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# Quantitative Measurement of Deformation Fields by High Resolution Dynamic Optical OFDR System

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**Abstract:** A metal plate is instrumented by an optical fiber, serving as a sensor. For each plate eigenmode, we compare the computed strain experienced by the fiber to measurements using a high resolution dynamic  $\phi$ -OFDR interrogator. © 2023 The Author(s)

## 1. Introduction

Fiber sensors allow the detection of strain, temperature, pressure, rotation, vibration. Among the wide variety of sensor types, we distinguish in particular discrete sensors from distributed sensors. In this second case, some of the sensors exploit optical phase variations to extract the useful quantity. In 1991, Sirkis proposed a model [1] linking the deformation of an optical fiber of length  $L_{fiber}$ , along its curvilinear abscissa  $s$  to an optical phase variation  $\Delta\phi$  :

$$\Delta\phi = \frac{2\pi n}{\lambda} \int_0^{L_{fiber}} \left[ \epsilon_T(s) - \frac{n^2}{2} \left( \frac{1}{2} (P_{11} + P_{12}) (\epsilon_{N1}(s) + \epsilon_{N2}(s)) + \epsilon_T(s) P_{11} \right) \right] ds, \quad (1)$$

where  $\lambda$  is the optical wavelength,  $n$  is the refractive index,  $P_{11}$  and  $P_{12}$  it's the elasto-optic coefficients,  $\nu$  it's the Poisson coefficient of the optical fiber,  $\epsilon_T(s)$  is the strain along the fiber propagation axis,  $\epsilon_{N1}(s)$  and  $\epsilon_{N2}(s)$  are the strains orthogonal to the fiber propagation axis. This model has been validated by interferometric measurements, i.e. by measuring the accumulated phase along the fiber, for a simple structure (embedded beam) [2]. We propose here to confront this model in a more advanced mechanical system, with a distributed interrogator.

## 2. Mechanical structure under test

We designed a steel plate (dimensions 312x300x14 mm), on which we integrated a standard single mode optical fiber at 1.5  $\mu\text{m}$  (coating 250  $\mu\text{m}$ ) by digging a groove in the form of a double spiral (see Fig.1). Three semicircles with a radius of curvature of 1 cm join the two spirals in the center of the plate. The total length of the optical path on the plate is 8.5 m. The structure is suspended to a gantry by elastic bands, to avoid boundary conditions, which are difficult to model accurately.

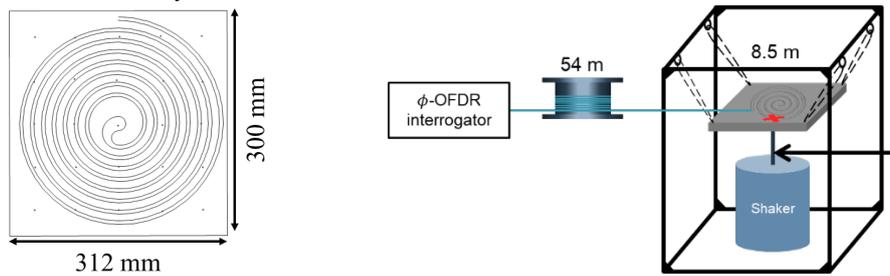


Fig.1. Left: Solution chosen for the fiber path on the plate. Right: Experimental diagram of the measurements under vibrations

The mechanical behavior of the plate has been simulated using CAST3M finite element method software. We also carried out mechanical experimental measurement using shock hammer and frequency response analysis to improve the model in terms of eigenmode frequency, modal damping and shape. Four eigenmodes have been identified (484, 729, 879 and 1227 Hz) with modal damping lower than 1%. For each eigenmode, we further compute the strain experienced by the fiber along its path, and the equivalent accumulated optical phase using (1). The traces are shown in Fig.2. in gray traces. The inclusion of residual uncertainties on eigenfrequency and modal damping in the accumulated phase explains the thickness of the traces.

