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Cross-Spectrum Technique for High-Sensitivity Remote Vibration Analysis by Optical Interferometry

Analyse vibratoire ultra-sensible à distance par interférometrie optique

Schwingunsanalyse mittels optische Interferenzmessungen

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SUMMARY

An application of cross-correlation techniques aimed to the improvement of the sensitivity of laser interferometric vibration sensors is described. The interferometer operates remotely, up to 200 meters away, from a moving target without requiring retroreflecting tools. The overall sensitivity in oscillation amplitude measurements is of the order of 0.1 microns in a bandwidth 0,1-150 Hz, with normal atmospheric conditions. Cross-correlation of the output signals of two identical interferometric vibration sensors pointing to the same target from simmetrical remote positions, allows reduction of the air-turbulence background noise giving an ultimate sensitivity of the order of 0,01 microns. Examples of application of this technique for in situ measurements on an hydroelectric arch dam are presented.

RESUME

On décrit une application des techniques de corrélation croisée pour l'amélioration de la sensibilité des instruments de mesure dynamique pour interférometrie laser. L'interférometrie fonctionne à distance, éloigné jusqu'à 200 m du point mobile de mesure, et sans nécessiter des éléments réfléchissants.

Dans des conditions atmosphériques normales, la sensibilité globale pour la mesure d'amplitudes de vibration est de l'ordre de 0.1 microns dans une gamme de fréquences de 0.1 a 150 Hz. La corrélation croisée des signaux provenant de deux interféromètres dynamiques identiques, mirant la même point de mesure à partir de deux positions éloignées symmétriques, permet de réduire le bruit de fond dû à la turbolence atmospherique signe garantissant ainsi une sensibilité extrème de l'ordre de 0.01 microns. Comme exemple d'application de cette technique on présente des mesures in situ pour un barrage-voûte.

ZUSAMMENFASSUNG

Es wird eine Anwendung der Kreuzkorrelationstechnik für die Verbesserung von Laserinterferenzschwingungsmessgeräten behandelt. Der Interferenzmesser kann, ohne Zurückstrahlkörper zu benötigen, bis 200 m entfernt von dem schwingenden Zielpunkt verwendet werden.

Die Gesamtempfindlichkeit unter normalen atmosphärische Zuständen ist ungefähr gleich 0.1 Mikron in einer Frequenzenbreite von 0.1 - 150 Hz. Durch Kreuzkorrelation von zwei symmetrischen Interferenzmessungen eines gleichen Punktes kann man das atmosphärische Störungsgeräusch vermindern, und so eine Empfindlichkeit von ungefähr 0.01 Mikron erreichen Dieser Beitrag beschreibt eine Anwendung von dieser Technik für die Ortsmessungen an einem Gewölbstaudamm.

INTRODUCTION

In this paper we describe an application of cross-correlation techniques aimed to the improvement of the sensitivity of a laser intereferometric vibration sensor. The interferometer operates remotely from a moving target without requiring retro-reflective mirrors. It is a polarizing interferometer based on a Michelson scheme with a short internal reference path and a long external path which projects to the target through a telescope (Fig. 1). The same telescope collects the laser light scattered back from the target. Any surface is suitable: concrete, metals, bricks, etc. The surface roughness provides the scattered light which is used by the interferometer. The power of the projecting laser light (λ = 632.8 nm) is kept below 5mW for safety reasons.

