SOME UNUSUAL APPLICATIONS OF HOLOGRAPHIC INTERFEROMETRY IN A SEMI-INDUSTRIAL ENVIRONMENT.

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1. ABSTRACT

This paper presents two rather specific applications of holographic interferometry. The first is related to the study of displacements and strains associated with the rapid (200 meter/second) crack propagation in pressurized polymer pipes. Denisyuk type holography using a double pulsed Ruby laser was found to yield practical results; due to the rather explosive nature, experiments were carried out at night, outside of the classical buildings.

The other series of tests is concerned with the localisation of most stressed zones in prototypes manufactured from steel castings. As the use of brittle lacquers is now prohibited, holographic interferometry was used to find the locations for putting the strain gauges. Relatively large (up to 1 x 1 m) and heavy (about 700 kgs) castings were tested, resting on an unisolated concrete slab, using a semi-professional ESPI system and a small argon laser.

Keywords: holographic interferometry, non-destructive testing, metrology, rapid crack propagation, prototype testing, design optimisation, double-pulse holography.

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2. INTRODUCTION

Optical measurement techniques have been used for tens of centuries by scientists and engineers, and the introduction of the laser only opened up a renewed interest in the use of light for measurements of parameters of interest in practical engineering. Because lasers have provided low cost and convenient sources of coherent light, interferometry and holography have come into wide spread use to make rapid measurements far beyond the resolution of the naked eye on everyday objects. Even so, the potential for the use of coherent light in these fields has barely been tapped. Optical diagnosticians have a wide variety of extremely sensitive and essentially operational techniques at their command, that have not yet found their way into general use by engineers. Part of the reason for the lack in applications appears to be caused by a shortage of communication between the technique developers and the end users. The developers rarely have a complete understanding of the measurement problem and its constraints while the end users may not know what is available or what technology is suitable for their problems.

Proceeding along this line of thought, this paper is an attempt to span the communication gap, that seems to exist between modern optical diagnostics developers and potential users of some of the advanced technology, by showing simple setups can yield satisfactory results.

On the other hand, we have also tried to show that the stability requirements set forth by physics people can be relaxed a lot, not only when using double-pulsed lasers, but also with CW lasers.

Two examples will be treated here : the first concerns the localisation of the zones of maximum stress for a new design of an intercooler of a two-stage aircompressor; the second is related to the rapid crack propagation of brittle fractures in pressurized polymer pipes.

3. EXPERIMENTS

3.1. Air cooler testing

The growing concern for environment and the related regulations have from time very strange consequences, even in experimental mechanics. The first example stems from this context. For a number of decades, our laboratory does stress analysis on complex welded steel structures, e.g. for the offshore pipelying industries and for pressure vessels. Vessels will only be fabricated in cast iron or cast steel when large series have to be manufactured and even then, only when the structure is very complex. Cooler stages for heavy air compressors are typical applications where those two requirements are found together; we will report (with permission) on experiments on a new design introduced by Atlas-Copco Belgium.

Stress measurements using strain gauges are used when normal vessels are concerned, as design people can rely on their experience to predict the location of the zones where maximum stress will occur. However, coolers are so complex that those locations have first to be detected by other methods.

Up to a couple of years ago, brittle lacquers or analogues were used, where a thin film of a specific lacquer is first applied to the specimen surface. When the test piece is loaded stepwise (e.g. by internal pressure in the case of a vessel), cracks are formed in the lacquer on those places where the largest strains (and hence stresses) occur.

Due to the high toxicity of the solvents used (the lacquers have to be very brittle, but in a controlled way), the products were withdrawn from the commercial circuit, and their use formally prohibited.

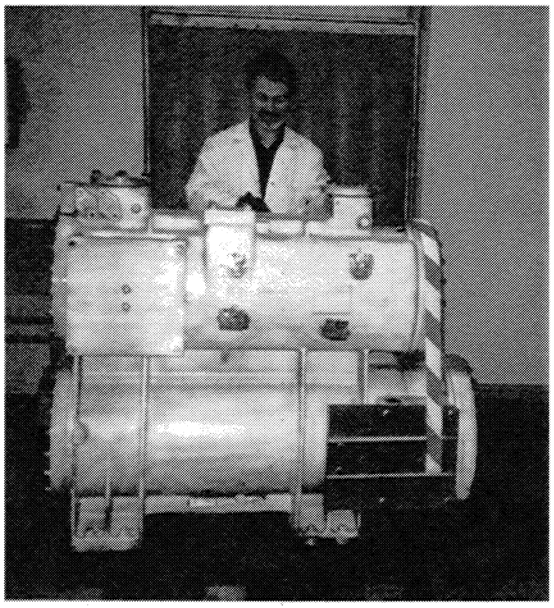

Fig. 1: Typical appearance of a cooler for air compressors.
(permission of Atlas Copco)

