MEASUREMENT OF LOW FREQUENCY TRANSDUCERS BY UNDERWATER LASER INTERFEROMETRY

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1. INTRODUCTION

Measurements of acoustic transducers in tanks have traditionally been of electrical properties, and these have reflected the equivalent circuit methods of analysis and design. In recent years, finite element and boundary element analysis has become a common means of designing transducers. This is essentially a mechanical technique, although it has been adapted by the introduction of a piezo-electric element matrix to provide an estimate of the electrical properties of the transducer. It is nonetheless limited in accuracy by the quality of data used to provide the piezoelectric properties. At present, these data are taken from catalogues and are not as reliable as designers would wish.

Laser interferometry provides a non-contact method of measuring displacements, either of a single point or of a surface. Their use underwater provides an extra tool in the diagnosis of transducer performance in water for comparison with design output. The wholefield methods operate by generating optical correlation fringes representing contours of displacement (or slope) across the illuminated object surface. Results could also be obtained by using a matrix of accelerometers attached to the transducer surface, but this is by comparison a very cumbersome method, particularly when applied under water.

First attempts at underwater interferometric measurement of surface displacements of Class IV flextensional transducers used electronic speckle pattern interferometry (ESPI) [1]. Subtraction and addition methods were used, the former gave clearer correlation fringe patterns but was susceptible to rigid body motion. The results were only suitable for qualitative data, but displacement patterns were obtained and it was very beneficial to confidence in boundary element modelling, that these optical techniques predicted similar surface displacement behaviour [2].

Later measurements have used electronic speckle pattern shearing interferometry (ESPSI)[3,4]. This method provides greater flexibility over the measurement boundary conditions and provided higher quality results compared to previous work. However, the fringes were in this case measurements of displacement gradient, so initial observation of the fringe patterns gave much less intuitive information about the surface displacement. This can be extracted at a later stage via numerical integration. Although the work described here was applied to flextensional transducers, it could be applied to any radiating surface which was flexing, whether by design or not.

2. WHOLEFIELD OPTICAL INTERFEROMETRY

2.1 Electronic Speckle Pattern Interferometry

Electronic Speckle Pattern Interferometry (ESPI), or less commonly TV-holography, is the name given to several laser speckle based techniques which are used for measuring discrete displacement components. Two different optical designs are available; one to produce out-of-plane (OOP) displacement data and the other to produce horizontal and vertical in-plane displacement data (HIP and VIP), all of which rely on CCD-TV cameras at the image plane for the recording of data [5,6] (Figure 1). The speckle pattern observed on the object is recorded at the image plane of the CCD-TV camera and is then post-processed in order to generate the correlation fringes describing out-of-plane displacement (Z-axis).

The interferometer data is displayed on a TV monitor as correlation fringes, which may be formed via a subtraction process using software or hardware based frame stores. For subtraction fringes, the change of intensity between the initial object state and the displaced state ($\delta I = I_A - I_B$) is produced by storing the initial undisplaced laser speckle intensity distribution as a reference image and subtracting all subsequent displaced intensity distributions from this reference. Knowing the interferometer sensitivity function, the optical phase change for the out-of-plane interferometer can be directly related to out-of-plane displacement (w), such that:

$$w = \frac{n\lambda}{2} \qquad 1$$

where n is the fringe order number and λ is the laser wavelength. Quantitative wholefield data is generated by applying phase stepping techniques to the subtraction ESPI correlation fringes [7]. Initially grey scale maps (0 - 255) of optical phase are produced, which are then calibrated resulting in wholefield calibrated displacement and vibration phase data sets and plots.