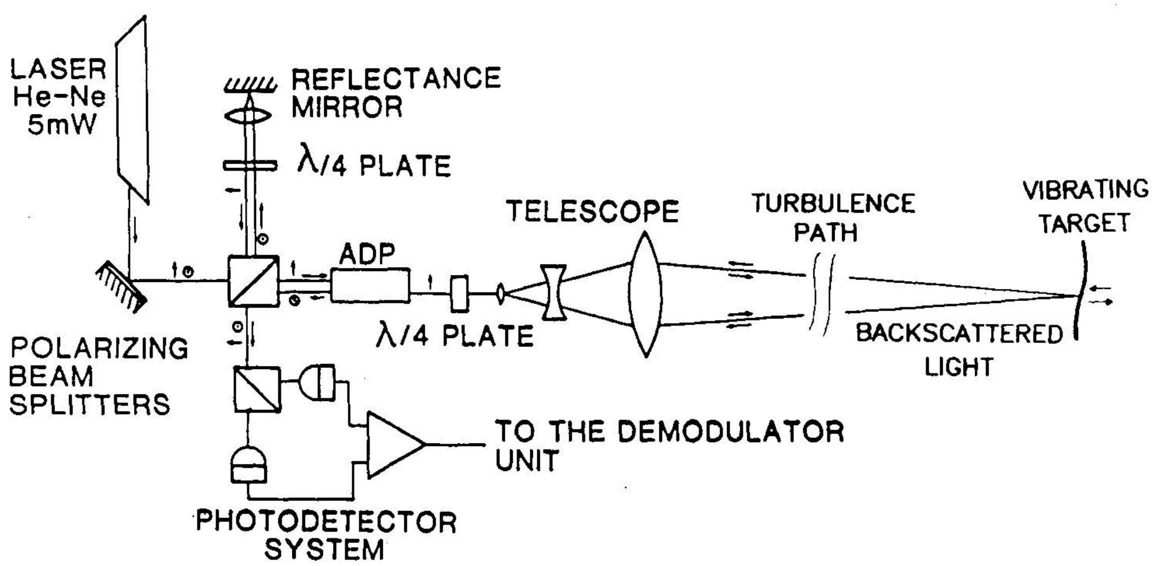

Fig. 1 - Optical set-up of the interferometer.

The interferometer operates up to 200 meters away from the target and is optimized for vibration measurement in the range 0.1-150 Hz which is suitable for tests of large civil structures. A detailed description of the interferometer and some examples of field applications are presented in Ref. 1 and 2. In Ref. 1 the sensitivity of the interferometer is discussed in terms of various sources of noise. The atmospheric turbulence gives the largest contribution since the random fluctuation of the refractive index along the propagation direction is detected by the instrument as target vibration. The effect of the beam wandering in the atmosphere due the turbulence, has been efficently reduced by an opto-electronic beam steering loop built in the interferometer. The overall average sensitivity in oscillation amplitude measurements performed at 100 meters away from the target is of the order of 0.1 microns. An example of the frequency domain behaviour of the turbulence effect in real environment is shown in Fig. 2. The data are obtained by aiming the interferometer to a fixed point on a rock 150 meters away. The spectral behaviour is roughly of the type 1/f.

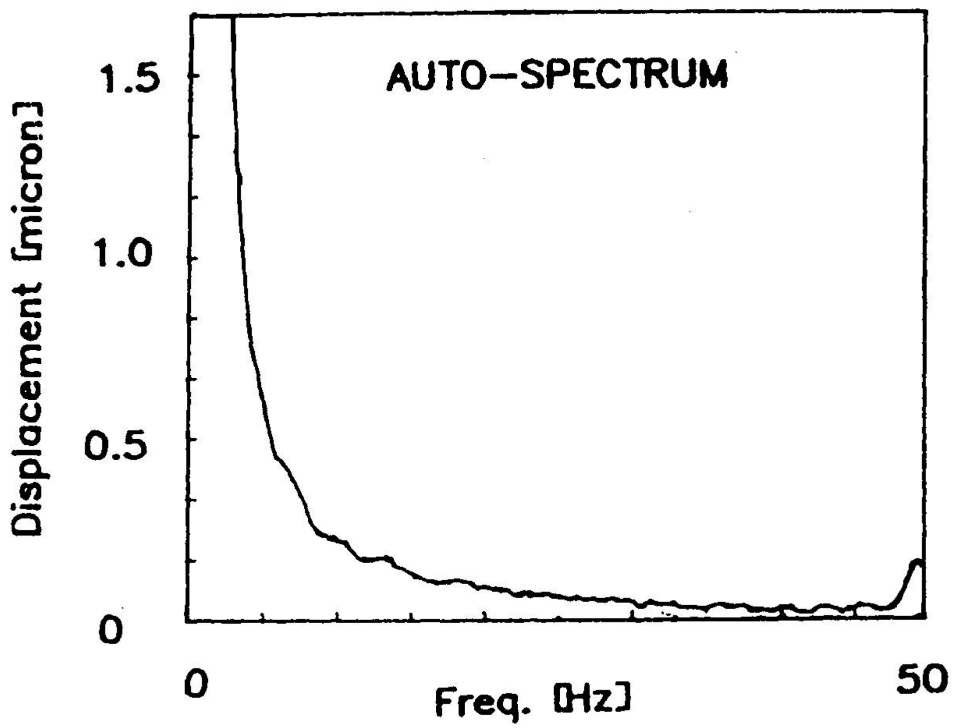

Fig. 2 - Typical noise frequency spectrum due to turbulence, measured by aiming the interferometer to a fixed point 150 meters away.

