The Study and Evaluation of Vibration Fields in the Complex Flow Induced Situations of a Natural Gas pump Line by the use of Holographic Interferometary

ABSTRACT

Holographic interferometary using a 'Q' switched pulsed ruby laser system has been employed to investigate acoustically induced vibrations occurring in a turbo compressor unit and the impact on piping components. The test conditions were at a remote pumping station with associated high ambient audible noise, vibration and high temperatures. Regions immediate to the compressor discharge and recycle piping and their acoustical fields were investigated.

The acoustic field interaction with piping walls is briefly described. The unique, in-situ holographic measurements of the large diameter shell pip ing that vibrates under unsteady internal excitations are performed and documented. The results are presented in the form of digitised holograms and computer generated three dimensional wave patterns illustrating complex piping excitation and responses. The correlation of pipe wall vibration and dynamic strain is shown on a specimen hologram. Finally, the indirect benefits of using the pulsed holography are briefly discussed. These include compressor performance evaluation and detection of piping low frequency vibration.

INTRODUCTION

Natural gas compressor facilities frequently experience severe high frequency pipe wall vibration and noise generation. These facilities incorporated radial inlet turbo compressors characterised by specific speeds of $N_s = 0.3$ to 0.6. The evaluated compressor was driven by a RB 211 jet engine of rated shaft power of 26 MW. Extensive studies have in the past been launched to mitigate these problems[1&2]. After successfully implemented modifications vibration[3], levels were reduced by 80 %. To obtain an understanding leading to further reduce the vibration levels and modify the existing vibration criteria, it was decided to use the holographic technology to study the situation.

The holographic interferometric camera used in this work is illustrated in figure1. This unit, which has been specifically designed to be portable for use under difficult field condition, employs a proprietary one-joule laser as the coherent illuminating source. This equipment represents a very powerful tool to evaluate the actual vibrational responses of gas conveying piping elements; the layout of the piping arrangement is shown in figure 2. The advantage of using this technology was two fold:

i) Holographic equipment of the type described, covers several square meters of the vibrating structure and acquired data simultaneously and instantaneously from every point within the camera view field. In effect this is the equivalent of hundreds of accelerometers or strain gauge probes. A further facility build into the camera head was a mirror which oscillated between laser pulses and thus gave phase information relating to the nodal structure of the vibrating object

ii) It provided three-dimensional images of in-situ vibrating structures with an imposed accurate fringe map of out of plane vibration, strain, and approximate stress data. Also, gradient, peak and phase information were documented in the holograms. These were necessary for further analysis, which enabled the authors to define and illustrate the actual non-stationary operating deflection modes, strains, and estimate the corresponding stresses.

All the studies and tests confirmed that high frequency piping vibrations were generated by pressure disturbances originating in the compressor. The predominant vibration and pressure pulsation were primarily at first and second blade passing frequencies. The excitation and piping responses have shown large instabilities of the compressor operation.

IN SITU MEASUREMENTS OF NON-STATIONARY VIBRATION FIELD

In addition to the complexity of the excitation, it was 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 or in some other way that guaranteed correct magnitudes and phase relationship information. In order to achieve this the holographic interferometric system was employed The camera/laser system was designed to cover several square meters of the vibrating structure so that a tremendous number of vibrating points within the camera envelope view could be recorded. These points were instantly and simultaneously captured and stored on holograms. In addition, the magnitudes and relative phases of vibrational displacements were available through analysis of the holograms. These enabled the authors to define and illustrate the actual non-stationary operating deflection modes for non-stationary excited piping.

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 worst out of plane deflections (radial and along the pipe axis) and their locations on the tested piping were determined and subsequently plotted in three-dimensional form. By measuring displacements at a range of the compressor operating conditions, variations in maximum and minimum values were documented. The quantitative data was collected and used to calculate strains in order to compare these to vibrational velocities.

