# DYNAMIC TEST OF AN ARCH DAM USING A LASER LIGHT VIBRATION SENSOR

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## SUMMARY

This paper describes a laser light vibration sensor based on the Michelson interferometer principle. It operates with a 5 mW He-Ne laser source even at 200 m away from the moving target without the need of retroreflective tools. Careful optimization of the electro-optic design reduces the effect of environmental disturbances and allows vibration amplitude resolution of 0.2 μm with flat response in the bandwidth 0.1-150 Hz.Field tests and actual measurements on an arch dam are shown.

## INTRODUCTION

We describe a laser light vibration sensor able to operate far away from the moving target without the need of retroreflective tools. This useful feature, combined with excellent accuracy, makes this instrument complementary and sometimes more flexible than conventional ones, like accelerometers, geophones etc. The instrument is placed away from the moving structure and is mounted on a tripod with incorporated span and tilt facilities. The laser beam can then be directed to different points on the structure to map its vibration characteristics.

The optical principle of the method has been known for many years, but only the advent of the laser allowed its practical application(1-5). The system is in principle a Michelson polarizing interferometer, designed to operate at large distance. The vibration target plays the role of a moving mirror in one light path of the interferometer, the other path being fixed. For normal field condition the system gives submicron resolution in the vibration amplitude at 200 meters away from the target in the frequency range 0.1 - 150 Hz. Narrow bandwidth operation increases resolution to 0.01 μm.

Such performance has been obtained by careful optimization of the electrooptical design and by addition of facilities which reduce the strong effect of environmental disturbances, like unwanted vibrations of the interferometer head and atmospheric turbulence.

## OPERATION PRINCIPLES

The system employs a He-Ne laser with a power of 5 mW at the wavelength of 6328 Å. The light beam is focused on the moving target by means of a telescope which also acts as a receiving aperture for the light back scattered from the target "Fig.1". The laser beam is phase modulated by an electrooptic crystal. Modulation is required to sense the direction of target motion. The outgoing and returning light are compared in a Michelson interferometer. The light intensity fluctuations are converted by two photodetectors in a balanced mixer to give a frequency signal determined by the target motion. The balanced mixer is used to eliminate most of the laser

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noise. A frequency tracker(6-7) gives the target velocity and hence by integration, the vibration amplitude.

## NOISE PROBLEMS AND REDUCTION OF UNWANTED DISTURBANCES

The attainable resolution and the ultimate performance of the system is affected by three main types of disturbances: electronic noise in the equipment, unwanted mechanical vibrations of the measuring head and propagation noise on the laser light beam due to atmospheric turbulence. Careful design reduces the electronic noise to negligible values, typically less than 0.05 µm of equivalent displacement in the bandwidth 0.1 to 150 Hz. The other two sources of disturbance are more severe and particular effort has been made to minimize them.

### Interferometer Vibrations

The interferometer is sensitive to relative motions. Mechanical vibrations of the measuring head will therefore affect the signal. Usually these vibrations are uncorrelated with the target motion. However the motion of very heavy targets, like arch dams, may react on the surrounding ground even at hundreds of meters away. The performance of the instrument can be greatly improved if the effect of mechanical vibrations of the measuring head are suppressed. This is accomplished by an accelerometer which measures the vibrations of the interferometer head in a direction parallel to the beam axis. The accelerometer output is integrated twice and properly equalized in gain and phase, in the frequency range 1 Hz-50 Hz, in order to match the response of the interferometer. Subtraction of the accelerometer signal from the interferometer output allows a tenfold suppression of the vibrations of the measuring head.

### Atmosheric Turbulence Noise

Propagation of a light beam through the atmosphere is affected by turbulence. Local pressure and temperature fluctuations induce refractive index variations along the optical path. Two main effects can be distinguished: i) random phase modulation of the optical beam due to the refractive index variations along the propagation direction; ii) wandering around of the light beam due to refractive index gradients normal to the propagation direction.