The idea described in this paper is to use two identical interferometric vibration sensors pointing to the same target from simmetrical remote positions and cross-correlate the two measured vibration signals. This configuration was experimentally tested in the laboratory on a simulation system and then used in field measurments. The obtained results show a good reduction of the turbulence background noise allowing an ultimate sensitivity of the order of 0.01 microns.

2. THEORETICAL BACKGROUND

Cross-correlation techniques are a powerfull tool to reduce uncorrelated informations among signals (Ref. 3). In our case, the vibration signal detected by the optical interferometric system (OIS) contain informations of the measurement path due to turbulence. When we use two OISs pointing to the same target, we obtain two vibration signals containing the same target vibration information (identical, except eventually for a constant multiplicative factor, which depends on the geometry) and two different noise contributions that can be considered a priori uncorrelated because the optical paths of the two intereferometric sensors are different. Therefore by averaging some suitable products of the two signals it is possible to obtain a spectral information of the vibrating status of the target without the turbolence noise. Let us consider the cross-spectrum C_{xy} of the two signals delivered by the interferometers. The cross-spectrum gives, in the frequency domain, the same information of the cross-correlation function in time domain. We call C^{N}_{xy} the cross-spectrum between the two signals X and Y averaged N times, that is the aritmetical average of N determinations of C_{xy} each of which lasts for a time mainly determined by the frequency resolution required in the cross-spectrum measurement. For instance, for a commune Fourier Analyzer, like the HP 3582 A, a frequency resolution of 0.2 Hz at a frequency span of 25 Hz requires a time of 10 sec for each determination. At a span of 1 KHz with a frequency resolution of 8 Hz the time reduces to 0.25 sec. If we denote by * complex conjugation, C_{xy} is defined by

$$C^{N}_{xy} = 1/N \; [\sum_{1}^{N}{}_{i} \; X^{*}_{i} \; Y_{i}] \qquad (1)$$

where

$$X = Ae^{j\vartheta_{A}} + N_{A}e^{j\vartheta_{NA}}$$

$$(2)$$

$$Y = Be^{j\vartheta_{B}} + N_{B}e^{j\vartheta_{NA}}$$

are the frequency spectra of the two signals. A, B, ϑ_{A} and ϑ_{B} represent amplitudes and phases of the deterministic part of the two spectra and N_{A}, N_{B}, ϑ_{NA}, ϑ_{NB}, the corresponding noise contributions. In absence of the deterministic part of the signal (that is with turbulence noise only) the cross-spectrum goes to zero for large values of N. In fact combining equations (1) and (2)

$$C^{N}_{xy} = 1/N \; [\sum_{1}^{N}{}_{i} \; N_{A}N_{B}e^{j(\vartheta_{NB}-\vartheta_{NA})}]$$

the mean square modulus of the cross-spectrum becomes

$$\overline{|C_{xy}|}^{2} = \overline{(N_{A}N_{B})}^{2}/N \qquad (3)$$

With the assumption of random phase distribution among the noise signals. In presence of the deterministic signals (that is with target vibration signal mixed with turbolence noise) the mean square modulus of the cross-spectrum becomes

$$\overline{|C_{xy}|}^{2} = \overline{(AB)}^{2} + \overline{(AN_{B})}^{2}/N + \overline{(N_{A}B)}^{2}/N + \overline{(N_{A}N_{B})}^{2}/N \qquad (4)$$

We see that increasing the number of averages the terms containinig noise reduce with respect to the derministic part of the signal and therefore the overall signal to noise is increased.
In order to give a qualitative understanding of cross-spectrum measurements on noise signals, in Fig. 3 we show the average noise level of the cross-spectrum measured in different conditions of frequency spans and number of averages N of the Fourier Analyzer for two independent white noise input signals of fixed amplitudes.For white input noise the cross-spectrum is flat with frequency. Therefore only its average value on all frequencies is reported in Fig. 3. We see that the noise cross-spectrum is reduced either by reducing the bandwidth (smaller frequency span) or by increasing the number of averages N.

