Holographic metrology for study and evaluation of vibration in complex structures

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Abstract: Holographic interferometry has been applied to *in situ* measurements of vibration fields of large diameter conduits undergoing unsteady internal excitations. The ambient conditions under which the measurements were carried out were extremely difficult. The measurements, covering an area of several square meters with each holographic recording, were performed using a portable one joule pulsed ruby laser system capable of producing two sequential Q-switched pulses each with duration of $\sim$25 ns with a variable pulse separation between 10 and 800 μs. The entire assembly of laser and holographic camera was constructed as a single unit incorporating an internal reference beam; the reference beam included a mirror with the facility to make an angular tilt between the two laser pulses with the objective of providing a facility to obtain information relating to the phase of antinodes within the recorded area of the hologram.

Keywords: holography, holographic interferometry, vibration analysis, pulsed laser, laser metrology

1 INTRODUCTION

Holographic interferometry is a powerful and versatile tool in experimental mechanics and has been used extensively for non-destructive evaluation to characterise vibration modes, reveal deformations, analyse stresses and strains, visualise flow fields and detect subsurface cracks and flaws. Generally, this technique has been confined to laboratory or semilaboratory environments for two reasons: the use of continuous wave lasers requires controlled environment with vibration isolation. Pulsed lasers, which do not need such stringent vibration control are generally bulky with limited portability. In addition, they are also prone to poor performance or failure in harsh industrial environments where large temperature variations and optical contaminants are experienced.

This paper describes a compact portable holographic camera incorporating a pulsed ruby laser that was developed specifically for non-destructive measurements in industrial environments. This prototype system was successfully deployed in harsh environmental conditions for *in situ* vibration analysis. The object of this non-destructive inspection work was a natural gas compressor facility that frequently experienced severe high frequency pipe wall vibration. An aircraft type turbine engine with a rated shaft power of 26 MW drove the compressor. Extensive studies had previously been undertaken to mitigate the vibration problems.[1,2] However, the lack of full field vibration data prevented any realistic measures to be undertaken until holographic interferometry was successfully employed in a pilot study.

A schematic layout of the piping arrangement studied in this work is shown in Fig. 1. Severe ambient vibrations and extreme audible noise were present in an environment with very high working

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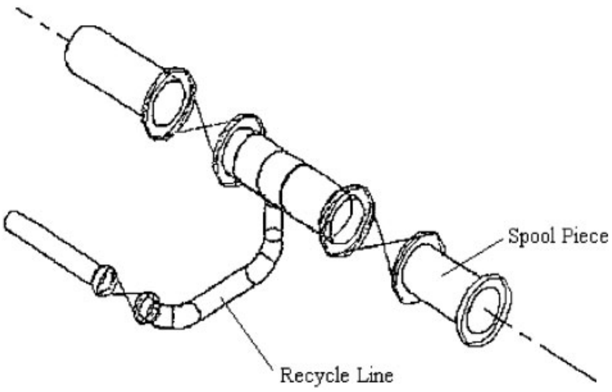
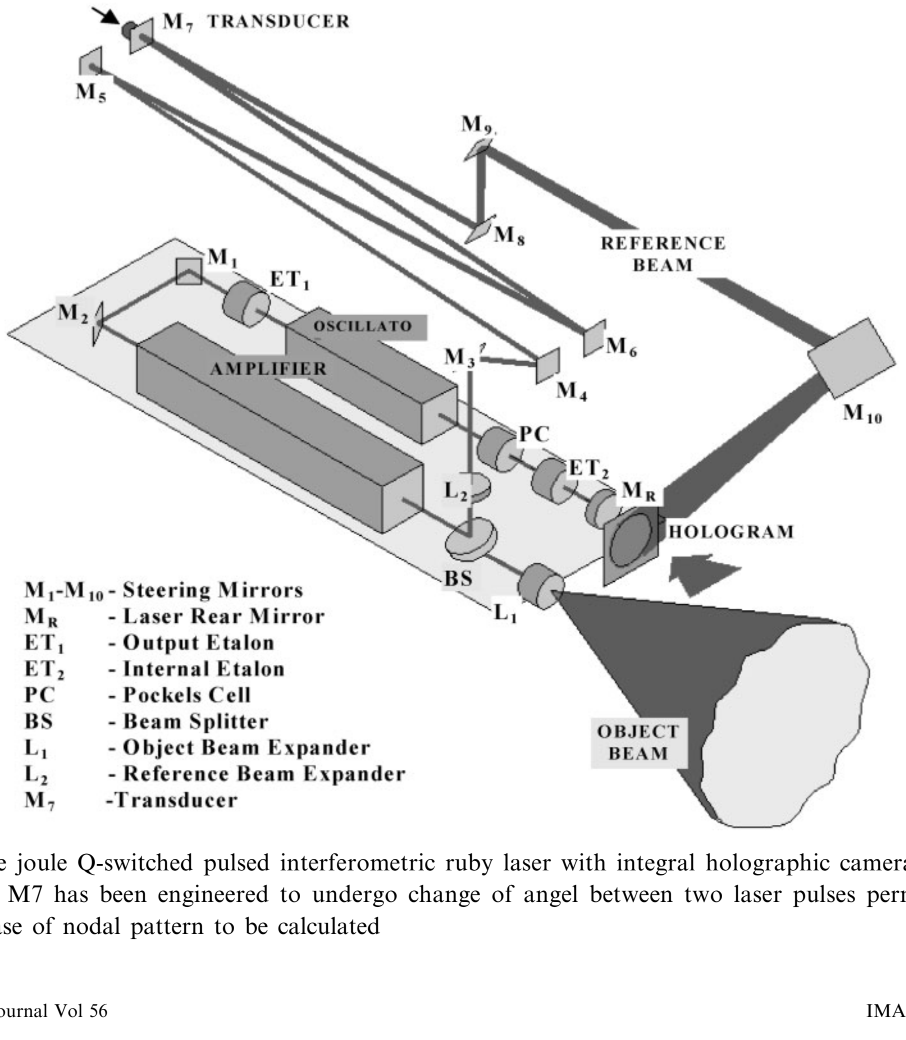


