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Fibre optical measuring network based on quasi-distributed amplitude sensors for detecting deformation loads*

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Abstract. **A new design of a sensitive element for a fibre optical sensor of deformation loads is proposed. A distributed fibre optical measuring network, aimed at determining both the load application point and the load mass, has been developed based on these elements. It is shown that neural network methods of data processing make it possible to combine quasi-distributed amplitude sensors of different types into a unified network. The results of the experimental study of a breadboard of a fibre optical measuring network are reported, which demonstrate successful reconstruction of the trajectory of a moving object (load) with a spatial resolution of 8 cm, as well as the load mass in the range of 1 – 10 kg with a sensitivity of 0.043 kg^{-1}.**

Keywords: *quasi-distributed amplitude sensors, distributed fibre optical measuring network.*

1. Introduction

The transition from discrete fibre optical sensors (FOSs) of physical parameters to extended distributed and quasi-distributed FOSs, which has been outlined in the last decade, made it possible to begin the development of distributed fibre optical measuring networks (DFOMNs) [1]. This problem is successfully solved based on tomographic methods for data collecting and processing, which allow one to significantly reduce the required number of measuring lines in a network [2, 3]. The problems related to processing tomographic data are successfully solved with the aid of neural network technologies [1]. Nevertheless, monitoring of large-scale natural and technogenic objects calls for high-dimensionality DFOMNs containing many extended FOSs and, therefore, further simplification of the structure of both the measuring network and the FOSs used in it.

When monitoring the state of large-scale objects (buildings, constructions), detection of strains is of greatest interest [4]; the most promising tools to solve this problem with the aid of large-scale DFOMNs appear to be quasi-distributed amplitude FOSs, which are based on either direct detection of radiation power loss or application of optical time-domain reflectometry (OTDR) [5].

The main drawbacks limiting application of amplitude FOSs are their low accuracy and sensitivity. When designing high-dimensionality DFOMNs, these drawbacks are aggravated. However, application of neural network technologies allows one to obtain reliable information about an object studied even in the presence of interferences and large errors of the data yielded by the measuring network [6]. In addition, as will be shown below, the development of smart measuring systems makes it possible to combine amplitude FOSs of different types into a unified network, thus decreasing the necessary number of sensors even more.

The purpose of this study was to design a distributed fibre optical measuring network, aimed at detecting the load application point and the load mass. This network should combine quasi-distributed amplitude FOSs based on direct detection of radiation power loss and a quasi-distributed OTDR sensor.

2. Quasi-distributed amplitude FOS

The amplitude FOS sensitivity to deformations is increased using special sensing elements (SEs) arranged along the optical fibre at specified points.

Such FOSs are based on quasi-distributed measurements and are called quasi-distributed [5]. Currently, OTDR sensors based on periodic microbends are successfully applied in quasi-distributed measurements of force, pressure, and shear [7]. However, we believe it unreasonable to apply these SEs in quasi-distributed amplitude FOSs based on direct detection of radiation power loss. We propose a simplified design of a sensing element for a pressure FOS. It is shown that one can successfully design a quasi-distributed OTDR sensor based on this SE.

It is proposed to use a special clamp as a SE of quasi-distributed FOS (Fig. 1). Under external load a pressing rod bends the optical fibre positioned on supporting rods, as a result of which the light power transmitted through the optical fibre changes.

Quasi-distributed FOSs of two types are used in the measuring network under consideration. In the first-type sensor a change in the light power transmitted through a multimode optical fibre is recorded by a photodetector directly at the output. The operation of the second-type sensor is based on OTDR [8]; in this sensor, the loss of power of reflected light transmitted through a single-mode optical fibre is recorded by an optical reflectometer.

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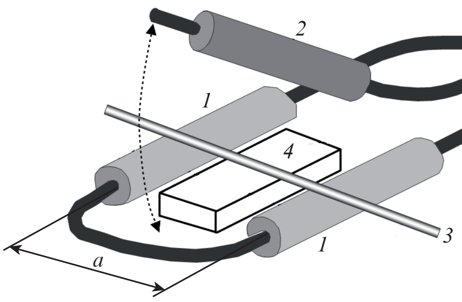

Figure 1. Sensing element of a quasi-distributed amplitude FOS: (*1*) supporting rods, (*2*) pressing rod, (*3*) optical fibre, and (*4*) elastic platform.