The survey concentrated on the discharge and recycle piping. In each case, the piping was covered with a grid which provided the reference location for the analysis. Two accelerometers were attached to the pipe wall within the camera's view envelope. The location of one accelerometer was used as a reference point and the location of the other was used to study phase relationships and relative amplitudes during the set-up. In the future applications, accelerometers will be eliminated by using a single point laser vibrometer, which would make the holographic technology fully non-intrusive and remote. The holographic camera was set at a typical distance of 1.75 meters from 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, for stationary signals. However, with non-stationary signals present, the decision was made to manually set a fixed inter-pulse delay of 139 microseconds. This time, delay a loose approximation to the time required for the pipe surface to deflect from its rest into maximum or minimum position. A consideration was given to various methods of synchronising the laser pulses with the transient vibrations, but this was not immediately possible and finally random triggering was used. This method was tested in the laboratory trial with a simple mix of three sine waves. The images representing the operating deflection shapes throughout the complete vibration cycle were obtained. The vibrating structure was satisfactory represented by about twenty randomly triggered holograms.

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. The laser pulses reflecting from the surveyed surface were detected with a photodiode incorporated within the camera head.

ANALYSIS & RESULTS

The first step in the analysis was to reconstruct and digitise, with a CCD camera, each hologram and print these recordings together with the reference accelerometer trace. For each image, the worst-case displacement and its location with respect to the reference grid was noted as well as the worst-case acceleration. The record was made of the actual peak-to-peak acceleration between the moments when pulses were fired. Consequently, the acceleration at the peak locations was determined.

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 emitted light at 694.3 nanometers, so the contour sensitivity was approximately equal to 0.35 microns per fringe. This assumes that the surface of the object was parallel to the film plane. Therefore, a cosine correction has 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 degrees. Other possible errors included variation in inter-pulse delay and inaccuracy in fringe counting. These were found to be less than 1% and 4%, respectively. This was considered acceptable for this application but it could be reduced if required.

Figure 3 illustrates an example of maximum vibrational displacement and maximum vibration velocity calculations. In this figure, there are twenty-eight fringes within a marked up distance of 0.08 m. Each fringe represents an out of plane displacement of 347 manometers representing 9.716 microns displacement. This value had to be multiplied by a factor of two 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 forty fringes after cosine error compensation. Forty fringes represent a displacement of 13.88 microns. Peak to peak maximum displacement equals to 27.76 microns. At a dominant frequency of 1.1 kHz, the maximum velocity is evaluated to be 0.040 m/s (0 - pk.) for the sample hologram. A full analysis of the records obtained has been made together with the underlying theory of the strain-stress-vibration and velocity relationship

The spool section, which was surveyed, is an NPS 36 size pipe with nominal wall thickness of 16.4 mm. The gas flow in all figures is from right to left. Figure 4 shows an extremely strong spiral pattern progressing from the left to the right of the picture, which is analogical to the theoretical predictions[4]. 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. In this illustration, deformations on the right hand side are equal to the mean values for that compressor speed and on the left hand side are significantly lower. A phenomenon equivalent to a shock wave could be propagating downstream, however, a traditional shock wave would increase deformation values well above the average value recorded. Therefore, another possibility of the deformation mechanism was considered in which a strong reflection downstream the piping spool caused a destructive vibration pattern interference.

The most representative holograms were plotted in three-dimensional contour representation to better visualise spool deformations. Digitising the contour line co-ordinates and assigning height values helped to present displacement information and use it in further analyses. The data stored in digital format enabled the authors to display subsets of positive or negative displacements that were rotated and scaled to accentuate details of interest. An example is depicted in Figures 7.

DISCUSSION & CONCLUSIONS

Holographic interferometary, using a portable pulsed ruby laser, has been successfully applied under the environmentally difficult industrial conditions found in a gas pumping station. It has been shown to give valuable data that could only other wise have been achieved by the application of a vast number of strain gauges or accelerometers. In this case silver halide film 8E75 was used as the recording medium. It has been suggested that a new form of dry thermo plastic film could be used to advantage to replace this material [5]. Besides the avoidance of wet processing the thermo plastic system would give almost real time result with immediate in situ digitisation. For future work the authors are actively considering this possibility.