The first effect cannot be overcome and sets the ultimate resolution limitation for field operation of the system which is equivalent to a target displacement. It is a low frequency noise mainly below 50 Hz.(8)

The second effect has been gratly reduced with a feed back control built in the interferometer. The system automatically compensates the angular displacements of the propagating beam acting on a small lens in the projecting telescope. The lens position is electrically controlled in a plane perpendicular to the beam axis. In the absence of control the laser spot wanders around randomly on the target. With normal atmospheric conditions the light spot is roughly 1 mm in diameter at 100 m away and goes around on the target by one or two centimeters. The target is a rough surface, like concrete for instance, which retroreflects light differently from point to point. A conical beam scan, induced by the lens control system, searches for the target point of maximum reflectivity within 5 microradians and than locks to it. This is accomplished by a feed back loop which senses the light intensity on the photodiodes and drives the telescope lens consequently. As a result the laser light spot is kept still on the target during field operation even in presence of moderate winds (say,with 5-10 m/sec velocity). One is left only with small random shape fluctuations of the light spot which are due to high order space derivatives of the refractive index along the light path. The influence of this effect on the interferometer sensitivity has not been investigated. It should be negligible.

The beam steering technique outlined above gives three important advantages: firstly it provides larger and much more stable light signals which make the electronic processing more efficient, secondly it reduces phase fluctuations in the laser beam which result from path length fluctuations due to the beam wandering, thirdly it avoids phase variations of the retroreflected light due to the continuous change of the set of scatterers on the target while the beam is wandering.

The noise reduction obtained with the insertion of accelerometer and beam steering techniques allows a typical resolution of about 0.1-0.2 μm in the whole instrumental bandwidth with a 100 meters target distance and normal atmospheric conditions.

Of course further increase in resolution can be obtained if narrow bandwidth operation can be allowed. This is the case for instance in dynamic testing of structures. They may be deliberately put into vibration by a known oscillatory force. Narrow band phase locked techniques can be used to measure vibration amplitudes at known frequencies. In fact a large noise reduction is obtained when the interferometer output is analyzed synchronously with the signal available from the exciting machine. We have used a double channel lock-in amplifier operating in the vector track mode. In this case a phase information is also available. Once a certain bandwidth is selected, which sets the response time, the lock-in amplifier measures only the r.m.s. amplitude of the part of the input signal which meets the two following conditions; it is at the frequency of the reference signal, within the selected bandwidth, and keeps a fixed phase relationship with the reference during the response time. The sensitivity of the system is increased by reducing the bandwidth.

## FIELD TESTS

Field tests of the system have been performed at the Barcis arch dam, in a mountain area of Eastern Alps.

The resolution of the system has been measured with an electrically controlled test target which is placed on a rock close to the dam. The interferometer head and the test target are shown at A and B in "Fig.2". The test target is mounted on a piezoceramic trasducer which can be driven accurately."Fig.3" shows a sample of the interferometer signal which is due to a 0.25 μm peak to peak sinusoidal oscillation of the target at 8 Hz where the signal analysis bandwidth is 100 Hz.

The highest resolution of the system is exploited with a narrow bandwidth operation. This can be used to advantage in the case of the dynamic test of an arch dam. The dam is set into oscillation by a rotating type shaking machine from which a reference signal is available. This signal gives the frequency and the phase reference of the oscillating lateral force impressed to the dam. The narrow band operation of the system has been checked first with the test target whose driving signal provided the reference for the lock-in amplifier. The resolution curve of "Fig.4" was obtained by reducing the applied voltage on the target and recording the lock-in amplifier output. The bandwidth was reduced for smaller vibration amplitudes. It is shown that a resolution of 0.01 μm r.m.s. is reached with a bandwidth of 0.001 Hz at 8 Hz oscillation frequency.The target distance is 60 m The trasducer response was previously calibrated in the laboratory by interferometric techniques.

