Analogic fiber optic position sensor with nanometric resolution

Frédéric Lamarque
Université de Technologie de Compiègne
Lab. Roberval de Mécanique UMR UTC / CNRS 6066
BP 60319 - 60203 Compiègne cedex France
frederic.lamarque@utc.fr

Christine Prelle
Université de Technologie de Compiègne
Lab. Roberval de Mécanique UMR UTC / CNRS 6066
BP 60319 - 60203 Compiègne cedex France
christine.prelle@utc.fr

Abstract

This paper describes a miniature analogic position sensor. This sensor is dedicated to high resolution displacement measurement (10 nm) between two positions on long range (few millimeters). The working principle of the sensor is presented as well as experimentation results.

Keywords

Fiber optic sensor, nanometric resolution, miniature sensor.

INTRODUCTION

In the field of high resolution integrated process, miniature high resolution sensors are necessary. Actually, the sensor resolution must be the best to detect the smallest phenomena and the size of the sensor must be the smallest to be easily integrated in a mini-system.

The commercially available sensors having a nanometric resolution can be separated into two categories :

- small size sensors but having a limited range. For example, capacitive position sensors are able to measure displacement with a subnanometer resolution but on a 100 µm maximun range,
- high range sensors but with prohibitive size. For example, Heidenhain propose an optical linear encoder (LIP 300 serie) for measuring step until one nanometer. The size of the sensor head is (55x33 mm2). Laser interferometer position sensors are often used for accurate measurements but classical interferometer are cumbersome devices placed far from the mini-system.

Several techniques are studied in different laboratories. An inductive sensor [1] has been studied. The size 18x3.2 mm^2 is interesting but the resolution is not mentioned (<550 µm).

A high resolution miniature encoder has been studied [2]. It is based on the diffractive inteferometric grating rule. With a 30 mm size and a 125 nm resolution, it is able of long range measurement. After interpolation, it is possible to obtain a 2 nm resolution [3].

With the same kind of technique, an optical micro encoder using a vertical cavity-emitting laser (VCSEL) as been studied. The encoder chip size is approximately 1.5x2.0x0.6 mm^3 and the measurement resolution is 0.1 µm [4].

An optical sensor with nanometric resolution has been developed in our laboratory [5] and in Japan too [6].

The first paragraph describes principle and performances of the sensor. The second one explains how to transpose the axial resolution of the sensor in lateral resolution and the limitations of that transposition. The next part presents first experimental results. Then, in the last paragraph, results are discussed and a technique using the transposition coupled with a grating to obtain a nanometric resolution and a large range is described.

FIBER OPTIC SENSOR PRINCIPLE AND PERFORMANCES

Principle

The head of the sensor consists of a 5 fiber optics bundle. The emission fiber placed in the centre emits light on a flat mirror. The light reflected by the mirror is injected in the reception fibers placed around the emission fiber (see Figure 2).

The amount of reflected light detected is a function of the distance between the sensor and the mirror.

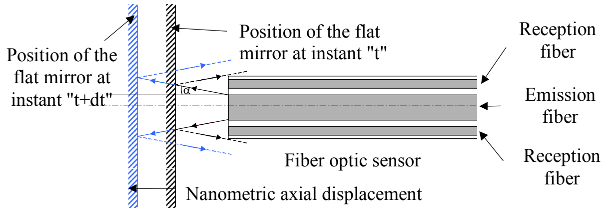

Figure 1 : Fiber optic sensor principle

The size of that fiber optic sensor head is 2 mm diameter and 10mm long, without signal conditioning module (see figure 2).

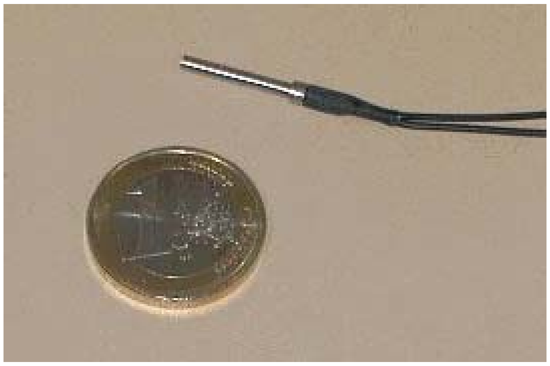

Figure 2 : Fiber optic sensor head

Performances

Different kind of sensor have been tested [5], particularly with different signal conditioning modules.

The sensor sensitivity depends on the reflection coefficient of the moving surface. The higher the coefficient is, the better the signal to noise ratio is.

An example of the sensor response is given (see figure 3).