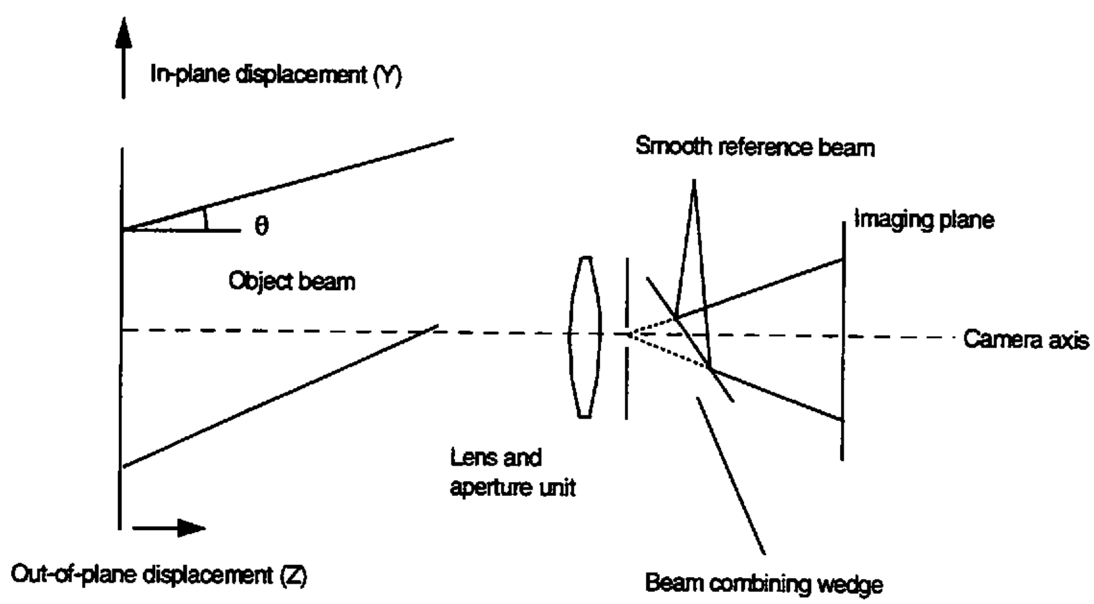

Figure 1: Schematic of an out-of-plane ESPI system

2.2 Electronic Speckle Pattern Shearing Interferometry

Electronic Speckle Pattern Shearing Interferometry (ESPSI) is a related speckle technique to ESPI [4-6]. Shearing interferometry has generally been restricted to quality testing of lenses and mirrors in optical manufacturing companies, and used for Non-Destructive Testing (NDT) of fibre reinforced composite panels in the aerospace industry. Some work has been completed to attempt to use shearing interferometry for strain analysis, and a limited amount of dynamic experimentation has been reported, but in terms of concepts rather than applied experimentation. The reason for the unpopularity is that the correlation fringe interferograms (formed as a product of the laser interferometry) no longer represent lines of isoamplitude but describe lines of constant displacement gradient or slope (the first spatial derivative of displacement). Consequently, qualitative analysis of displacement functions, be they static, dynamic or transient is no longer a straightforward intuitive process, but relies on a thorough understanding of the interferometer design and of the object behaviour.

The attraction of the technique is that certain specific interferometer designs incorporate considerable adjustment capabilities, allowing the sensitivity of the analytical equipment to be tuned to the amplitude range of the object being studied. Furthermore, the optical configurations are less prone to optical noise caused by environmental disturbances such as thermals and vibration. The Michelson version of the interferometer designs (Figure 2) works by superimposing two identical speckle patterns, which are produced when coherent monochromatic laser light illuminates the object surface. Each of the two speckle images is composed of random amplitude and phase distributions, and when combined with a lateral shift δx, produces a unique intensity distribution describing the object surface. When the object is displaced the intensity distribution changes.

Correlation fringes are formed by electronically subtracting (in real-time) the deformed state from the reference state. If the angle α subtended by the illumination and viewing directions is small, and the amount of lateral shear (δx) applied to the interferometer is small, the optical phase change can be related to the out-of-plane displacement gradient by:

$$\frac{\partial w}{\partial x} = \frac{n\lambda}{2}\,\delta x \qquad 2$$

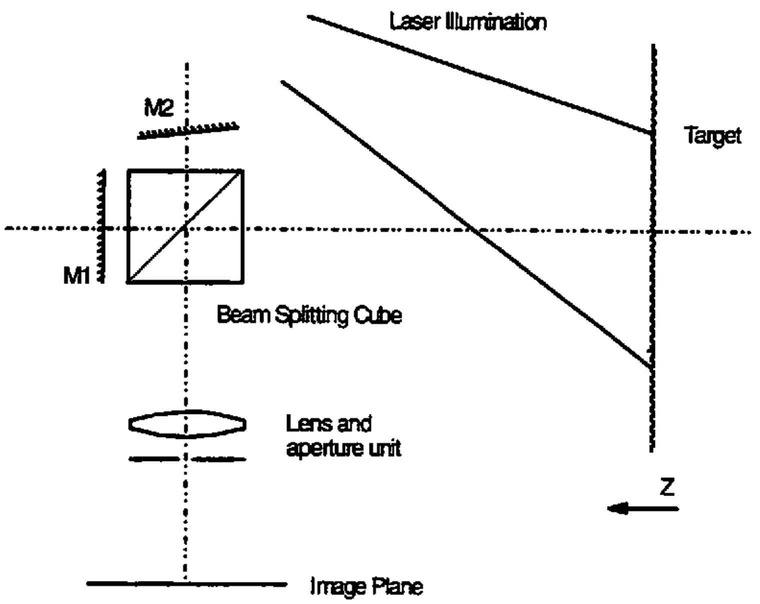

Figure 2: Schematic of an out-of-plane ESPSI system

3. ANALYSIS OF FLEXTENSIONAL TRANSDUCERS

The flextensional transducers were examined in air using OOP ESPI and OOP ESPSI. ESPI was necessary to provide a broad understanding of the object behaviour in terms of recognisable displacement resonant modes, allowing later shearing fringe interferograms to be interpreted.

Both the ESPI and the shearing interferometers utilised a Spectron Nd:YAG single pulse laser (max. 30mJ), frequency doubled to 532nm, with a maximum repetition rate of 25Hz. Using pulse generators and synchronisation circuits, the laser was synchronised to the CCD TV camera, such that the pulse repetitively illuminated the first field of each frame. Furthermore, the nature of the electronics ensured that the laser pulses illuminated the transducers at the same point on the oscillatory cycle or waveform. Different parts of the waveform could be examined by altering the delay between the firing cycle of the Q-switched laser and the sinusoidal excitation frequency, in terms of subtraction correlation fringes, produced by the same equipment used for the CW experimentation.

A broad understanding of the transducer characteristics was developed in the laboratory, identifying the main resonant modes of importance, their spatial structure and frequency of operation in air. Transducer excitation was achieved using an HP3330A digital frequency synthesiser with amplifier, incrementally sweeping through a frequency range of 500Hz to 15,000Hz, pausing and optimising as each resonant mode was discovered. In all cases the vertical and horizontal displacement derivative components were examined using ESPSI, with lateral shear values of δx=5%. The second part of the experimentation involved repeating the laboratory based testing with the transducer immersed in a large water tank (10m x 6m x 6.5m). The transducer was suspended and positioned near to one of the upper tank viewing windows. The laser, optics, excitation and recording equipment were housed in the viewing gallery, with the laser and optics illuminating and examining the transducer through the window.

4. EXAMINATION OF TRANSDUCER RESULTS

The thrust of this work is to continue the development of metrology techniques for the measurement of engineering data in ordinary and extra-ordinary conditions. The optimisation and use of speckle shearing interferometry in this context has been demanded by the large surface amplitudes achieved by the flextensional transducers - often hundreds of microns. The traditional speckle displacement interferometers are very good at surface deformation measurement but have restricted displacement resolution and sensitivity which is generally non-adjustable. The ESPSI optics have the virtue of being adjustable in sensitivity such that the instrumentation may be matched to the static or dynamic regime in question.

For the purposes of clarity and comprehension two sets of results are presented here which describe the fundamental resonant mode of a small flextensional transducer (semi-major axis - 75mm, height - 100mm, material - aluminium alloy).

The first data has been obtained from the ESPI displacement interferometer with the wrapped optical phase map shown in Figure 3. This has been obtained from the interferometer correlation fringes via phase stepping techniques. The data in Figure 3 is then 'unwrapped and calibrated with respect to the interferometer sensitivity and geometry, leading to the calibrated displacement mesh plot shown in Figure 4. Examination of the displacement mesh shows the main resonant antinode of the transducer which in this case is the entire surface of the unit breathing in and out, towards and away from the observer. It should be noted that in Figure 3 data quality is compromised at the edges of the transducer due to the high radius of curvature at these extremities. This form of data is easily obtained within a controlled laboratory environment, but as discussed in previous publications [1,3-4] is not a satisfactory solution for the under water analysis of the transducers, which is