To perform our optical measurements, we use a  $\phi$ -OFDR interrogator developed in Thales [3, 4]. An OFDR interrogator relies on a continuous laser whose frequency is linearly swept in time. The spatial resolution (SR) of the measurement is inversely proportional to the modulation amplitude of the laser frequency; the modulation period sets the sampling rate. On the one hand, we modulate the laser over 3 GHz, which leads to a 3 cm SR, lower

than the spatial modulations of the individual modes (typically tens of cm). Under these conditions, the modulation frequency is 3 kHz, which fulfils the Shannon-Nyquist criterion for the considered eigenfrequencies of the plate. As shown in Fig. 1, the sensor fiber consists of the fiber bonded to the plate and one additional cable, which connects the interrogator lab to the mechanical test lab. When the fiber arrives in the second lab, it is free for several meters and then connected to the fiber bonded to the plate. The signal passes through the outer spiral and then through the inner spiral. The plate is excited at each eigenfrequency thanks to a shaker with a modal excitation rod. This rod is screwed on the shaker. We placed a force sensor (PCBPieziotronic 208C02) between the rod and the plate. The optical phase extracted from our interrogator is normalized by the injected force, without any other data adjustment. Fig.2 shows experimental measurements obtained only on the area corresponding to the fiber glued on the plate.

#### 4. Results

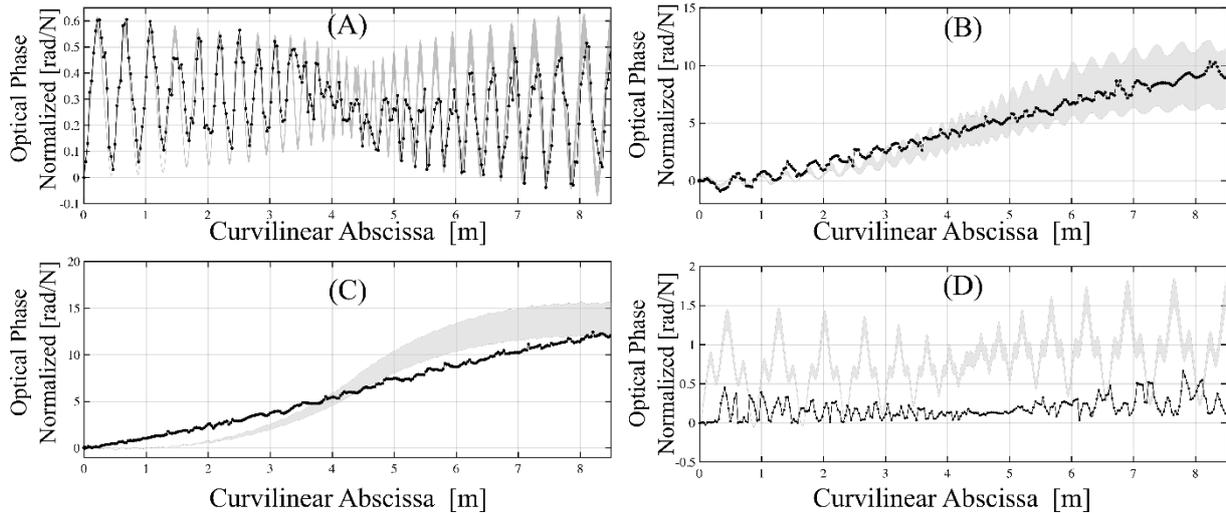


Fig.2. Normalized accumulated optical phases for the first four plate eigenmodes under vibrations (A: 484 Hz, B: 729 Hz, C: 879 Hz, and D: 1227 Hz). Gray: simulations; black: optical measurements at  $\delta z = 3 \text{ cm}/3 \text{ kHz}$ .

On the first eigenmode (Fig.2A), we observe an excellent agreement between the simulated and optically measured phases, in terms of amplitude and shape. For the second mode (Fig.2B), the agreement between measured and predicted phases is also very good. We note a phase slip of the spatial oscillations: after 3 m of curvilinear abscissa, the measured and predicted spatial periods are in phase opposition. We observe the same phenomenon with degraded SR and larger time sampling. For mode 3 (Fig.2C), the measured optical phase exhibit consistent order of magnitude with respect to simulation, but exhibits a linear evolution along the fiber instead of a sigmoid shape. Finally, the agreement on the fourth eigenmode is poor (Fig.2D). The measured phase shows a spatial modulation but does not reproduce the predicted one. It is worth noting that the characteristics (spatial modulation, eigenfrequency) are close to the measurement parameters, especially for the frequency (1.2 kHz) at the limit of the Shannon criterion (1.5 kHz). These two points may explain the poor agreement between the measurement and the prediction.

#### 5. Conclusion

We presented a controlled mechanical test for quantitative comparison of simulated deformation fields of an instrumented plate with a dynamic (3 kHz) and high spatial resolution (3 cm) distributed measurement system using an optical fiber. The agreement between the model and the measurement is very variable from one mode to the other (excellent for the first one, poor for the last one). Further studies on both the interrogator and the simulations are needed to analyze the differences observed on the different modes.

#### 6. References

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