As the experimental study of the sensing element showed, the sensitivity of a quasi-distributed FOSs of the first type increases with a decrease in the distance *a* between the supporting rods; however, at some critical *a* value the fibre structure changes irreversibly. The optimal parameters of the design (with a standard multimode optical fibre) are as follows: the rod diameter is 2 mm and the distance between the supporting rods is 8 mm.

The optimal distance between the supporting rods in a quasi-distributed OTDR sensor is 15 mm. Figure 2 shows the reflectograms recorded for identically loaded SEs with different distances *a* between the supporting rods. It can be seen that at larger distances *a* the same external load causes higher power loss, thus impeding detection of signals from the next SEs in the measuring line (Fig. 2a); an increase in *a* reduces the sensitivity (Fig. 2c).

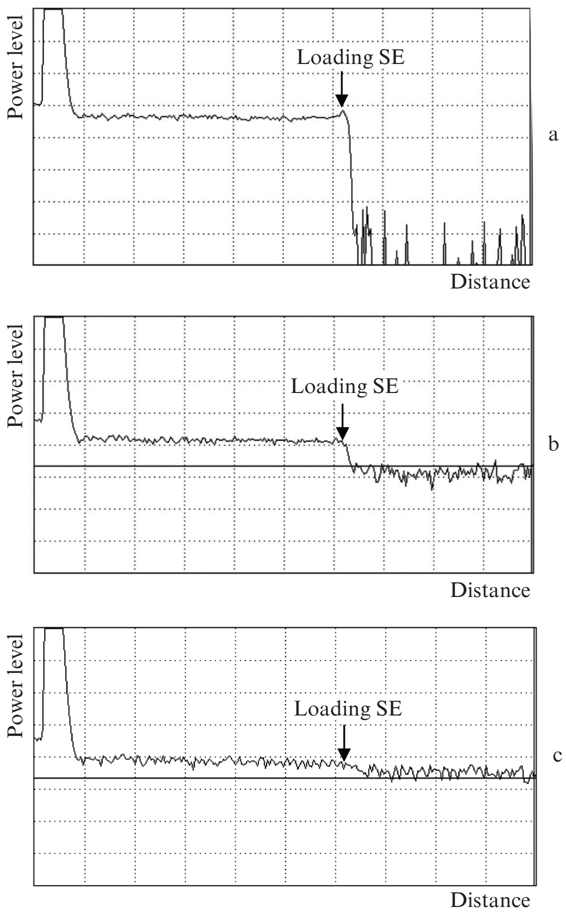

Figure 2. Reflectograms demonstrating the result of external loading of the sensing element of a quasi-distributed FOS at a = (a) 10, (b) 15, and (c) 20 mm. The scale is 12.6 m division^{-1}.

3. Fibre optical measuring network based on quasi-distributed amplitude sensors

The fibre optical measuring network under consideration is a combination of an array of quasi-distributed amplitude FOSs, which directly detect radiation power loss, and one quasi-distributed OTDR sensor. The first-type sensors are applied to measure the mass of an object loading the network, while the second-type sensors are used to determine the load application point. The above-described sensing elements are located on the light guides of sensors of both types. The distance between the SEs in the first-type sensor is determined by the area of the segments into which the controlled surface is divided, while the corresponding parameter of the OTDR sensor is determined by the reflectometer resolution. As the experimental results showed, at a reflectometer spatial resolution of 3 m, signals from two neighbouring SEs are well-discerned at a distance of 8 m between these elements. The corresponding reflectogram is shown in Fig. 3a (1, 2). However, with allowance for the specific features of optical signal generation under a load on neighbouring SEs, we chose the optimal distance to be 19 m. The corresponding reflectogram is shown in Fig. 3b (2, 3). To reduce the distance between SEs in the measuring network, fibre network fragments between them were wound on reels located at the lower network level.

