Definition of a Dynamic Optical Sensor for Measuring Unsteady Pressures

P. Chapuis, J. Maillard

J. PHYS IV FRANCE 7 (1997)
Colloque C3, Supplément au Journal de Physique III d'août 1997

Definition of a Dynamic Optical Sensor for Measuring Unsteady Pressures

P. Chapuis and J.M. Maillard

Company BERTIN et Cie, Mechanical and Optoelectronic Divisions, 54 rue Pierre Curie, Z.I. des Gâtines, BP. 3, 78373 Plaisir cedex, France

Abstract. This study presents our contribution to define an optical dynamic sensor. Given that the studies carried out are of an exploratory nature, the first task was to validate the mechanical behavior of the specimen body in the sensor and to check that the signals recorded were reproducible.

To subject the sensor to deformation rates of 10 to 10^2 per second, tests were carried out using the KOLSKY-HOPKINSON apparatus.

The results show that specimen body responds in a satisfactory manner. It remains within the elastic zone for the loads exerted and this is consistent with the results of the sizing calculations carried out.

It was also possible to verify complete reproducibility of the interferometric signals on the basis of several tests conducted on the same sensor located between two polyurethane sheets.

It is also shown that the sensitivity of the standard monomode fiber used in the MACH-ZENDER apparatus is highly dependent on deformation rates.

This result leads us to opt for the use of a polarimetric apparatus using birefrigent shaping fibers in order to limit the intrinsic sensitivity of the two-arm apparatus.

The fact that the fiber is sensitive to deformation rates does not appear in the bibliographical références . We identified it on the basis of tests on the traction/compression machine by varying the load climb rate and on the basis of HOPKINSON bar dynamic tests.

Résumé. Cette communication présente notre contribution dans la définition d'un capteur dynamique optique. Nous avons tout d'abord valider le comportement mécanique du capteur dans son environnement et nous avons observé la reproductibilité des signaux enregistrés. Pour solliciter le capteur à des vitesses de déformation de l'ordre de 10 à 10^2 par seconde nous avons réalisé des essais sur le montage de KOLSKY HOPKINSON.

Les résultats montrent que la fibre optique dans le montage réalisé (MACH ZENDER) est fortement sensible à la vitesse de déformation. Nous montrons également, à l'aide d'un modèle unidimensionnel du montage de HOPKINSON et de la transformée par ondelettes du signal interferométrique délivré par la fibre, qu'il est possible d'identifier expérimentalement le gain du capteur .

1. INTRODUCTION

In order to increase the accuracy of the results obtained with tools using the finite element technique and to correlate these results, it is necessary to carry out an experimental comparison which is more exact than simply measuring the penetration depth. It must provide the basis for readjusting the material law coefficients.

Furthermore, one of the present problems encountered by experimenters carrying out impact tests is how to set up reliable measuring systems with low-cost target materials.
Eliminating the electrical connection which remains a sensitive element in the standard instrumentation is a promising path made possible by optical technologies.

These considerations, together with BERTIN's experience in using optical fibers as intrinsic sensors for static structure deformation measurement, naturally led us to opt for this technology.

The feasibility of a dynamic optical sensor used for measuring unsteady pressures was investigated as the means of meeting these needs.

2. TECHNOLOGIE USED

The technology adopted uses the optical fiber as an intrinsic sensor.

The fiber has a double role. It converts the variation of the physical magnitude to be measured (the measurand) into an optical signal and it transmits this information by its natural wave guide function.

The measurand influences the wave propagation conditions resulting in a variation either of the transmitted flux or the phase or radiation polarization. In these two cases, dephasing of the transmitted rays depends on the optical path which itself depends on the fiber core index n1 and its length L.

Any measurand likely to modify the fiber core index or its length (temperature, pressure or deformation for example) creates a dephasing variation between a measurement fiber and a reference fiber. This is the case with a MACH-ZENDER interferometric sensor.

Polarimetric sensors can be produced using a different type of apparatus. The measurand still influences the optical path but in this case it is the interference between two orthogonal polarization modes of the radiation propagated in a birefrigent fiber that is measured. Thus to produce the sensor a single fiber is only required.

For the applications in question the physical magnitude required to be measured (the measurand) is a pressure level.