Figure 3: Wrapped optical phase map obtained from ESPI analysis

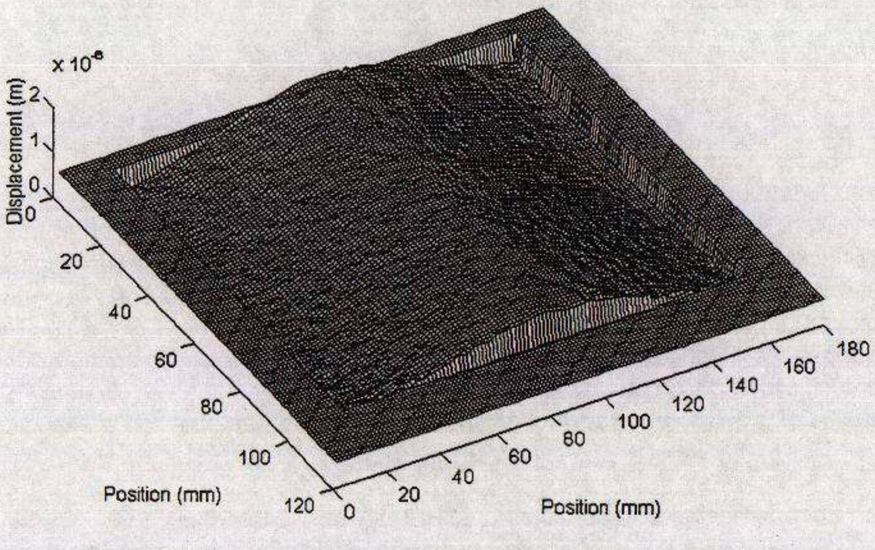

Figure 4: Calibrated transducer surface displacement

required to accurately validate FE/BE model predictions of dynamic operational behaviour.

The second set of data presented in Figures 5 and 6 show the application of the ESPSI interferometer to the transducer dynamics. This form of analysis has been completed for in-air laboratory studies and under water tanks studies, producing similar sets of subtraction correlation fringes describing transducer surface motion. Careful selection of the interferometer sensitivity (lateral shear value) allows the instrumentation to examine considerably larger surface displacements (50μm - 150μm) than equivalent ESPI analysis (<20μm).

The obvious differences between the ESPSI and ESPI results is the geometry or form of the results. Both sets of data are describing the same surface phenomena, but the ESPSI analysis is representing this information in terms of displacement gradient rather than displacement. Consequently, the displacement gradient results demonstrate two antinodes rather than the one exhibited by the displacement data. Visual interpretation of the shearing analysis results is just a function of understanding the context of the measurand (displacement derivative - slope). Furthermore, the derivative data can be numerically integrated to generate the underlying displacement profile.

Both of the wholefield optical analysis systems are capable of measuring relative and absolute displacements, with respect to drive voltage input although there are clearly sensitivity issues concerned with both forms of instrumentation. In both cases of displacement measurement the governing criteria is to have accurate synchronisation with the transducer drive electronics, allowing the precise application of the pulsed laser systems. Beam delivery during the completed studies has involved optical windows in the test tank facility, providing direct visualisation of the operating transducers. The small scale of the ESPSI optics provides the opportunity to develop small instrumentation packages which may be directly entered into the water based facilities, although stability criterion for the instrumentation has as yet not been investigated for this approach. An issue of concern in this instance would be laser beam delivery. Improvements of single mode fibre optic damage thresholds and relaxation of ESPSI illumination requirements leads to the belief that fibre optic delivery of moderate pulsed laser output (0 - 20mJ) is a realistic option.

4. CONCLUSIONS

Wholefield laser based interferometric testing underwater is currently not used as a regular test method for developed transducers, but it is a useful experimental technique in the design of new devices. This series of experiments has taken two laser interferometric techniques; Electronic Speckle Pattern Interferometry (ESPI) and Electronic Speckle Pattern Shearing Interferometry (ESPSI), which have been applied in the laboratory and in underwater conditions. ESPSI produces fringe pattern data representing lines of constant displacement gradient or slope, unlike the displacement fringes produced by ESPI. Furthermore, adjustment of the amount of lateral shear applied to the interferometer can optimise the optical sensitivity to the boundary conditions of the object under test, allowing a greater displacement range visualisation than equivalent ESPI analysis. Both systems are capable of providing absolute and relative displacement measurements with respect to input drive voltage.