1 Gas conveying piping elements, layout of piping arrangement: turbine is located to right of spool

temperatures in the region of 38°C. There was also the presence of a high level of daylight, which could not be excluded from the area of operation. The location of this installation was a very remote barren land in Canada where even the minimum facilities that might normally be expected for holographic work were non-existent.

The holographic interferometric camera incorporated a proprietary design one joule ruby laser as the coherent light source (*see* Fig. 2). The laser head was specifically designed to be compact and portable for use in field or industrial conditions. It was sealed from external contaminants and its inside temperature was maintained constant at a few degrees above ambient through a network of heating elements. The power supply console, using solid state capacitors and the cooling unit were also specially designed for portability. All the modules of the holographic camera and power supply can be manhandled and loaded into a transport vehicle by two people. The assembly and disassembly of the system is made quick and easy by easy disconnects between modules.

The camera/laser system was set up to cover several square metres of the vibrating structure so that a great number of vibrating points within the camera envelope of view could be simultaneously recorded. In addition, the magnitudes and relative phases of the vibrational displacements were available through analysis of the holograms as discussed below. These



2 One joule Q-switched pulsed interferometric ruby laser with integral holographic camera: mirror M7 has been engineered to undergo change of angel between two laser pulses permitting phase of nodal pattern to be calculated enabled the definition and illustration of the non-stationary deflection modes for the excited piping.

The results obtained from the holograms are presented in the form of photographic images obtained when the holograms were reconstructed.

2 HOLOGRAPHIC SYSTEM AND TECHNIQUES

As discussed above, a one joule Q-switched ruby laser (Fig. 2) was employed as the coherent light source. This was made up of an oscillator fitted with a 100×7.5 mm ruby rod together with a Pockells cell (PC) with an associated driver enabling double Q-switch pulses, each of ~ 25 ns duration, with inter-pulse delay variable between 10 and 800 μm. An intracavity mode selection aperture and a temperature controlled internal etalon (ET_2) with a second etalon (ET_1), also temperature controlled, used as the output mirror. The resulting output of the oscillator was ~ 30 mJ in the Tem_{oo} mode. Providing the etalons are carefully tuned, it is the author's opinion that this combination provides probably the best arrangement to maximise the coherence length of the oscillator emergent beam from a ruby laser employing a conventional type oscillator. A coherence length of several meters has in the past been observed and reported[3] using this oscillator configuration.

Before amplification, the oscillator beam is passed through a spatial filter employing a single element specially designed lens of 50 mm focal length to focus the beam onto a diamond pinhole aperture of 200 μm diameter (not shown), thus providing a 'clean' or relatively noise free beam for amplification. Amplification is obtained using a 150 mm long by 14 mm diameter ruby.

The amplified beam is split into reference and signal components. A reference beam with a compensation path length of 1.5 m was used in this case. This was obtained by splitting off a 5% sample of the output beam from the laser by the use of a beam splitter (BS). The beam is then diverged by lens (L_2) travelling via a series of mirrors (M1 to M10) to fill the holographic recording film; the intensity of the reference beam is optimised by the use of a neutral density filter located in the beam (not shown). One of the reference compensation path mirrors (M7) was mounted on a piezoelectric cell so designed to give the mirror a fractional degree of angular tilt between the two Q-switched laser pulses, thus slightly changing its angle with reference to the recording hologram. The signal beam, used to illuminate the object, is passed through a 50 mm diameter $-$ 25 mm negative expanding lens (L_1), manufactured from a very high refractive index glass. The rear face of this lens was plane and slightly offset to avoid a focused reflection component off the laser beam, which could cause damage within the laser. The complete assembly of laser and holographic camera is incorporated into a single housing to facilitate tripod mounting for portability in field applications.