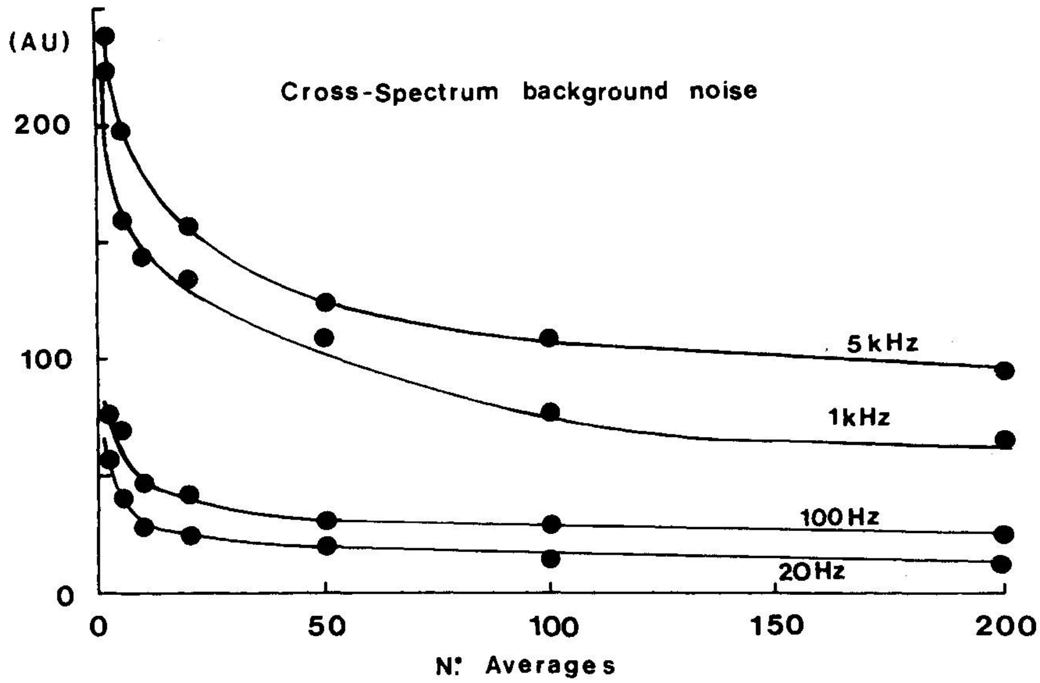

Fig. 3 - Average cross-spectrum of two uncorrelated white noise signals reported as a function of the frequency span of the spectrum analyzer and the number of averages.

Again the use of two white noise signals of fixed amplitudes N_A and N_B allowed us to check equation (3). We measured the mean square modulus of the cross-spectrum for a fixed frequency span of the Fourier Analyzer (100 Hz) for increasing N's. The data are reported as a function of N in a log-log plot. They follow a straight line with a minus one slope. The straight line is the prediction of equation (3) with the values N_A and N_B given by the white noise generators. In order to increase the accuracy of the test, each data point corresponds to the aritmetic mean of repeated measurements (the number of which is indicated above the dots in Fig. 4) in the same experimental conditions.

