Accuracy-enhanced compensated optical fibre two-dimension microdisplacement transducer based on direct intensity modulation

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Several industrial applications require precise microdisplacement measurements. Optical intensity modulated sensors are very suitable to meet these needs because they are simple and cost-effective. Many have been presented that monitor one-dimension displacement in the direction of the optical axis of the system [1]. Some lateral displacement sensing methods are based on quadrant or dual detectors [2], and others are based on reflective approaches that require microprocessing systems in order to obtain the two-dimension position [3, 4]. In this paper, we present a detection scheme for monitoring 2-D displacements that is based on direct intensity coupling between fibres. It can be used in industrial applications such as displacement, position, acceleration, or pressure sensors. Both the transducer head and the associated optoelectronics are very simple to construct and they employ inexpensive components. It is not sensitive to ageing and temperature effects, and its measurements have little error that can be improved by adequate selection of the coupling characteristics of the fibres. We prove the influence of the modulation function on the accuracy of the transducer, and show the way to minimise the output error.

The sensor head is composed of five optical fibres, that are depicted in Fig. 1 together with the X and Y axis. The in-plane movement to be detected changes the position of the illuminating fibre end with respect to the four-fibre collecting arrangement. The x and y position parameters are obtained from the light coupled from the former into the latter. As the operating displacement range is centred on the (0,0) position, the working zone in the coupling curve is the same for the four receiving fibres, so they all have the same modulation function. Besides, the collecting fibre bundle is easy to realise in practice by including the fibres in a tube with an inner diameter equal to $1+\sqrt{2}$ times the diameter of the fibres. The in-plane position of the emitting fibre, $P(x,y)$, is given by the following expressions:

$$x = \frac{1}{2\sqrt{2}}\left(d_3^{\,2} - d_1^{\,2}\right) \tag{1a}$$

$$y = \frac{1}{2\sqrt{2}}\left(d_4^{\,2} - d_2^{\,2}\right) \tag{1b}$$

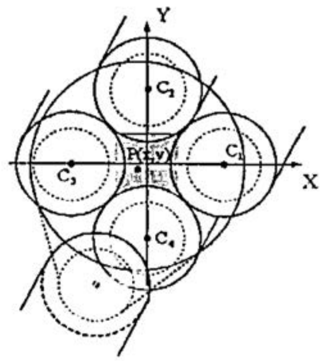


Figure 1. Optical transducer head for measuring the two-dimension position of the illuminating fibre end with respect to the fixed four-fibre arrangement.

where d_1, d_2, d_3, and d_4 are the transverse distances from the illuminating fibre to the four collecting ones, and can be approximated by a linear function of the four detected voltages:

$$d_i = mV_i + n, \qquad i = 1,2,3,4 \tag{2}$$

Eq. (2) is the modulation function of the transduction process, and it has been obtained by linearisation of the coupling curve within the working zone, which is limited by the minimum and maximum transverse distances that can be reached in the measuring range.

The transduction scheme presented in this work implements an approximation of Eqs. (1) that avoids the squaring of the detected signals and makes the output insensitive to environmental changes. The expression for the x parameter is:

$$x = \frac{1}{2\sqrt{2}}\rho\left(\frac{V_3 - V_1}{V_3 + V_1}\right) \tag{3}$$

where ρ is a weakly variable parameter that is substituted for a constant as follows:

$$\rho = (d_3 + d_1)(d_3 + d_1 - 2n) \cong 2d_0(2d_0 - 2n) \tag{4}$$

d_0 is the transverse distance from the (0,0) position to the receiving fibre centres, and has a value of $1/\sqrt{2}$ in length units normalised to the diameter of the collecting fibres. The maximum error of the approximation occurs at the corners of the two-dimension position range, (±Δ/2, ±Δ/2), Δ being the amplitude of the maximum displacement permitted on each axis. Such error can be expressed:

$$\begin{aligned}\delta\rho = &\left\{\left[\left(\frac{1}{\sqrt{2}} - \frac{\Delta}{2}\right)^2 + \left(\frac{\Delta}{2}\right)^2\right]^{1/2} + \left[\left(\frac{1}{\sqrt{2}} + \frac{\Delta}{2}\right)^2 + \left(\frac{\Delta}{2}\right)^2\right]^{1/2}\right\} \times \\ &\times \left\{\left[\left(\frac{1}{\sqrt{2}} - \frac{\Delta}{2}\right)^2 + \left(\frac{\Delta}{2}\right)^2\right]^{1/2} + \left[\left(\frac{1}{\sqrt{2}} + \frac{\Delta}{2}\right)^2 + \left(\frac{\Delta}{2}\right)^2\right]^{1/2} - 2n\right\} - \sqrt{2}\left(\sqrt{2} - 2n\right)\end{aligned} \tag{5}$$