In summary our conclusions are:

1) The multimode frequency excitation in the investigated system produced high frequency vibrational waves which were very complex in nature because of coupling between the pipe shell displacements in circumferential, radial, and axial directions and because of shell stresses.

2) The application of pulsed holographic interferometary facilitated the evaluation of non-stationary vibrational field. The operating deflection modes, strains and corresponding stresses were accurately evaluated. Consequently, significantly higher vibration levels than specified by the industry standards were suggested as acceptable.

3) The pulsed interferometary was successfully used to evaluate peak to peak displacement and strain values in situations were pipe shell was clamped and complex vibrations (likely non-resonant) were present.

4) The holograms constitute a permanent record for the complex vibrational field. Studying the holographic results from the time perspective revealed new finding: a low frequency vibration of one pipe section.

5) The pulsed holographic interferometary can be used to indirectly evaluate the compressor performance.

Apart form the spiral wave propagation, non-stationary (transient like) pressure fluctuations were generated. This behaviour was noticed while the compressor operated at supposedly stable condition, at certain fixed operating point. This observation is uncommon in turbo-compressor facilities. Generally, the pressure fluctuations exist at compressor nozzles but these are defined as steady state and clearly are stationary. In 'healthy' compressors, the amplitudes of blade passing frequencies are at least a magnitude lower than measured in this study. Therefore, documentation of piping responses constitutes a compressor 'health' assessment tool. This is an indirect benefit to the vibration field evaluation.

The pulsed holographic interferometary enabled the authors to conduct refinement of the vibration acceptance criteria. Usually, many viewers readily interpret the black and white fringe pattern maps. However the authors decided to go a step further and digitised the contour line co-ordinates assigning height values to the displacements for several vibration patterns. With this additional information, it was possible to build wire frames that can be rotated to show the points of interest. During the in-depth analysis of one series of holograms, it was determined that the recycle piping moved in a beam motion with average vertical velocity of 35 mm/s. This finding constituted additional benefit to the analysis results and it was noticed after the tests were performed and during the detailed interferogram analysis.