3. DESCRIPTION OF THE SENSOR

3.1 Mechanical Desciption

The test body comprises a metallic capillary surrounding the optical fiber and bonded to it in the measurement zone (Figure 1).

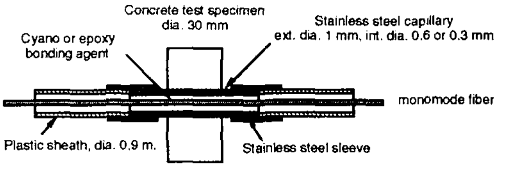

Figure 1

In the ideal application scenario of a field of isotropic external forces applied to the capillary, the pressure detected by the fiber is proportional to the pressure in the vicinity of the capillary. This is the case with fluids.

In the case of solid body substance, the proportionality coefficient between the pressure in the vicinity of the capillary and the pressure detected by the fiber depends on the capillary loading mode.

This requires the gobal sensitivity sensor evaluation wich is a function of intrinsic optical fiber sensitivity and a coefficient named the gain.

We define the gain variation as a function of the shape of the force field applied to the capillary which must be previously established by a finite element calculation.

It should be noted that the applications of this type of sensor are limited to materials for which a foreign body can be inserted during the manufacturing phase (concrete, materials with low melting point or multilayer materials).

This technology was used for concrete and multilayer polyurethane.

For essentially heterogenous materials (such as concrete), the capillary and the bonding agent provide stress smoothing and mechanical protection for the fiber.

The combination of capillary, bonding agent and fiber in the measurement zone results in an isotropic pressure being exerted on the optical fiber regardless of the external loading mode of the capillary.

3.2 Optical Apparatus

	Hopkinson bar	
	ΔT (rad)	ΔP (rad)
Birefringent fiber (stress)	2	0,1
Birefringent fiber (shape)	0,001	0,25
fiber FASE	0,1	540
Mach Zender monomode fibers	24	243

Table 1

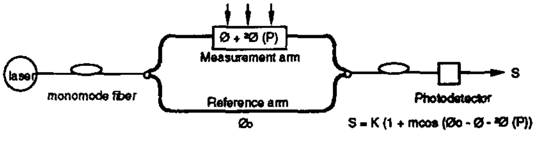

Figure 2

The optical apparatus used during the tests is the MACH-ZENDER type (Figure 2). There are two reasons for this: it can be quickly set up and it complies with the theoretical sensitivity specifications for the monomode fiber.

Table 1 provides the theoretical sensitivity levels of the various optical fibers that can be used for an active fiber length of 0.03 m a Δp of 150 Mpa and a $\Delta T = 10°C$.

4. SENSOR BEHAVIOR CALCULATIONS

4.1 Static Calculations

In static configuration, a 2-D finite element calculation is carried out on a cross-section representing our sensor. The stress is assumed to be planar.

Two loading cases are considered given the unavailability of a coupled analysis of the global behavior of the sensor in the concrete specimen or between the polyurethane plates.

The first loading case corresponds to the application of a constant normal force flux on the boundary of the outer face elements of the steel capillary.

The second loading case corresponds to the application of a normal force flux with sinusoidal distribution on the outer boundary of the outer face elements of the steel capillary.

These two types of load are shown in Figure 3.

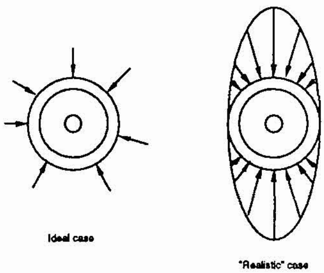

Figure 3

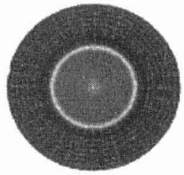
Figure 4

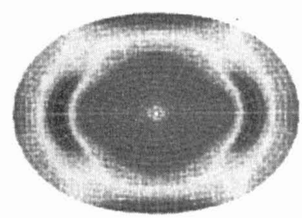
Figure 5

Figures 4 and 5 show a view of the models and the results obtained.

It was seen that when a pressure of 10 MPa is applied in both cases, the fiber response is 0.87 MPa in the case of load 1 (ideal case) and 1.52 MPa in the case of load 2 (realistic case).

We define the gain like the ratio between the pressure obtained in the optical fiber center and the applied pressure.