The objective of the tilting mirror arrangement in the reference beam is to provide phase relationship and directional information pertaining to the nodal structure recorded as contouring fringe patterns in the hologram. If, at the reconstruction stage of the holographic record, the operator's viewpoint is slightly moved across the hologram, in the direction of the swept reference beam, the recorded interference fringes appear either to expand or collapse inwards depending on their motion. From this information the actual movement of outward motion (expansion) or inward motion (contraction) of the antinodes can be ascertained across the entire field of view contained in the hologram.

A 75 mm diameter sector blade type shutter, set to one-tenth of a second exposure, together with a red filter glass was set up in front of the recording hologram. The transmission characteristics of the red filter glass was specially chosen to match the wavelength of the laser (λ=694.3 nm). The filter glass and shutter combination was necessary to eliminate the high level of ambient light present in the working area reaching the recording material. This would have resulted in a very high emulsion fog level causing total spoiling of the holographic record. The shutter had 'flash' synchronisation contacts, which were use to trigger the laser and other recording equipment when fully opened.

The recording material used was taken from a stock of Agfa 8E75 film. This had been kept in cold storage to preserve their quality since their initial production. After exposure these records were developed to maximise the emulsion speed, washed, then bleached and dried. This was accomplished in portable but limited facilities that had been set up near the remote location where the work was undertaken.

The holographic camera was set at a typical distance of 1.5 m from the centre of the surveyed surface. The reference accelerometer output was connected to a controller circuit capable of automatically locking the laser onto the minimum and maximum values. However, with non-stationary signals present, the decision was made to manually set a fixed interpulse delay of 140 μs. This time delay was considered as a close approximation to the time required for the pipe surface to deflect from its rest into maximum or minimum antinodal position. A consideration was given to various methods of fully synchronising the laser pulses with the transient vibrations, but this was not immediately possible and finally random triggering was used. The vibrating structure was satisfactory represented by about 25 randomly triggered holograms of each event, thus images representing the operating deflection shapes throughout the complete vibration cycle were obtained.

In addition to the complexity of the excitation, it had been observed that the vibrational responses were non-stationary. Therefore, in order to define the operating deflection modes it was necessary to include the magnitude and relative phase at all points on the vibrating structure. This meant that all of the vibration signals had to be measured simultaneously which can only currently be achieved in practise by such a technique as holography.

During the field tests, for every hologram that was recorded, a corresponding reference accelerometer signal along with the laser pulses was recorded. Each record showed a fraction of the complete displacement that had been recorded at the reference accelerometer position.

3 RESULTS

A full engineering analysis was carried out subsequent to the field trials and a report has been published elsewhere[4] and is considered to be outside the scope of this paper, which concerns itself mainly with the applied holographic technology used. In summary, the first steps in the analysis were to reconstruct the holograms with a HeNe laser and digitise the images for the production of prints. Printed records were also made of the records of reference accelerometer trace and the trace recording of the laser output showing the actual peak to peak delay between the Q-switched pulses. For each image, where appropriate, the antinode phase was marked together with the worst case displacement and its location, with respect to the reference grid, was noted as well as the worst case acceleration. With this information the acceleration at the peak locations was determined.

3 Specimen hologram used for calculation of velocity, strain and displacement

As with any wide angle coverage of fringe holographic patterns, a significant potential source of the results uncertainty was angle error. Each fringe in the holograms represented a displacement of half wavelength of the laser light; the ruby laser emits light at $\lambda=694.3$ nm. Thus the contour sensitivity was approximately equal to 0.35 μm per fringe assuming that the surface of the object was parallel to the film plane. It was necessary for a cosine correction to be made around the circumference of the tested piping. For simplicity of operation a correction factor of 1.21 allowing 10% margin for error was used which was derived from angle of 45°. Other possible errors included inaccuracy in fringe counting particularly where high fringe densities were present.