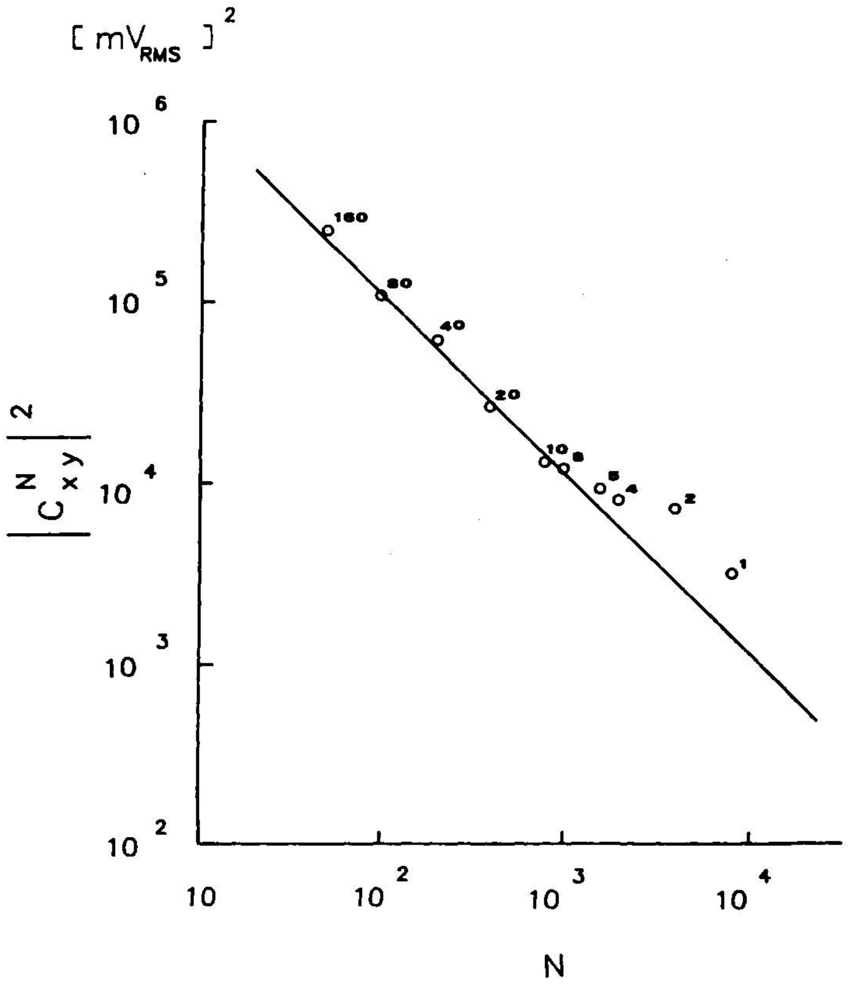

Fig. 4 - Log-log plot of the average square modulus of the cross-spectrum as a function of the number of averages for two uncorrelated white noise signals of known amplitudes. The straight line is the prediction of eq. (3).

3. LABORATORY SIMULATION

The cross-spectrum technique has been tested in the laboratory with a simulation of the turbulence noise. The experimental set-up is sketched in Fig. 5. The laser vibrometers are placed on a stable granite table. They are directed to a piezoelettrically driven target along simmetrical paths. A turbulence simulator is inserted on the trajectory of both laser beams. The simulator introduces a random optical path modulation with the same spectral characteristics of real atmospheric turbulence measured in the field (see Fig. 2).

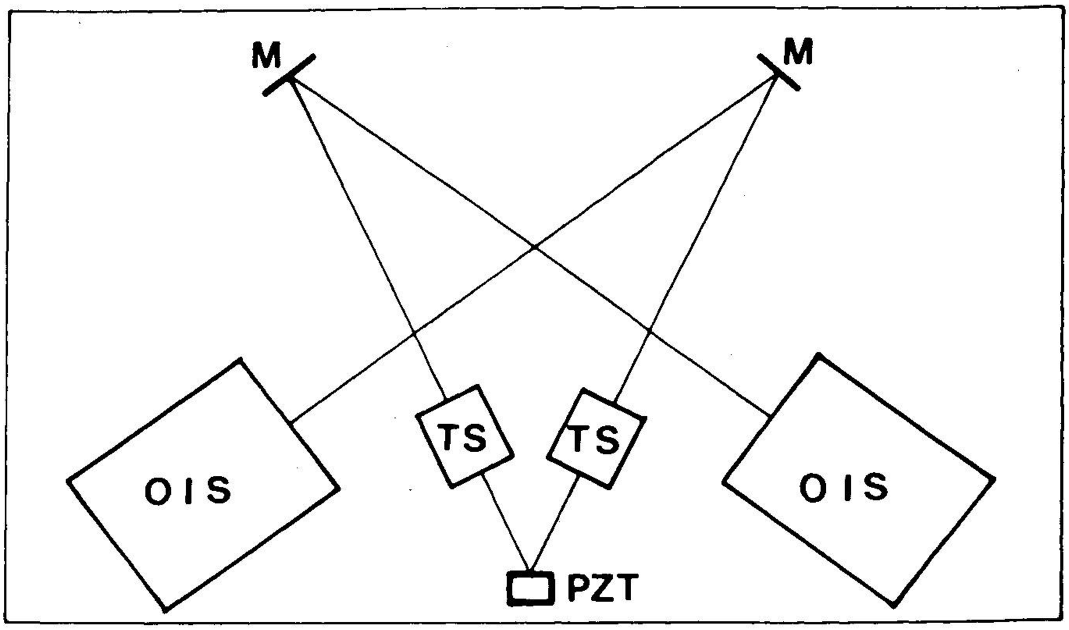

Fig. 5 - Experimental set-up for simulation of the turbulence noise.

Fig. 6 shows the operating principle of the simulator. Two glass plates are mounted on the shaft of two galvanometers which are driven by an electrical signal of opposite polarity. The plate rotation introduces the desired optical path modulation and an undesiderable beam displacement. This is compensated by the antiphase rotation of the other plate. The simulator are driven by random noise signals produced by two independent noise generators which have a 1/f spectral distributions (obtained via amplification and filtration of a diode junction noise).