As an example of the system performance for a forced dynamical test, "Figs.5a and 5b" shows the deformation of the Barcis arch dam measured at various points for two horizontal planes, 6 meters and 19 meters below the dam crest respectively, at 10.37 Hz, which is a resonance frequency for the structure. Two shaking machines placed on the dam crest, points D and E of "Fig.2", rotate synchronously. The interferometer measures the component of the dam displacement along the laser beam direction. Therefore the radial and tangential displacements of each point of the dam are obtained with two independent measurements performed from station points A and C in "Fig.2". Vertical displacements are not taken into account.

Table I gives the numerical values of the r.m.s.radial and tangential displacements drawn in the upper graph of "Fig.5". The point sequence is from left to right. The phase responce, references to the shaking force, is also reported for each point. It is seen that a vibration node is very accurately determined by the sign change in the phase.

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TABLE I - TANGENTIAL AND RADIAL DISPLACEMENTS OF THE BARCIS ARCH DAM EXCITED AT 10.37 Hz AT 6 m AND 19 m BELOW THE DAM CREST RESPECTIVELY

| Coord.of the tested points on the dam wall | | Radial displacements | Tangential displacements | Relative Phase |
|---|---|---|---|---|
| X (m) | Y (m) | (µm) | (µm) | (degrees) |
| | | 6 m below the crest | | |
| 4.6 | 9.0 | 17.58 | 11.55 | - 116° |
| 6.4 | 10.7 | 16.95 | 06.07 | - 115° |
| 8.3 | 12.3 | 16.22 | 03.65 | - 114° |
| 10.3 | 13.7 | 14.90 | 02.68 | - 113° |
| 12.4 | 15.0 | 12.51 | 03.54 | - 108° |
| 14.5 | 16.1 | 08.82 | 02.17 | - 101° |
| 16.8 | 17.1 | 04.47 | 00.03 | - 77° |
| 19.1 | 17.9 | 03.50 | 01.24 | + 8° |
| 21.5 | 18.5 | 09.12 | 01.04 | + 40° |
| 23.9 | 18.9 | 16.28 | 00.05 | + 48° |
| 26.4 | 19.2 | 23.23 | 00.71 | + 52° |
| 28.8 | 19.3 | 29.78 | 00.24 | + 54° |
| 31.3 | 19.2 | 33.93 | 07.67 | + 66° |
| 33.7 | 19.0 | 37.27 | 08.46 | + 65° |
| 36.1 | 18.6 | 38.71 | 08.78 | + 64° |
| 38.5 | 18.0 | 37.58 | 08.19 | + 65° |
| 40.9 | 17.2 | 34.51 | 08.28 | + 67° |
| 43.1 | 16.2 | 29.72 | 07.42 | + 71° |
| 45.3 | 15.1 | 25.52 | 02.17 | + 60° |
| 47.4 | 13.9 | 18.40 | 02.54 | + 62° |
| 49.4 | 12.5 | 11.47 | 03.00 | + 67° |
| 51.4 | 10.9 | 05.55 | 02.76 | + 85° |
| 53.1 | 9.2 | 02.46 | 01.49 | + 175° |
| | | 19 m below the crest | | |
| 9.6 | 13.7 | 05.70 | 03.09 | - 88° |
| 13.8 | 17.7 | 03.61 | 01.96 | - 56° |
| 18.6 | 20.7 | 01.88 | 03.19 | + 25° |
| 24.0 | 22.7 | 07.69 | 04.19 | + 43° |
| 29.7 | 23.4 | 13.17 | 00.57 | + 48° |
| 35.5 | 22.9 | 12.15 | 03.01 | + 51° |
| 40.9 | 21.2 | 04.78 | 05.19 | + 61° |
| 45.9 | 18.5 | 02.35 | 03.37 | - 150° |
| 50.2 | 14.6 | 05.06 | 01.79 | - 160° |
| 53.1 | 9.6 | 03.57 | 01.60 | - 170° |