Figure 4 schematically shows a breadboard of the fibre optical measuring network based on quasi-distributed amplitude sensors for detecting deformation loads. This breadboard is a platform 0.64×0.80 m in size, arbitrarily divided into 20 segments. Ten quasi-distributed amplitude FOSs of the first type are oriented parallel to each other, so that light guides of two sensors pass through each segment. In this con-

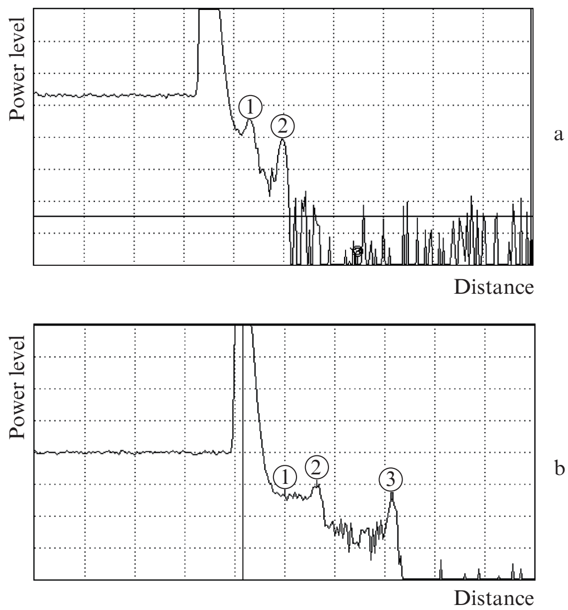

Figure 3. Reflectograms of the OTDR sensor with SE located at distances of (a) 8 and (b) 19 m.

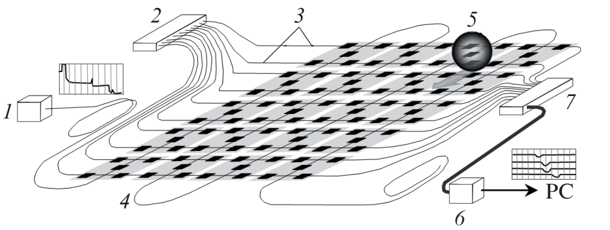

Figure 4. Fibre optical measuring network based on quasi-distributed amplitude sensors:
(*1*) reflectometer; (*2*) emitter block; (*3*) quasi-distributed first-type FOS; (*4*) quasi-distributed OTDR sensor; (*5*) object; (*6*) ADC; (*7*) photodetector block; and (PC) personal computer.

figuration, there are two SEs of one sensor in each segment; i.e., four SEs per segment in total. The OTDR sensor combines the SEs located at the centre of each segment into one measuring line.

Thus, each segment contains five SEs (Fig. 5). Sensing elements are placed on a soft cushioning substrate with a solid base beneath. Each segment is coated by a rigid material from above.

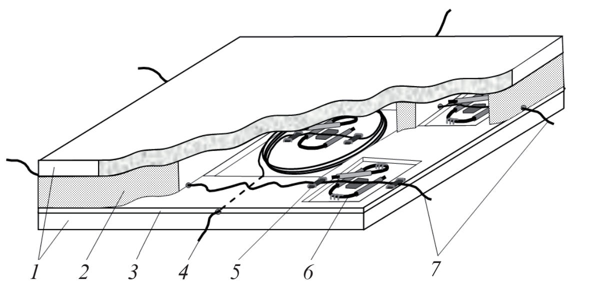

Figure 5. Segment of fibre optical measuring network based on quasi-distributed amplitude sensors: (*1*) protective segment plate made of rigid material; (*2*) elastic medium; (*3*) elastic protector; (*4*) single-mode optical fibre of the OTDR sensor; (*5*) fibre lock; (*6*) sensing element; and (*7*) multimode fibre of the first-type sensor.

The measuring network operates as follows. When a segment is loaded, the fibre light guides passing through the SEs are deformed. The corresponding changes in the light power transmitted through the fibres are recorded by photodetectors in the first-type sensors and by a reflectometer in the OTDR sensor. The corresponding data are fed into a PC, where a special program, based on the neural network principles of data processing [6, 9], treats the network data. After teaching the neural network, the amount of the fibre optical measuring network data becomes sufficient for determining the motion trajectory and the force exerted by the load. These data can be used to classify the object affecting the network.

Figure 6 shows the dependence of light power on the mass of an object loading the SE of a first-type sensor. One can see that the SE sensitivity is $\Delta P/\Delta m = 0.043\ \text{kg}^{-1}$.

Figure 7 shows the results of determining the mass of an object loading different segments of the fibre optical measuring network. We performed 15 measurements using loads of 1.5 and 7 kg. It can be seen that the mass measurement error does not exceed 5%. The mass to be determined for the network breadboard is in the range of 1–10 kg.