This means that the global sensor sensitivity is equal to intrinsic theoretical fiber sensivity multiplied by gain. For static condition static gain is estimated at

- 8.70 e-02 when a uniform radial pressure is applied
- 1.52 e-01 when a sine-shaped radial force field is applied.

4.3 Linear Dynamic Calculations

The frequency of the first ring modes of the capillary alone is determined analytically. This is used to evaluate the lowest frequency at which dynamic coupling between the excitation and the structure response begins to occur.

It can be seen that the natural frequency of the ring is 1.8 MHz for a capillary of thickness 0.2 mm. This means that dynamic coupling of the sensor may occur around this frequency with pressure pulses having a period of approximately 0.5 µs.

A front of planar waves propagating at a speed of 4000 m/s moves through the sensor in 0.25 µs given the dimensional characteristics of the capillary (external diameter 1 mm).

This indicates the need to calculate the transient dynamic response of the sensor subjected to a pressure pulse of an appropriate duration.

The purpose of this calculation is to assess the relationship between the input pressure level and the pressure detected by the fiber in the case of dynamic loading.

This relationship must not be identical to the one previously calculated in the static case.

4.4 Transient Dynamic Calculations

For these calculations we made use of the numerical simulation software for impact phenomena or wave propagation problems. It is a Lagrangian formulation code using finite element spatial division and an explicit time integration scheme. The articles referred to in the bibliography (8, 9, 10) provide the required details concerning the content of this software.

The action of a pressure pulse is simulated on the optical fiber + bonding agent + capillary assembly embedded in a material with characteristics similar to concrete (wave propagation rate). The dynamic loading of the sensor is created by the action of a planar wave front. This planar wave front is generated by the impact of a steel plate on the block forming the specimen and containing the capillary.

Figure 6 show the mesh of the central part of the fiber.

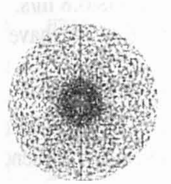
Figure 6

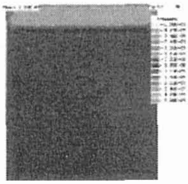
Figure 7

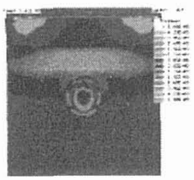
Figure 8

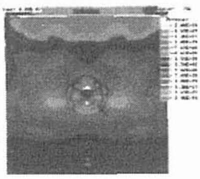
Figure 9

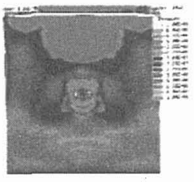
Figure 10

Figures 7,8, 9, 10 show the four characteristic states of the pressure wave before it arrives at the sensor, as it moves across the sensor and after crossing the sensor.

The total duration of the phenomenon is 0.5 µs.

The curves in Figures 11 and 12 show respectively the average pressure and stress according to the direction of wave propagation calculated in the elements at the center of the optical fiber.

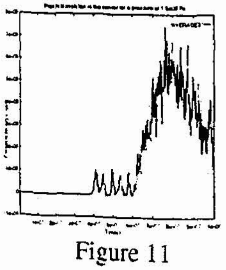
Figure 11

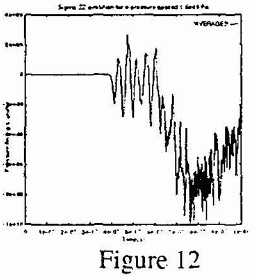
Figure 12

It can be seen that for an input pressure level of 1500 Mpa, the average calculated on the elements representing the fiber core corresponds to a pressure of around 500 to 700 Mpa.

Corresponding to this pressure reduction factor on the fiber of 2 to 3, in accordance whith our gain definition, there is a sensor dynamic gain of between 0.3 and 0.5.

5. SENSOR TESTS

5.1 Analysis Of The Dynamic Tests

The curve of figure 13,14,15 represents the interference fringes recorded during a dynamic test using Hopkinson bars and our apparatus presented figure 2.

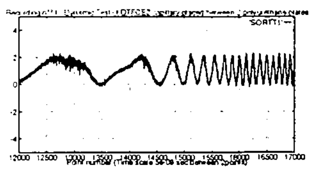

Figure 13

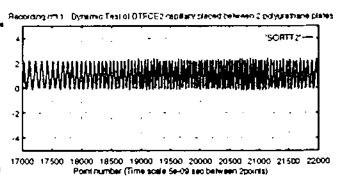

Figure 14

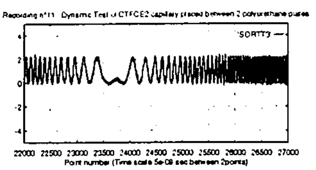

Figure 15

During these tests the sensor is placed between two polyurethane plates. The impact speed is 6.8 m/s.