The SPATE method (Stress Pattern Analysis by Thermal Emission) was not chosen, because the cyclic loading would have introduced too much problems (see the dimensions of the object on figure 1). Holographic interferometry was thought to be a viable variant, and the specimen was placed on a concrete slab (five small concrete blocks of 3 x 1,2 x 0,2 m, bolted together with two ϕ 20 mm threaded bars. This slab rested on 10 concrete cubes of 200 x 200 x 200 mm; those, on their turn, rested directly on the floor of the building (after a short period: the inner tires that were intended to support the slab, in order to absorb vibrations, exploded one after the other by creep in about six days' time). We controlled by a simple Michelson setup that the "table" was relatively stable (1 fringe shift per 30 secs), so we did not bother any more. In fact, we were lucky that the floor rested directly on a sand layer of about 2 meter thick.

The basic opto-electronic system used was a Steinbichler ESPI system, OPTOCAD software of Breuckmann, and a LEXEL 400 mW Argon laser emitting at 514 nm; coherence length approximately 1 m. The laser, the optical head, the operator sitting on a chair, and the computer and its accessories were all placed on the same concrete slab (figures 2a and b) without further problems. The pressure changes used for forming suitable fringe patterns, was about 0,5 bar (0,5 N/m^2); this is quite low compared to the normal service pressure of 15 bar, and the burst pressure that lies between 100 and 150 bar. All the test coolers (the biggest up to now weighed 700 kgs for a water content of 300 liter) were tested to fracture; we were able to correlate the final rupture zone with the discontinuities in the fringe patterns.

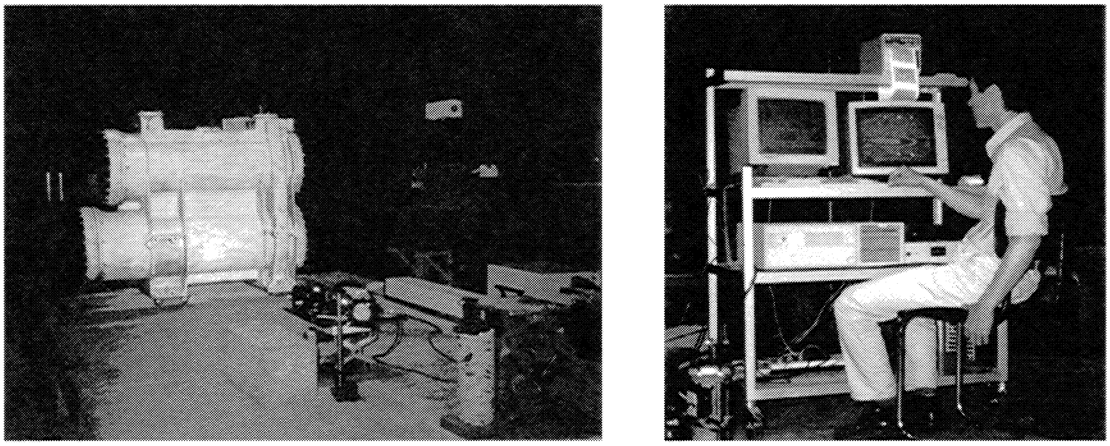

Fig. 2: Experimental setup: a) vessel and ESP head
b) controls and controller
(permission Atlas Copco)

Due to the dimensions of the coolers, and the limited power of the laser, we subdivided the structure in smaller pieces: six parts for the side walls, three for top and bottom. As records are made with a low resolution CCD-camera (256 x 256 pixels), 3D-information is completely lost and the resulting picture has a very grainy appearance. The advantage, however, is that fringe patterns can be observed in real time, and that image processing can give results in a rapid, quantitative way (about 20 seconds for our setup, but more expensive ones can yield data almost at video frame rate). "Naked eye" analysis of the fringe patterns learn you very quickly where the highest stresses can be expected, after some learning however. Use of a number of strain gauges, and finally of a "movable" gauge, showed us that the points to be looked for, combine a relatively high fringe density with the "concentration" and/or local bending of the individual fringes (figure 3a).