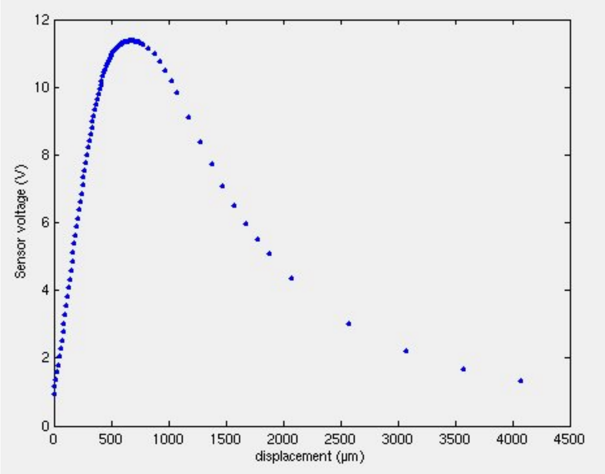

Figure 3 : Fiber optic sensor characteristics

The rising part of the curve correspond to the best linear responsivity domain. In the best conditions, this rising part is about 400 µm. In that case, the sensor axial resolution is 1.6 nm rms and the minimum lateral resolution is 250 µm.

An application of this sensor is for example profilometry [7].

Then, for a nanometric positioning on a few millimeter stroke, the maximum range (400 µm) is too small.

The next paragraph will explain how to change the sensor configuration to improve the range of measurement.

LATERAL DISPLACEMENT MEASUREMENT

Principle

A tilted mirror is used to transpose the axial resolution into a lateral resolution [8]. In that configuration, the optical axis of the sensor remains perpendicular to the moving surface but the displacement vector is no more perpendicular to the surface (see Figure 4).

Let us define R_a as the axial resolution, R_l as the lateral resolution in the displacement direction and α as angle between the mirror and the displacement direction.

The simple relation between the axial resolution and the lateral resolution is :

$$\sin\alpha = \frac{R_a}{R_l}$$

To obtain a complete transposition of the axial resolution into a lateral resolution, we should have $\alpha = 90°$. Of course this is an extreme case which is note physically interesting. So, we have to make a trade-off between the highest resolution and the largest range.

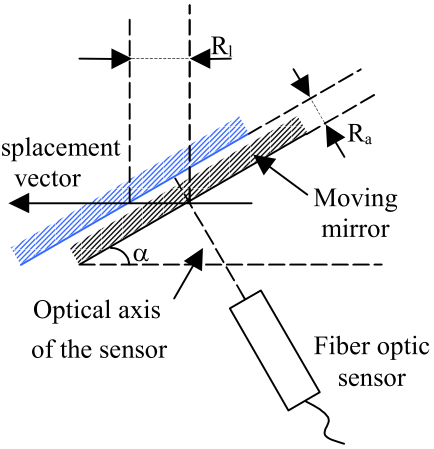

Figure 4 : Fiber optic sensor used with tilted mirror

Results

Increase of range

Experiments have been carried out to show the range improvement using a tilted mirror.

For a simple alignment procedure, experiments have been carried out with $\alpha = 45°$.

A mirror is placed on a precise linear displacement table so that the normal vector of the mirror surface remains in a 45° angle with the displacement vector. The fixed fiber optic sensor is placed so that its optical axis is perpendicular to the mirror surface.

The table where is placed the mirror is moved by 10 µm steps. For each position, the sensor voltage is collected. Measurements have only be done on the rising part of the characteristics where the responsivity is maximum.

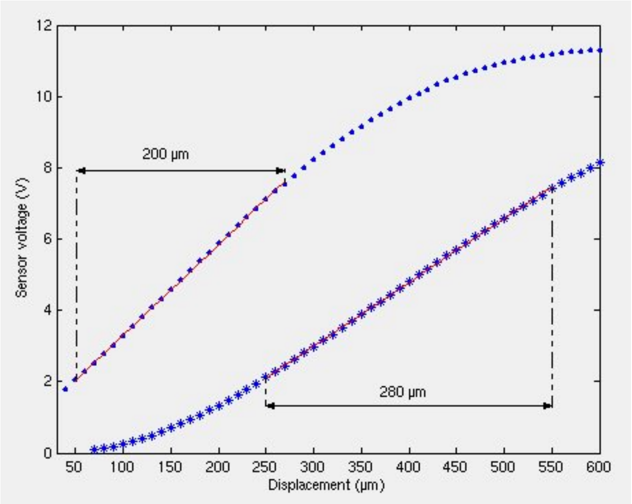

Figure 5 : Comparison between the two configurations

Figure 5 shows a comparison between the sensor response when it is used in the two following configurations:

- the normal vector of the mirror surface and the displacement vector of the mirror are in the same direction (•••),
- the angle between these two vectors is equal to 45° (***).

These two configurations will be respectively named axial incidence configuration (α = 90°) and "α = 45°" configuration.