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Figures

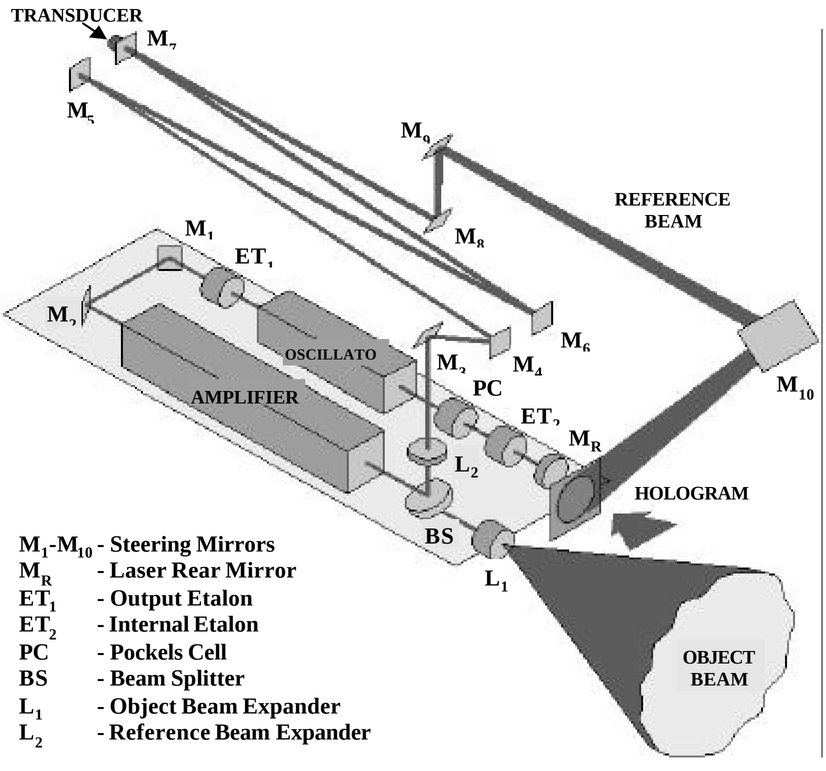

Figure 1 One Joule 'Q' switched pulsed interferometric ruby laser with integral holographic camera. Note: mirror M4 has been engineered to undergo a change of angel between the two laser pulses permitting the phase of the nodal pattern to be calculated.

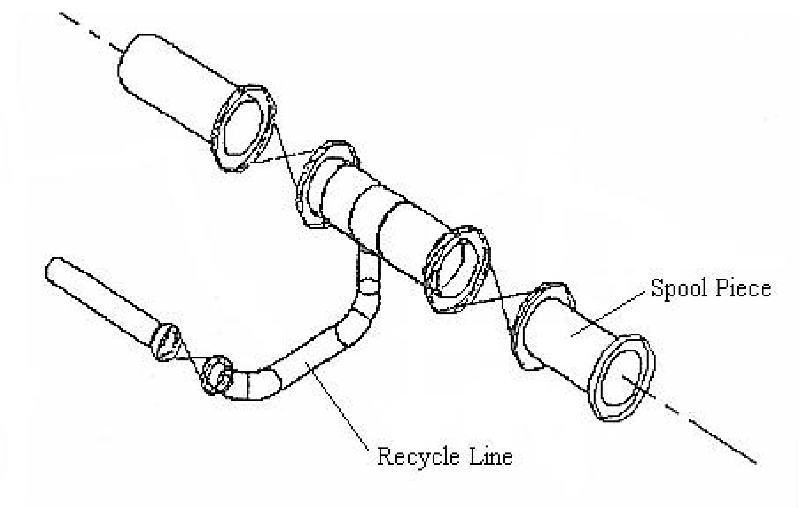

Figure 2. Gas conveying piping elements, the layout of the piping arrangement. The turbine is located to the right of the spool

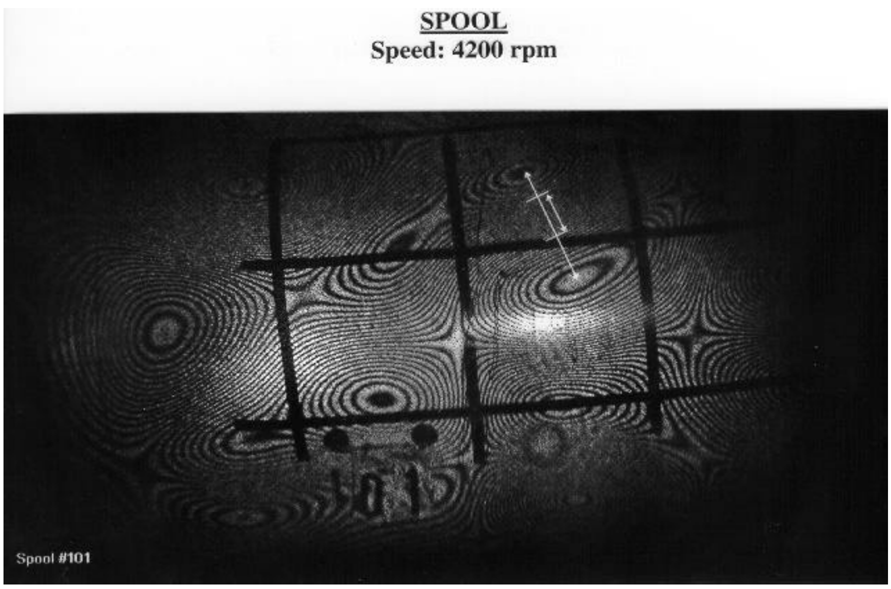

Figure 3. Specimen hologram used for the calculation of velocity, strain and displacement