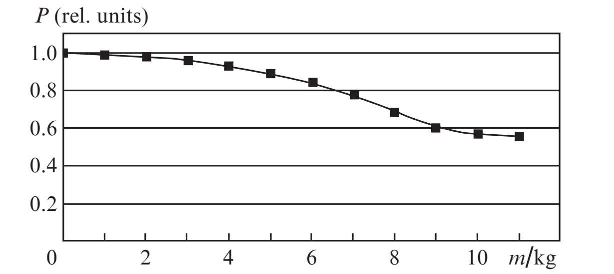

Figure 6. Dependence of the light power on the mass loading the SE of quasi-distributed first-type FOSs.

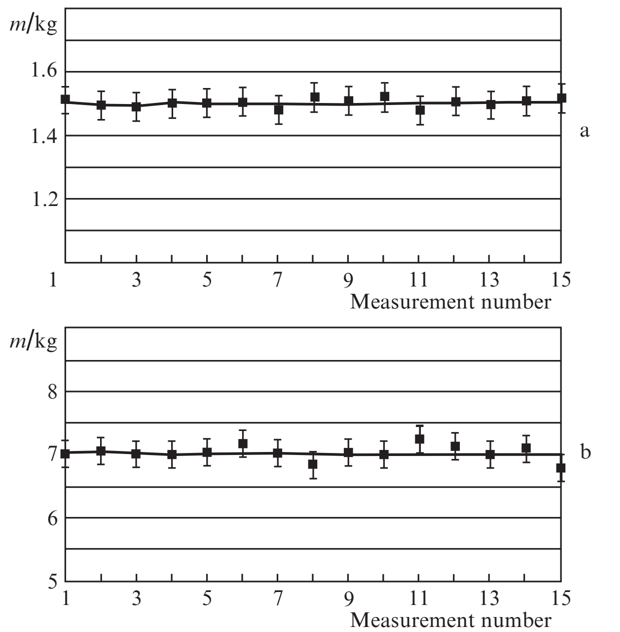

Figure 7. Measured mass of an object loading the fibre optical measuring network (m = (a) 1.5 and (b) 7 kg).

The reconstructed trajectory of a 1.5-kg object is shown in Fig. 8. The error in determining the object position was controlled by the segment sizes (8 × 8 cm) and, correspondingly, amounted to 8 cm. The total operating speed of the system was 50 ms.

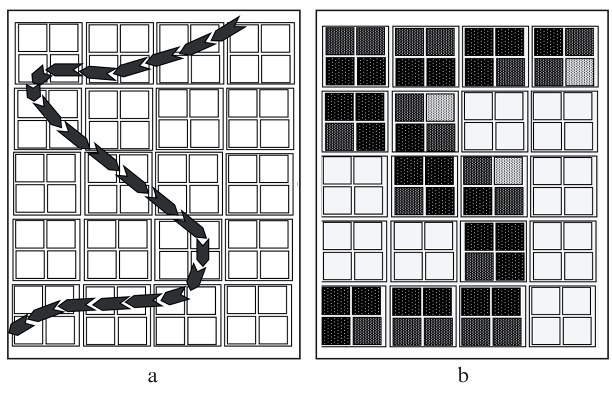

Figure 8. (a) Real and (b) reconstructed trajectories of an object loading the fibre optical measuring network.

As follows from the results obtained, the DFOMN breadboard under consideration, which contains nine quasi-distributed FOSs, allows one to monitor the state of 80 surface area elements. When solving a similar problem using a tomographic DFOMN, one needs 18 FOSs [10].

4. Conclusions

We developed a fibre optical measuring network, designed for determining the load application point and the load mass. It is shown that neural network methods of data processing make it possible to combine an array of quasi-distributed amplitude sensors, based on direct detection of radiation power loss, and a quasi-distributed OTDR-sensor into a unified network. The results of the experimental study of a fibre optical measuring network breadboard are presented, which demonstrate successful reconstruction of the trajectory of a moving load with a spatial resolution of 8 cm, as well as the load mass in the range of 1 – 10 kg at a sensitivity of 0.043 kg^{-1}; the measurement error is 5%.

The results of this study can be used to design distributed optoelectronic information measuring systems aimed at monitoring the state of large-scale objects.

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