The best linear characteristics, by means of mean square, have been computed for each response. A 1% linearity criterion have been chosen. With such a criterion, a linearised characteristic can be used on a 200µm range for the first case and 280 µm range for the second one. The responsivities are respectively 25.7 mV/µm and 18.0 mV/µm. It allows to verify the theoretical position of the mirror (45°). Experimental responsivities lead to an angle of 44.5°.

Resolution

The resolution has been observed performing 10 nm steps with a piezoactuator moving a mirror.

The first experiment has been carried out in the "α = 90°" configuration. The steps measured by the fiber optic sensor are shown on the Figure 6.

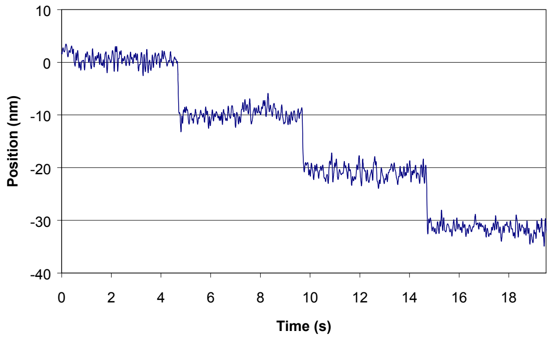

Figure 6 : 10 nm steps in "α = 90°" configuration

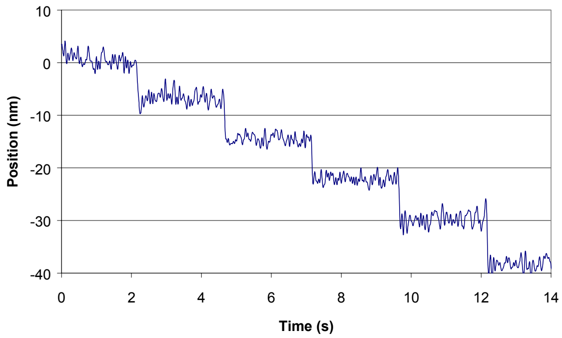

Figure 7 : 10 nm steps in "α = 45°" configuration

The second experiment has been carried out in the "α = 45°" configuration. The figure 7 shows the steps measured by the sensors. Due to the "α = 45°" configuration, the expected steps are 7.1 nm for a 10.0 nm displacement of the mirror. The measured steps are 7.6 ± 0.5 nm.

The limit of resolution has been measured at 2.5 nm.

The loss of resolution exists as expected but the resolution is enough for our application.

LONG RANGE MEASUREMENT

The "α = 45°" configuration allows a 40% wider range. But, sensor responsivity is less important than in the axial incidence configuration. Another point is that the limit of resolution will be upper in the "α = 45°" configuration. For this value of α, the limit of resolution will theoretically be 2.3 nm instead of 1.6 nm obtained in the axial incidence configuration. Nevertheless, our goal was to increase the range while keeping a resolution in the 10 nm order of magnitude.

A way to increase widely the range of the sensor for a given nanometric resolution is to use a grating instead of a flat mirror in order to get a periodic measurement on a long range. This new configuration will be describe in the next part.

Long range sensor

Sensor principle

The previous method using tilted mirror is limited due to the lost of responsivity when the distance between the sensor and the mirror becomes to large.

The idea to solve that problem consists in using a grating with a triangular shape and two fiber optic sensors (Figure 8).

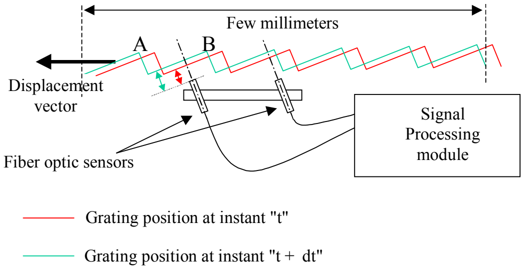

Figure 8 : Long range fiber optic sensor principle

The use of this grating allows to increase theoretically the range to the length of the grating minus the distance between the two sensors.

If the grating, fixed on the mobile part of the system, is moving to the left from the point A, the distance between the sensor head and the surface will increase(see Figure 8). The measure, when the sensor is in front of the point B is the same that the one at the point A. Then a device just has to count the edges measured by the sensor to have a displacement measurement superior to the one obtained with only a single tilted mirror.

The illuminated zone is never infinitely small, then during the crossing between a tooth to the next one, two teeth are illuminated in the same time and the voltage given by the sensor is no more valid (see Figure 9).