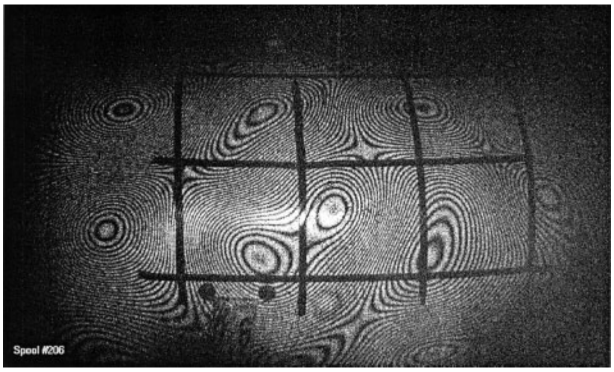
Figure 3 illustrates an example of maximum vibrational displacement and maximum vibration velocity calculations. In this figure, there are 28 fringes within a marked up distance of 0.08 m. Each fringe represents an out of plane displacement of 347 nm representing 9.716μm displacement. This value had to be multiplied by a factor of 2 to obtain peak to peak displacement derived from the accelerometer trace. Maximum vibration velocity is calculated from the distance between two antinodes. The distance contains 40 fringes after cosine error compensation. Forty fringes represent a displacement of 13.88 μm. Peak to peak maximum displacement equals to 27.76 μm. At a dominant frequency of 1.1 kHz, the maximum velocity is evaluated to be 0.040 m s^{-1} (0 – pk) for the sample hologram.

The spool section, which was surveyed, is approximately a 2 m diameter pipe with nominal wall thickness of 16.4 mm. The gas flow in all figures is from right to the left. Figure 4 shows an extremely strong spiral pattern progressing from the left to the

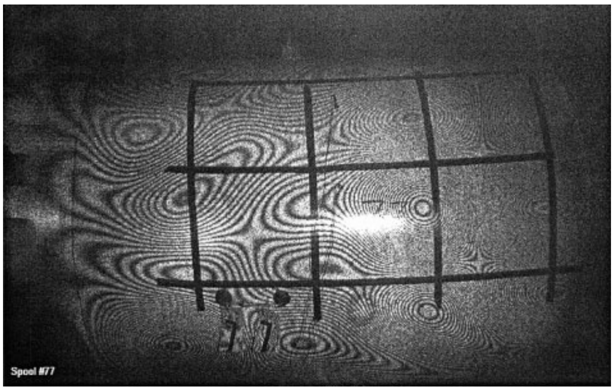
4 Spool section showing strong spiral wave

right of the picture, which is analogical to the theoretical predictions.[5] Other spiral patterns were repeated throughout the survey. Figure 5 illustrates fringes for the highest compressor speed. This figure shows a destructive mixing process of spiral patterns that propagated in opposite directions.

Figure 6 depicts a sudden drop in displacement amplitude near the left edge of the middle reference square in the tested piping spool. A phenomenon equivalent to a shock wave is seen to be propagating downstream, however, a traditional shock wave would increase deformation values well above the average value recorded; another possibility of the deformation mechanism was considered to be caused by destructive vibration pattern interference.



5 Recorded at highest compressor speed showing destructive spiral wave formation



6 Transient phenomena similar to shock wave progressing through spool: this is seen as increase in displacement on right side (up stream) region denoted by increase in fringe density

4 DISCUSSION AND CONCLUSIONS

Holographic interferometary, using a portable pulsed ruby laser, has been successfully applied under the environmentally extremely difficult industrial conditions found in the environment of a gas pumping station. It has been shown to give valuable data that might only other wise have been achieved by the application of a vast number of strain gauges or accelerometers. In this case, an existing stock of 8E75 silver halide film was used as the recording medium processed to give maximum emulsion speed. Agfa 8E75 and 10E75 material is commercially no longer available. For recording in the red at ruby wavelength other materials are now commercially obtainable but might prove difficult to use in the environmental conditions described above. Furthermore, emulsion speed rating of 10E75 or the specially processed 8E75 would be required in order to cover the very large areas recorded in this test if only a one joule laser was used; any laser with a greater output would probably be physically too large to be used in these very difficult conditions without a great deal of auxiliary equipment to get the laser into position. However, there is no reason why other pulsed laser systems such as frequency doubled ND : YAG could not be used, which has an output in the green at a wavelength of $\lambda=532$ nm and for which materials suitable for holographic recording are freely obtainable. Furthermore, such a frequency doubled ND : YAG system could be housed in a similar compact and portable manner as described above.[6]

The advantages of using this technology were as follows:

(i) the holographic equipment of the type described can record an area of several square metres of the vibrating structure and acquire data simultaneously from every point within the field of view

(ii) the phase relationship of antinodal structures can be examined and ascertained. This is accomplished by the facility of the mirror built into the holographic optical reference beam giving a small angular displacement of the reference beam between laser pulses thus enabling phase information relating to the nodal structure of the vibrating object to be ascertained

(iii) it provides three-dimensional images of *in situ* vibrating structures with an imposed accurate fringe map of out of plane vibration, strain and approximates stress data. Also gradient and peak as well as the phase information can be documented. These provided the information at the analysis stage, which will define and illustrate the actual non-stationary operating deflection modes, strains, and estimate the corresponding stresses.

The operating deflection shapes of the investigated piping were defined using the holographic technology. In the presence of non-stationary excitations, the vibrating points were related to each other using their relative phase and magnitude information stored in holograms. The quantitative data were collected and used to calculate strains in order to compare these to vibrational velocities.

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