The underwater experimentation has shown ESPSI to be suitable for the generation of wholefield interferometric data from transducers, whilst operating in their working environment. Importantly, wholefield quantitative data can be extracted which allows the transducer designers to better understand the dynamics of the units and to potentially verify FEA models. In all cases, the quality of the correlation interferograms has been sufficient to potentially allow further computer based post-processing of the data. Furthermore, this successful and unique application of wholefield speckle shearing interferometry could probably be extended to many other analysis cases, requiring in-situ underwater experimentation and operation.

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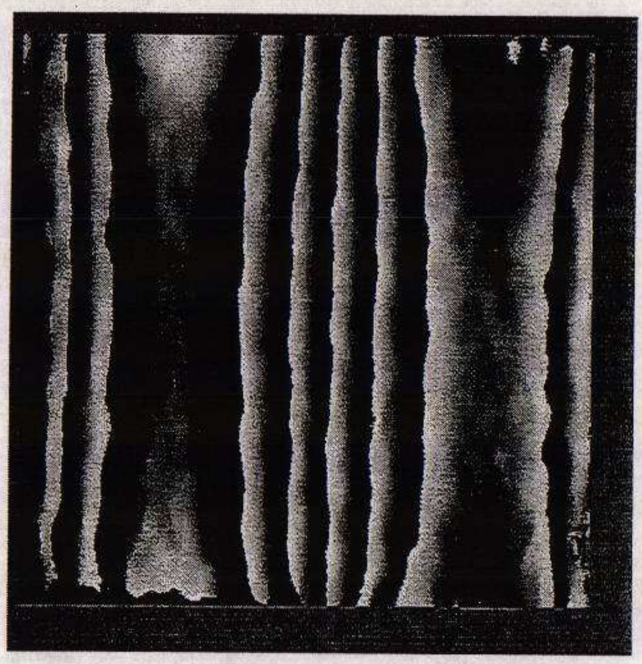

Figure 5: Wrapped optical phase map obtained from ESPSI analysis

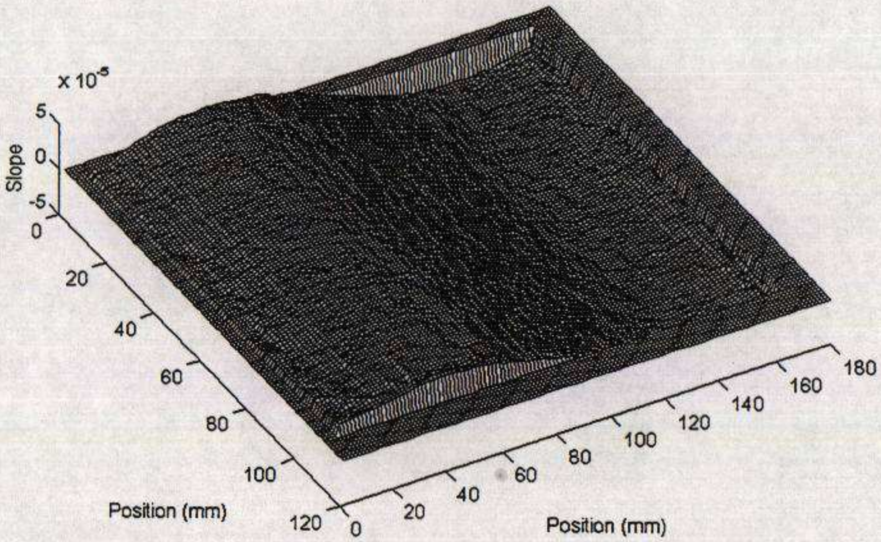

Figure 6: Calibrated transducer surface displacement gradient

5. ACKNOWLEDGEMENTS

This work was funded by BAeSEMA Ltd and was undertaken at the test tank facility at Filton while the third author was working there. Permission to publish this paper is gratefully acknowledged. The optical analysis equipment and facilities were provided by the Department of Mechanical Engineering, Loughborough University under the auspices of European Community BRITE Contract BRE2 - CT92 - 0332.

6. REFERENCES

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