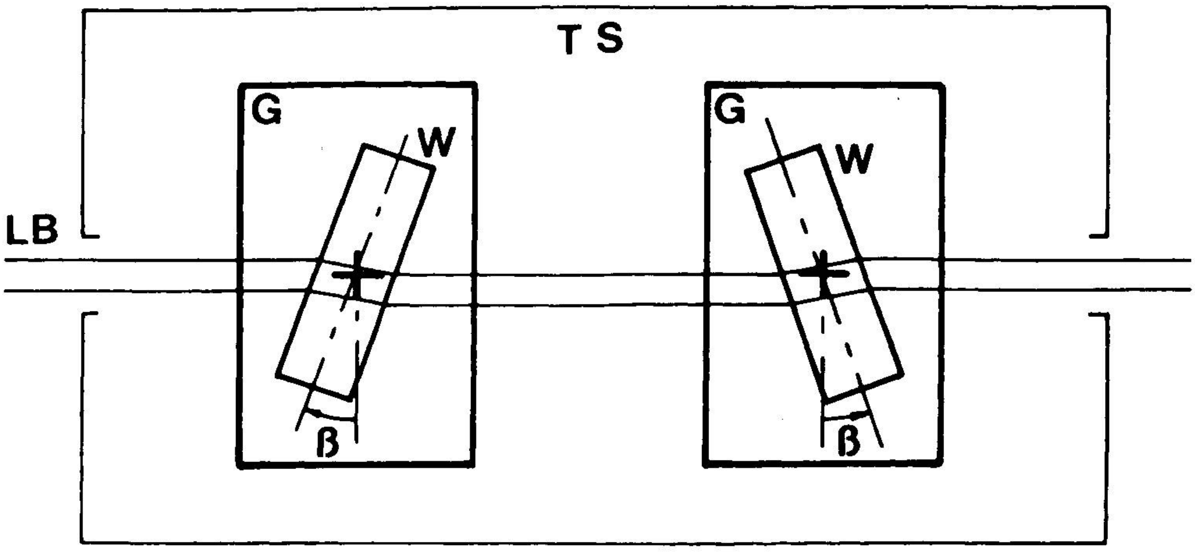

Fig. 6 - Operating principle of the optical turbulence simulator.

The vibrometer signals are analized by an HP 3582 A Fourier Analyzer connected to an HP 85 desktop computer. Figg. 7a) and 7b) show the performance of the cross-spectrum technique applied to the simulation signals. Fig. 7a) reports the individual spectra of the two vibrometer signals with both noise and deterministic parts. The target vibrates at 5 Hz with an amplitude of about 0.34 microns. The cross- spectrum of the same signals, analyzed in the same conditions (100 averages) as for Fig. 7a), is shown in Fig. 7b). The increase of sensitivity is quite noticeable.

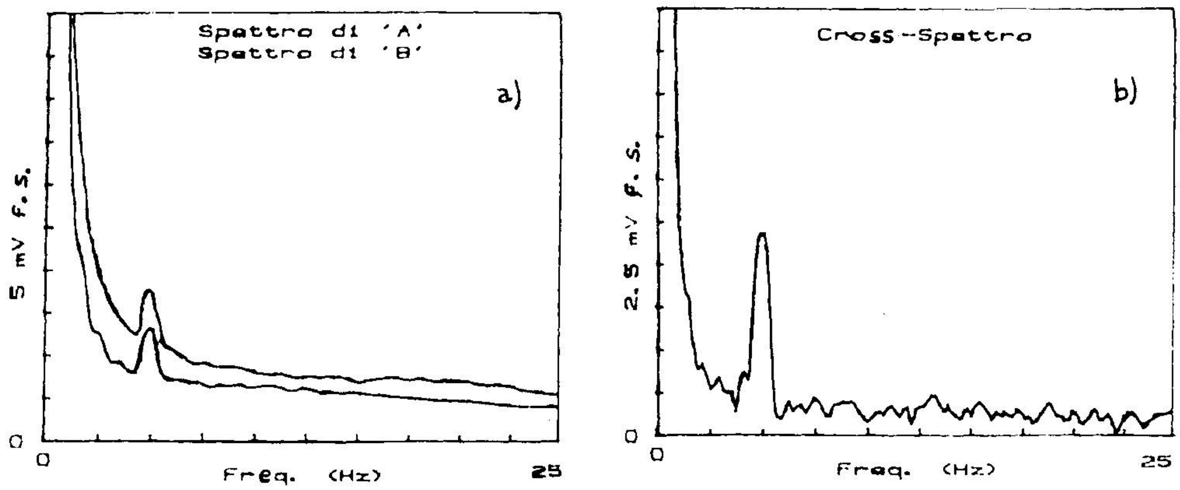

Fig. 7 - a) Spectra and b) Cross-spectrum of signals from the simulation system.