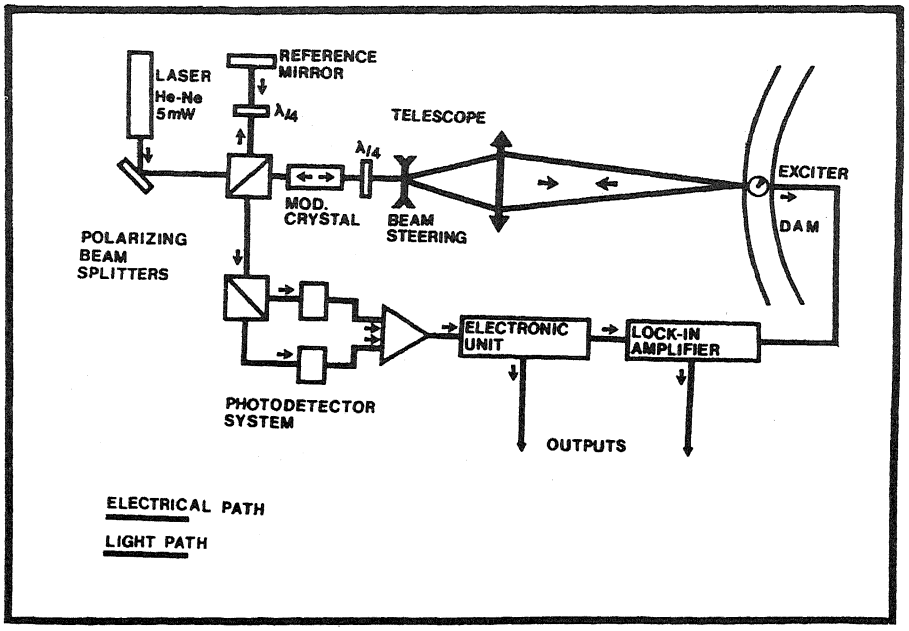

FIG.1 SCHEMATICS OF THE MEASURING SYSTEM.

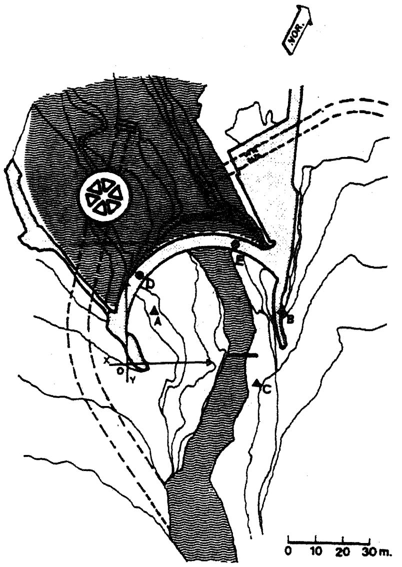

FIG.2 MAP OF BARCIS DAM.

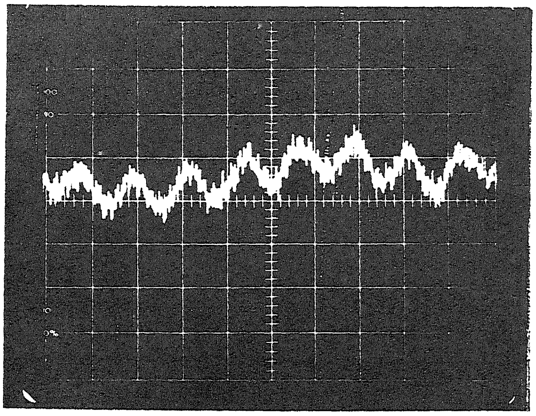

FIG.3 TYPICAL INTERFEROMETER SIGNAL FOR A 8 Hz SINUSOIDAL OSCILLATION OF THE TARGET WITH 100 Hz BANDWIDTH. THE VERTICAL SCALE IS 0.25 µm/cm.