This curve shows a periodic evolution of the interference fringe frequency, this means that we have a periodic evolution in the pressure gradient.

Our objective is to reproduce this curve using a simplified model of the loading evolution.

The set of results from the deformation gauges bonded to the input and outlet bars of the apparatus provides the wave transfer time as it crosses the specimen. Interference fringes at constant frequency correspond to a constant load climb gradient.

Analysis of the interferometric signal using wavelet techniques provides the time evolution of the pressure gradient. We have made wavelet analysis of the curve presented in figure 13, 14, 15. By taking the integral of peaks curve of this wavelet analysis and re-aligning the force values obtained from the input and outlet bar deformation gauges, it is possible to identify the empirical gain associated with the sensor. We have obtained a gain equal to 40.

6. CONCLUSION

Although computations predict a gain (as defined above) of 0.087 to 0.152 depending on the assumption on application of loading on the capillary in statics and a gain of 0.3 to 0.5 in transients, experimental observations show a gain value between 40 and 50.

One identifies two reasons which may explain this 100 ratio between the sensor apparent sensitivity calculated and the measured one.

- The first one concerns the evolution of the mechanical properties of the specimen material and its possible influence on the shape and intensity of the pressure field around the capillary. For several materials like concrete , the Young modulus varies with the strain rate. The pressure level around the capillary, proprotionnal to ρcv, depends on the loading rate through the variation of the sound velocity C. In this sensor, C acts as a variable and influences its apparent sensitivity.

- The second one concerns the evolution of the intrinsic properties of the monomode fiber and particularly the electromagnetic wave propagation characteristics in the core and in the sleeve.

The restoration of time-based interferometric signals from a uniform loading model using the theory developed on the KOLSKY-HOPKINSON bars is very encouraging. In particular the possibility of associating a model representing the load climb on the sensor by reflecting a succession of waves on the specimen-HOPKINSON bar input and outlet interfaces with wavelet analysis of the optical time signals provides the means of obtaining the pressure level and sensitivity variation in the fiber.

It seems that the initial analysis on the basis of the evolution curve of the force measured on the outlet bar of the HOPKINSON apparatus is not sufficient. The non-linear time evolution of the pressure gradient must also be taken into account to avoid overestimating the apparent sensitivity of the fiber.

Acknowledgements.

The authors would like to acknowledge the support of « Commissariat à l'Energie Atomique (CEA/CESTA) » and we thank particulary Mr Denis HENNEQUIN for his constructive criticisms and suggestions.

References.

[1] Patrice BAILLY "Modélisation des essais de compression dynamiques" - Laboratoire de Recherche Universitaire de BOURGES Université d'ORLEANS

[2] HZAQ, G. GARY, L. ROTA -"Mesure du comportement dynamique des matériaux fragiles aux essais de barres de Hopkinson". LMS Ecole Polytechnique, 91128 PALAISEAU

[3] Patrice BAILLY 1994 "Une modélisation d'un matériau fragile avec prise en compte d'effets dynamiques".Compte Rendu, Académie des Sciences PARIS Vol. 318 series II pages 727 to 732 -

[4] Pierre HALLEY 1985 "Les systèmes à fibres optiques"- EYROLLES

[5] M. FRANCON May 1986 "Thèmes actuels en optique" MASSON -

[6] M. ZHAO HAN 1992 "Analyse de l'essai aux barres de Hopkinson. Application de la mesure du comportement dynamique des materiaux".Thesis

[7] Robert D. BLEVINS "Formulas for Natural Frequency and Modeshape"

[8] Zeus: "Tutorial Numerical Simulation of Impact Phenomenon".

[9] J.A. ZUKAS "Some Common Problems in the Numerical Modeling of Impact Phenomena." Computing Systems in Engineering Vol. 4, No. 1

[10] J.A. ZUKAS, Theodore NICHOLAS, Halloch F. SWIFT, LONGIN, B. GRESZCZUK, Donald CURRAN 1982 "Impact Dynamics". John WILEY and SONS