Figure 4. Spool section showing strong spiral wave. Other similar spiral patterns were observed

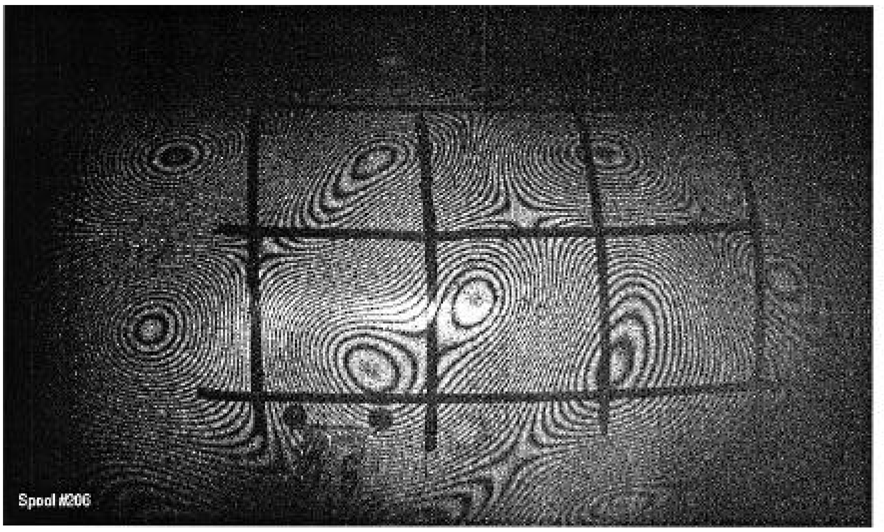

Figure 5. Recorded at highest compressor speed showing destructive spiral wave formation

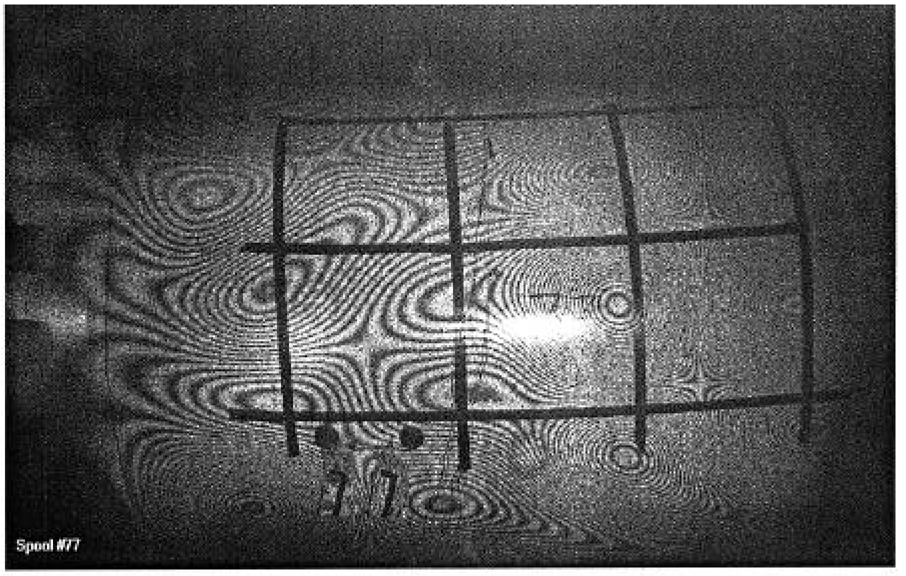

Figure 6. Transient phenomena similar to a shock wave progressing through the spool. This is seen as a increase in displacement on the right side region denoted by increase in fringe density