4. - FIELD MEASUREMENTS

The cross-spectrum technique has been tested in situ on an hydroelectric arch dam placed in the Eastern Italian Alps, 150 meters large and 100 meters high. The work was aimed to access the maximum sensitivity of the laser interferometric vibration sensor in field measurements.

The dam vibration was excited by the random noise produced by a waterfall (approximately 10 tons of water per second falling into the lake, 50 meters away from the dam from a height of 10 meters). The two laser vibrometers were placed about 150 meters away from the dam, one at each side of the valley below the dam. The distance between the two interferometers was about 200 meters. The optical paths of the two laser beams are completely different so that the turbolence noise is uncorrelated in the two signals. Fig. 8a) shows the frequency spectrum of the signals given by the two laser vibrometers pointing to two different points of the dam. The peaks, which correspond to the resonance frequencies of the dam, are barely detectable untop of a turbolence noise background. The cross-spectrum of the two signals, after 64 averages, is shown below in Fig. 8b).

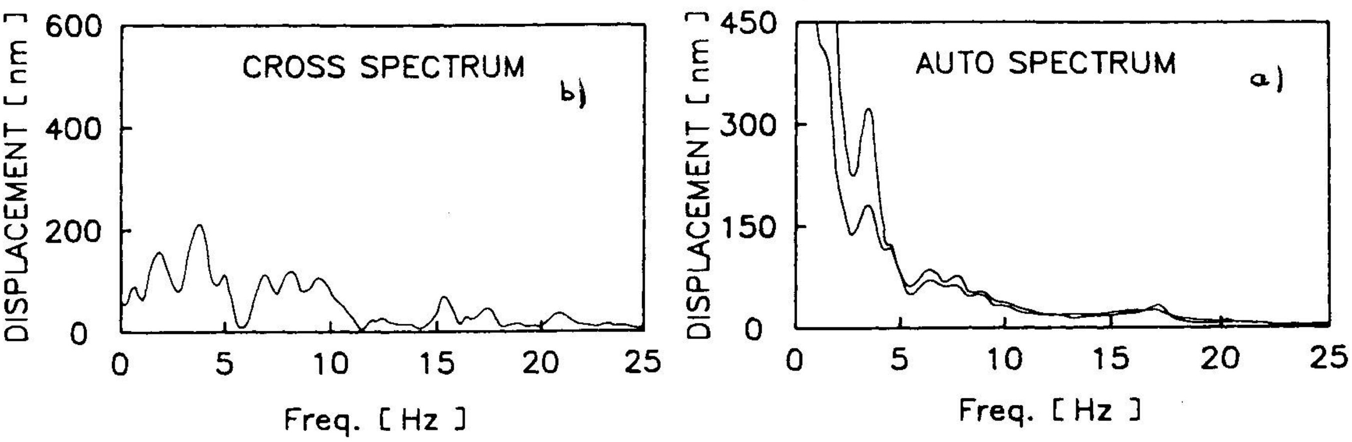

Fig. 8 - a) Spectra and b) Cross-spectrum of signals obtained in situ, measuring the natural vibration of an arch dam.

The noise contribution is strongly reduced and the structure resonance of the dam is evident. Figg. 9 and 10 show two examples of measurements of the dynamical responce of the dam with random excitation (noise from the waterfall).