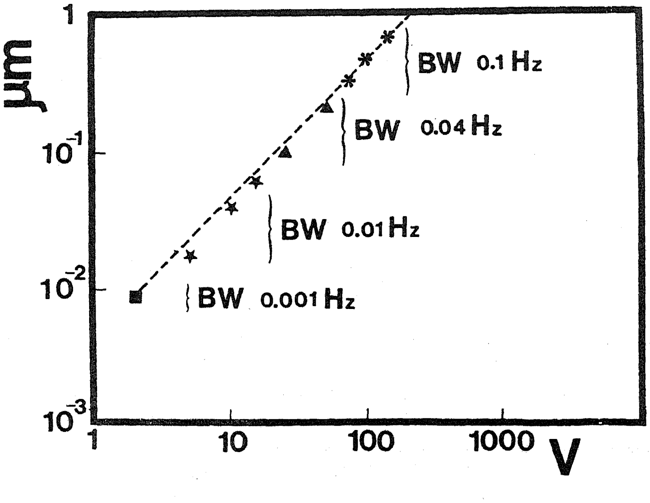

FIG.4 RESOLUTION CURVE WITH NARROW BANDWIDTH (BW) OPERATION. MEASURED DISPLACEMENTS (r.m.s.) VERSUS TEST TARGET DRIVING VOLTAGE (r.m.s.) AT 8 Hz.

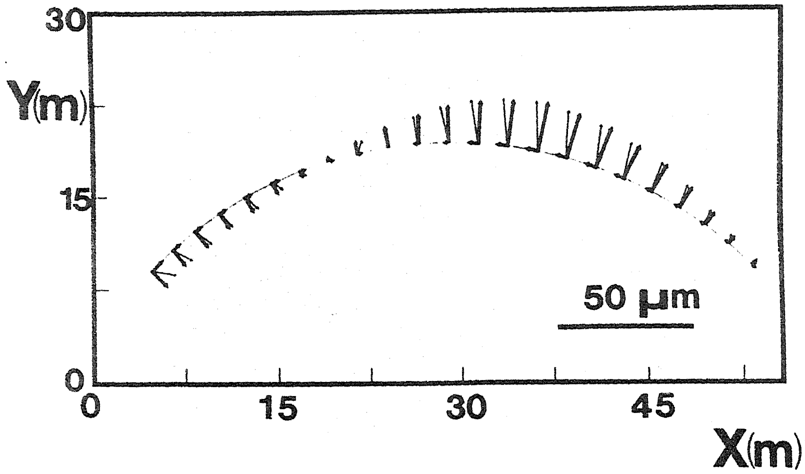

FIG.5a) MEASURED DEFORMATION OF BARCIS DAM IN HORIZONTAL PLANE 6 METERS BELOW CREST AT 10.37 Hz. REFER TO FIG.2, FOR X AND Y FRAME SYSTEM.

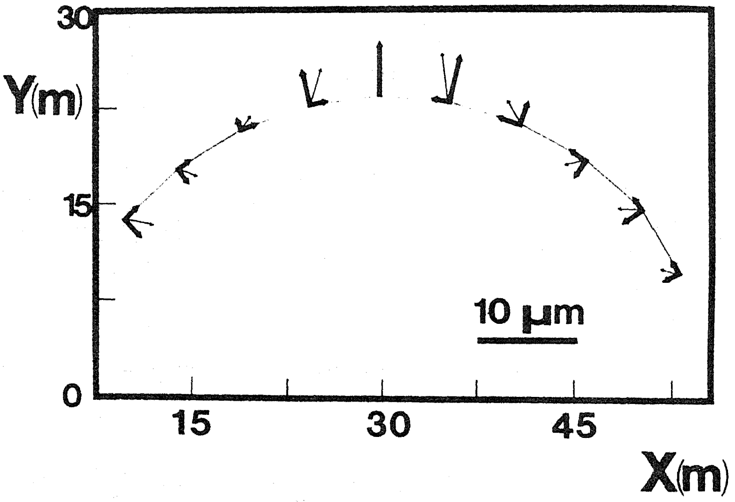

FIG.5b) MEASURED DEFORMATION OF BARCIS DAM IN HORIZONTAL PLANE 19 METERS BELOW CREST AT 10.37 Hz. REFER TO FIG.2, FOR X AND Y FRAME SYSTEM.