectors for out-of-plane vibration measurement was reported \cite{6}. A circular grating Talbot interferometry for analysis of in-plane vibration was also demonstrated \cite{7}. Not only is the Talbot effect proved to be useful in...
vibration measurement, but also in other applications including investigation of physical nature of matter-wave [8], construction of a compact high-resolution spectrometer [9], detection of optical vortices [10,11], and inspection of the diffraction grating characteristics such as the period $d$ [12].

Here, we propose a simple vibration measurement technique which employs a single asymmetric diffraction grating with a small open fraction. The calculated results show the resolution ranges from micro to nanoscales.

2. Theory and method

The basic idea of this sensor based on the advantage of the light intensity gradient in the Talbot effect. To obtain the large changing of the intensity in the interference pattern, we utilize an asymmetric diffraction grating with small open fraction as shown in figure 1.

Figure 1. An incident wave is assumed as a plane wave diffract with wavelength $\lambda$ through the grating period $d$ with aperture width $fd$. The self-images of the grating with rather a narrow shape have appeared at each Talbot length $L_T = d^2/\lambda$ [13]. The single slit width $D = fd$ is placed in front of a photodetector for measuring the intensity gradient along the $z$-axis.

For the theoretical description, considering the plane wave $\psi_0(z_0)$ is transformed by the grating transmission function $T(x_0)$ at $z = z_0$ to be

$$\psi(x_0, z_0) = T(x_0)\psi_0(z_0) = \sum_{n = -\infty}^{+\infty} A_n \exp\{ik_n x_0\} C_0 \exp\{ikz_0\},$$

(1)

where $A_n = \sin(n\pi f)/n\pi$ is the Fourier components for periodicity along the $x_0$ axis with wavenumber $k_d = 2\pi/d$ [14]. The factor $C_0$ and $k = 2\pi/\lambda$ is the amplitude and wave vector, respectively.

According to the Fresnel approximation [15], behind the grating with $z_0 = 0$, the wave function on the $xz$-plane in the near-field regime (figure 1) is given by

$$\psi(x, z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dx_0 \exp\left\{i k \left( z + \frac{ik}{2} (x - x_0)^2 \right) \right\} \psi_0(x_0, z_0).$$

(2)

By using the Gaussian integral, the exact wave function can be obtained. The intensity distribution which is corresponding to the modulus square can be written in the form,

$$\psi^* \psi = C \sum_{n, m = -\infty}^{+\infty} A_n A_m \exp\left\{i(n - m)k_d x_0 + i \frac{(n^2 - m^2)\pi z}{L_T} \right\},$$

(3)

where all of the constant factors have been excluded into factor $C$. Examining the longitudinal intensity gradient in experimental can be done by placing a small aperture, such as a single slit (figure 1), in front of a photodetector. Therefore, to obtain satisfactory theoretical results.
calculation, the obtained intensity function has to be integrated over the slit width. Regarding the boundary integral around \( x = 0 \), we obtain

\[
I(z) = \int_{-fd/2}^{fd/2} dx \psi^* \psi = \frac{Cd}{\pi} \sum_{n, m = -\infty}^{+\infty} A_n A_m \sin \left( \frac{i(n-m)\pi f}{d} \right) \exp \left( \frac{i(n^2-m^2)\pi}{L_T} \right).
\]

The large variation of integrated intensity or relative percentage around \( z = 2L_T \), in the approximately linear interval, will be assigned to vibrating analysis in term of relative percentage as

\[
\%\Delta I = \frac{I(z_2) - I(z_1)}{I(z_1)} \times 100.
\]

The theoretical simulations with sensitivities consideration are presented in the next section.

![Figure 2](image)

**Figure 2.** Simulated intensity modulation of detected light as a function of longitudinal distance \( z \) according to equation (4) for the diffraction grating with open fractions \( f \) of (a) 0.1 and (b) 0.5. The period \( d \) is 1 \( \mu m \). The distances \( \delta z = z_2 - z_1 \) enclosed by the red lines are locations of the detector for vibration measurement.

3. Results and discussion

The simulation assumes a diffraction grating illuminated via a coherent light of a typical 532-nm laser. The diffracted laser beam is then incident on a reflective surface of a vibrating object which is driven by a frequency generating system. The reflected light beam from the object surface travels through a single mask slit with a size similar to that of a bright fringe of a diffraction pattern and falls upon a photodiode located near the Talbot plane. Measured intensity variations of the laser light are then monitored by the photodiode for vibration information of the object.

Figure 2 shows dependences of calculated intensity modulation \( I \) (equation (4)) upon the longitudinal distance \( z \) for a diffraction grating with open fractions \( f \) of 0.1 and 0.5 and a grating period \( d \) of 1 \( \mu m \). The intensity distributions for both values of \( f \) peak at the two Talbot length \( 2L_T = 3.76 \mu m \). The distribution is broader for the larger value of \( f \). Changes in light intensity are in response to displacements of the reflective object, alternatively corresponding to vibrations of the object. The photodiode needs to be positioned at locations where the intensity modulations \( I \) are linearly related to the longitudinal distance \( z \). These are specified by the enclosed red lines shown in the figure and have the distance difference \( \delta z = z_2 - z_1 \) of 8 nm. For such a position range, a grating with a smaller value of \( f \) gives rise to a higher gradient of intensity modulation or relative percentage (as defined in equation (5)) with respect to \( z \). For example, relative percentages are 20% for \( f = 0.1 \) (figure 2 (a)), and only 1% for \( f = 0.5 \).
(figure 2 (b)). Therefore, the grating with a small open fraction yields higher sensitivity and is more suitable for vibration measurement.

![Graph](image)

**Figure 3.** Sensor resolution as a function of grating period $d$. The resolutions calculated from the relative percentage of 20%. The dash line is the fit with $y = 0.0012167x^{1.8896}$ and $R^2 = 0.998$.

Figure 3 illustrates a relation between grating period $d$ and sensor resolution which can be calculated from a given intensity gradient of the relative percentage with respect to the longitudinal distance $z$. This $z$ distance is therefore our definition of the sensor resolution. The simulations assume a grating open fraction of 0.1 and the relative percentage of 20% (equation (5)). The sensor resolution improves with the grating period $d$ decreases. This is because smaller values of the period $d$ result in smaller values of the Talbot length $L_T$ and is therefore more sensitive to the displacement of $z$.

4. **Conclusions**

We introduce the vibration sensor based on the near-field Talbot effect. The method consists of a few optical elements such as a diffraction grating, single slit, and photodiode. Even though the method is simple, our theoretical results show that the resolution of this technique can be achieved to the micro and nanometer levels. Our practical idea can be experimentally performed and possibly useful in metrology and many industrial applications.

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