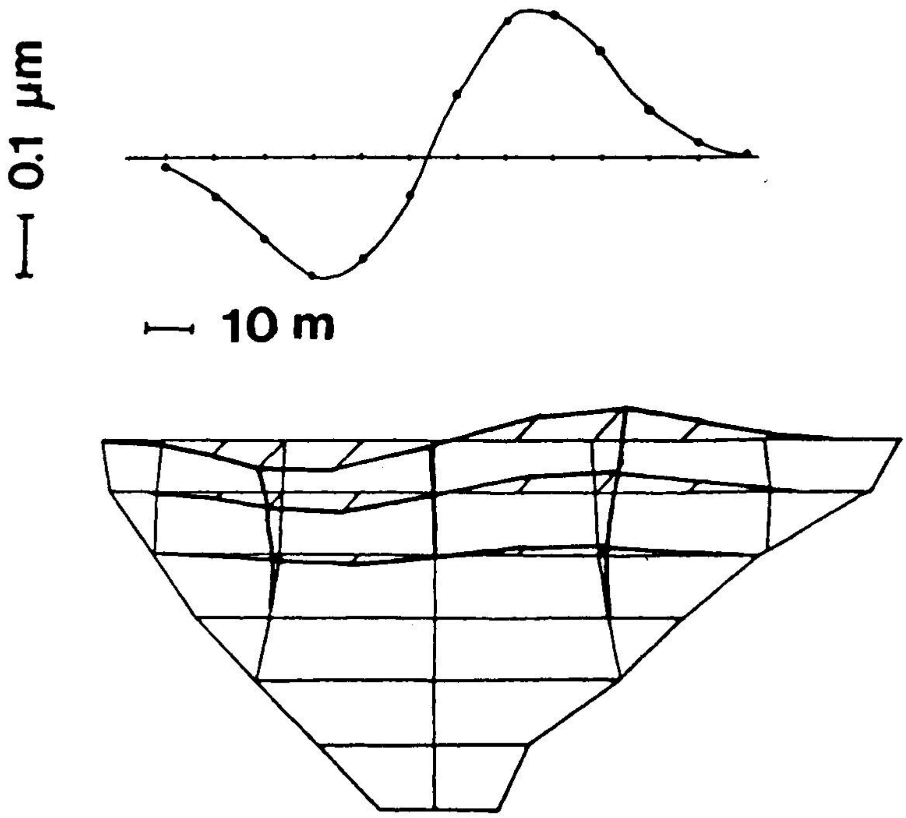

Fig. 9 - First antisimmetrical mode at 3.8 Hz measured by the interferometric vibrometers compared with a finite-element calculation.

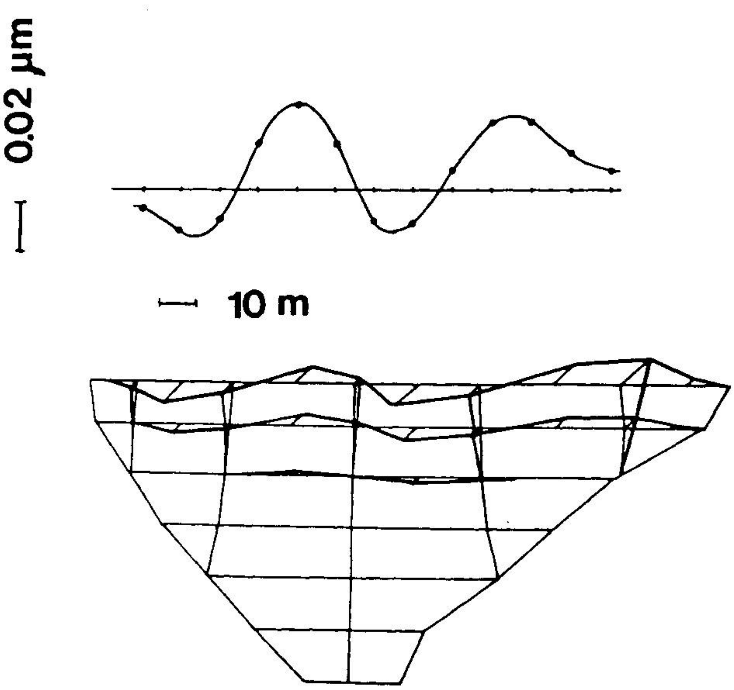

Fig. 10 - The same as Fig. 9 for the first simmetrical mode at 7.6 Hz.

One vibrometer is aimed to a fixed point of the dam. The other one is scanned and data are recorded. For each resonance frequency it is possible to draw the vibration pattern along the line of scanning. Normalization of the amplitude of the fixed vibrometer accounts for the fluctuations in the random excitation force (Ref. 4). The upper parts of Figg. 9 and 10 correspond to the measured vibration patterns at 3.8 and 7.6 Hz measured with this technique along the upper horizontal line of the dam. The lower parts of the figures give the dinamical responce of the dam predicted with a "Finite Element" model calculation (Ref. 5) for that frequencies. The agreement between calculated and measured pattern is good. The sensitivity of the technique is remarcable because it allows measurements of vibration amplitudes which are well below the rubulence noise level (compare Fig. 2 with Fig. 9 and 10).

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