The relative error in x is the same as the relative error in ρ, as they are linearly related by Eq. (3), and can be obtained by dividing (5) by $\sqrt{2}\left(\sqrt{2} - 2n\right)$. The main feature of this error is that it depends on the value of the n coefficient in the modulation function, and it can be considerably reduced by appropriate election of the optical coupling curve. Fig. 2 shows the magnitude of the approximation error as a function of the value of n, for three different measuring ranges: 0.1, 0.2 and 0.3, in normalised length units. The error can be made negligible if the independent coefficient in Eq. (2) is about 1.4, and it can be significant if the value of n is far from this number. Therefore, the modulation function makes a great difference in the performance of a sensor using this detection scheme, and special attention must be paid on the direct coupling characteristics of the optical fibres employed.

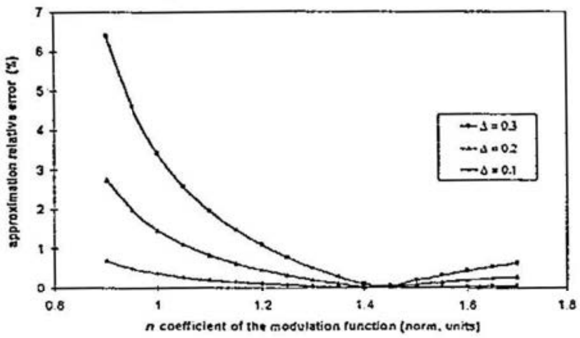


Figure 2. Approximation error as a function of the n coefficient in the modulation function for some measuring ranges.

The modulation functions for several multimode optical fibre pairs and different axial distances between them were measured, and practical conclusions were extracted. The coupling curves were taken by varying the transverse distance in 1-micron steps and averaging the measurements in 12 directions in the transverse plane. Relative power measurements were made by dividing the coupled light power by the emitted one. The position of the illuminating fibre was changed by means of a four-degree-of-freedom computer-controlled micropositioning system. The mode distribution was stabilised and uniformed both before and after the coupling procedure. The schematic of the complete laboratory set-up employed is shown in Fig. 3, and a picture is displayed in Fig. 4. Various types of fibres, both illuminating and collecting, were tested, and their modulation functions were obtained. Fig. 5 shows two of them, along with their mathematical expressions for a measuring range amplitude of 0.3. Taking into account their n coefficients, the approximation error for the first transducer is 3.5 %, while the error of the second one is 1.4 %. We also obtained that the longer the axial offset between fibres the larger the value of n, and that a larger illuminating fibre helps make the n coefficient closer to the ideal value. In order to minimise the approximation error the emitting fibre core should be large, and the longitudinal distance to the collecting bundle must be 6 or 7 times the receiving fibre size. The linearity error is 1.2 % and 0.6 %, respectively, for the two mentioned modulation functions.

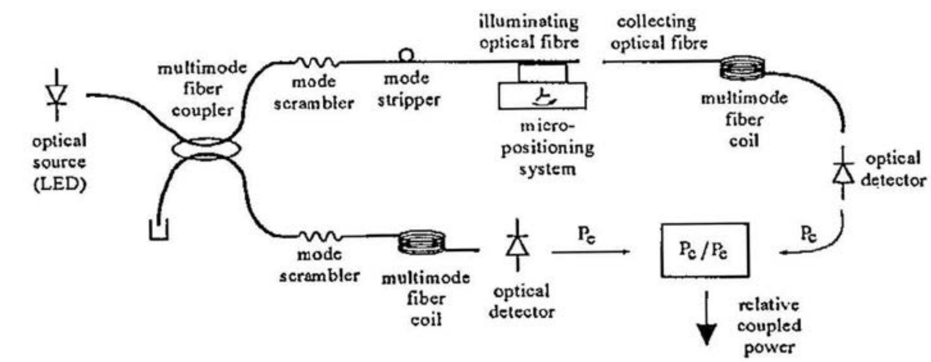
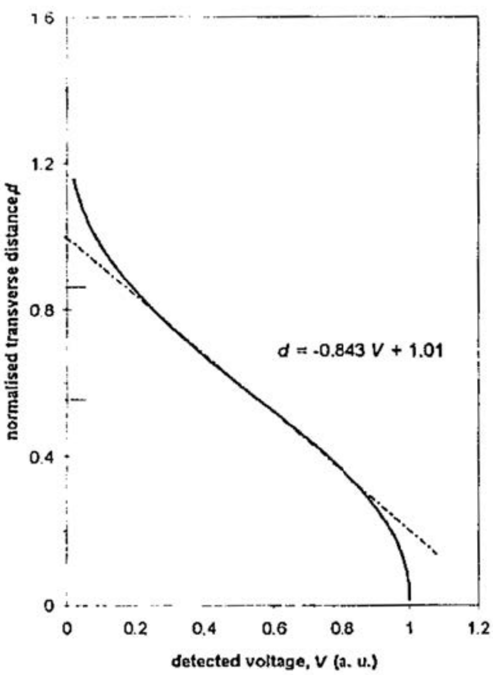