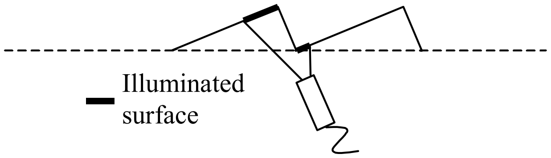

Figure 9 : Edge crossing problem

To prevent the edge crossing problem, two fiber optic sensors will be used. The distance between the 2 sensors should be different from the grating period in order that the 2 sensors do not cross a edge at the same time. The signal processing module contains a counter to count the edges and synchronize the measure on the first sensor or on the second one according to the grating position.

Results with a conventionally machined grating

First experiments have been led using a conventionally machined grating (see figure 10). This grating is 35 mm long.

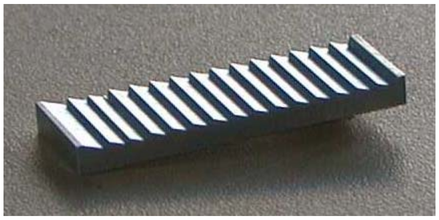

Figure 10 : Conventionally machined grating

Knowing the geometrical dimensions of the grating, it is possible to theoretically determine the "valid zone" where the sensor is not crossing an edge. The lower part of Figure 11 shows the theoretical position detected by the sensor versus the grating position. Due to the edge crossing, the "valid zone" on a tooth is very small. Outside that zone the measure will not be taken into account.

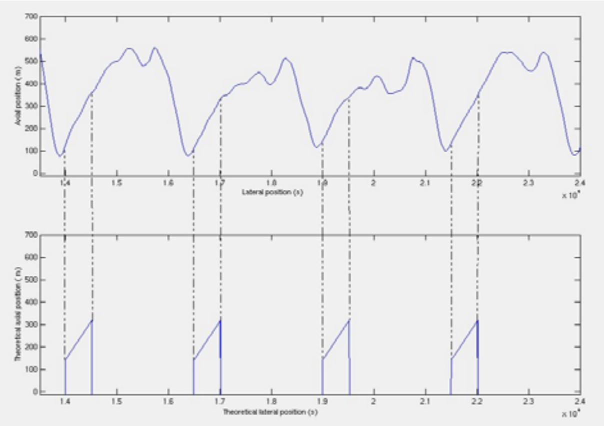

Figure 11 : Experimental and theoretical responses

The upper part of the Figure 11 shows the experimental results. The grating is moved in front of the fiber optic sensor. The displacement measured by the sensor is plotted versus the grating displacement. The non-triangular shape is due to edge crossing phenomenon. The grating parameters have not been optimized for our application. That is why the non valid zone is so important. Taking into account our fiber optic parameters and our grating parameters, the only "available reading area" is restricted to 523 µm on a 2500 µm step size.

Nevertheless, if we only consider the "valid zone", a correct accordance between the theoretical and experimental curves is observed.

Simulation with a two heads sensor

Taking into account the illuminated zone and the distance between the two sensors, it is possible to simulate the two sensors measurements in order to choose well adapted grating dimensional parameters.

The Figure 12 shows a simulation of the "valid zone" of the two sensors (—: sensor 1, -.-.- sensor 2). The small overlap of the two curves shows that it will always be possible to have a valid measure either on the sensor one or on the sensor two.

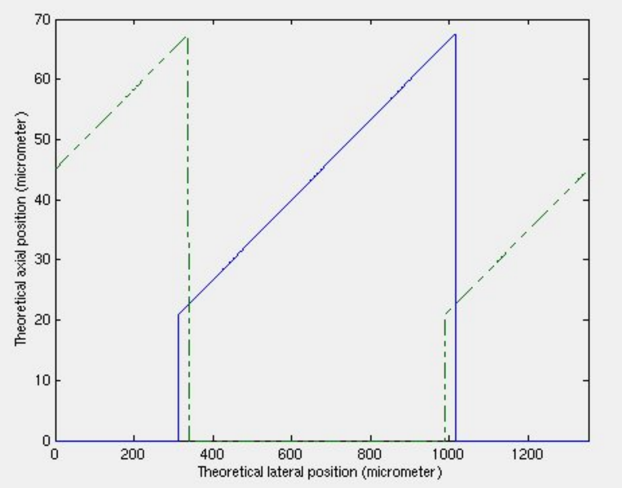

Figure 12 : "Valid zone" of the two sensor configuration

CONCLUSIONS

This paper has presented a new way to use a fiber optic position sensor having a nanometric resolution.

Using a tilted mirror, it is possible to increase the sensor range within keeping a resolution better than 10 nm.

Then first results using a grating have been shown. With a grating it is possible to increase the range of the sensor until millimetric range.

The next grating is already machined with a diamond tool on the high precision lathe of the laboratory to have accurate dimensional parameters. These parameters have been fixed according to the simulation presented in the paper.

Soon, the diamond tool machined grating will be tested with a two heads sensor to avoid the crossing edge problem.

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