Figure 3. Schematic of the experimental set-up for the measurement of the optical intensity coupling between fibres.

Figure 4. Laboratory set-up for measuring the direct coupling function between optical fibres.

Finally, the detection scheme is not sensitive to environmental and external factors, because they affect the two voltages in Eq. (3) equally. The proportionality factor in both electric signals derived from environmental effects, such as a change in the light emitted by the source or in the light lost due to fibre bending or in the gain of both photodetectors, is removed from the division and does not alter the value of x. Therefore, this transducer compensates for intensity variations that are not related to the transduction process implicitly, that is, without the need of a reference arm that monitors the intensity within the system. The y parameter has the same treatment than the x position.



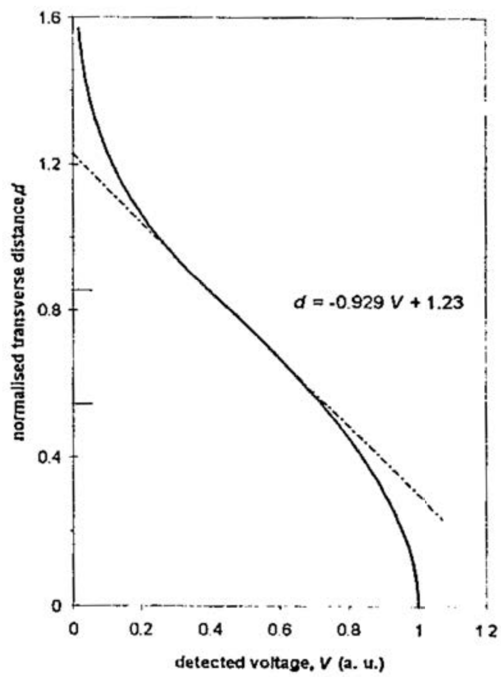


Figure 5. Experimentally obtained coupling curves and their associated modulation functions for a measuring range of 0.3. a) Coupling between two 100/140 fibres at an axial distance of 500 μm; b) Coupling from a 200/240 fibre into a 100/140 one separated 700 μm.

To sum up, a four-fibre collecting arrangement has been studied that can be used in a two-dimension position transducer with high accuracy and potential low cost. Although based on intensity modulation, it is not sensitive to temperature effects or fibre channel losses, due to its compensating detection scheme. A method of minimising the measurement error, consisting in the adequate selection of the optical fibres and their axial distance, has been developed. It allows to build a fibre sensor with very simple implementation and low error, that can be used either in static measurements, such as displacement or pressure, or in dynamic ones, such as velocity or acceleration.

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References

[1] Wang, D.X., Karim, M.A., and Li, Y., "Self-referenced fiber optic sensor performance for microdisplacement measurement". *Opt. Eng.*, Vol. 36, No. 3, pp. 838-842, 1997.

[2] Remo, J.L., "High-resolution optic displacement measurement using a dual-photodiode sensor". *Opt. Eng.*, Vol. 36, No. 8, pp. 2279-2286, 1997.

[3] Johnson, M., and Goodman, G., "One- and two-dimensional, differential, reflective fiber displacement sensors". *App. Opt.*, Vol. 24, No. 15, pp. 2369-2372, 1985.

[4] Braunschweiler, A., Llosas, P., Bertholds, A., and Baur, C., "Optical position sensor for automatic microassembling operations". *Opt. Eng.*, Vol. 34, No. 9, pp. 2660-2664, 1995.