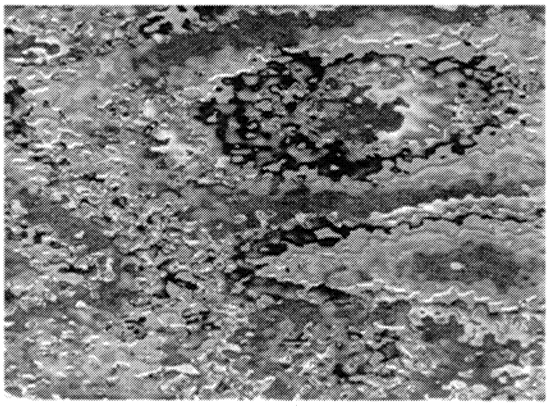

Fig. 3a: Typical fringe pattern where high stresses are to be expected.
(permission Atlas Copco)

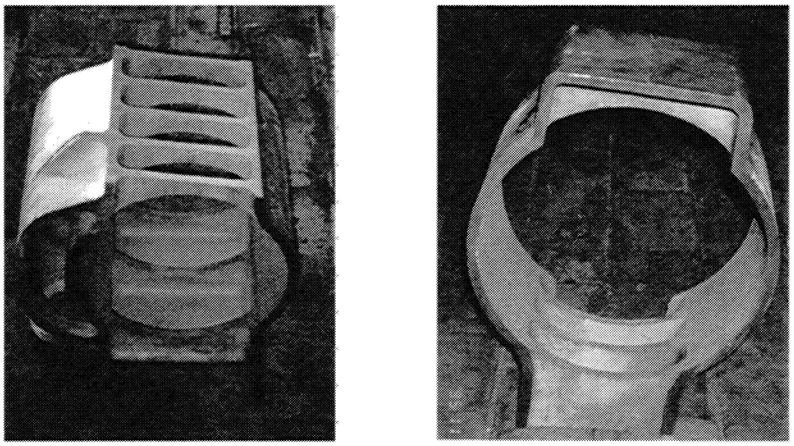

Fig. 3b: Vessel cut to small pieces.
(permission Atlas Copco)

The zone depicted in this picture, is the transition between the conical and the cylindrical part of the cooler, where in addition the inner part of the conical piece is reinforced by stiffeners (see figure 3b, cut-out after failure). Probably each type of object will need some learning process, but from the first of the series we were already able to localise the zones of maximum strain; after the third, it was possible to predict the localisation of the final crack.

In addition to those qualitative results, we succeeded, by using strain gauges, to have a rather complete image of the stress distribution in the apparatus, thereby helping the constructor to optimise the design of the next newcomer in the family.

3.2. Polymer pipe testing

The second example comes from the pipes and pipelining sector.

More and more, plastic pipes are used for low pressure gas and water distribution. One of the main problems with their wide commercial applications is rapid crack propagation (RCP)[1]. This results in enormous losses of energy resources and also in environment pollution. Recent incidents show that it is of importance to find criteria to assess the safety conditions for large diameter piping before their installation. (Hungary 1990, Belgium 1988, 1989, Japan, USA....).

These and other incidents show the importance of finding criteria to assess the safety of larger diameter pipes before installation in distribution systems[2,3]. Especially, the newly developed 3rd generation polyethylene materials, of which large diameters are already produced, need extended RCP evaluation. So, even if the installed pipe seems to be safe, it is imperative to obtain an understanding of the various factors that can affect RCP[4].

Holographic non-destructive testing technique (HNDT) has been already applied to analyze pipe vibration and to control the corrosion influence. One of the first demonstration of holographic technique for still pipe vibration analysis was reported in [5]. In [6] this method was used to detect interior cracks and erosion in the tubes of coal-fired boilers. Authors of [7] have applied holographic NDT methods to compare the experimental data of pipe vibration analysis with that of modal analysis simulated on finite element codes, using COSMOS/M release 1.65-368 software. It was also proved there exists a possibility to learn the level of the still pipe corrosion from vibration mode parameters and frequency response. Finally, some experimental results related to RCP study in plastic pipes were reported in [8,9].

In this paper, we will present some results of holographic tests during RCP propagation tests, thus mainly destructive testing. Due to the rapididy of the phenomena involved (the cracks propagate at about 200 to 250 m/sec) and the relatively "explosive" nature of the test (pipes of 100 to 200 mm diameter, cooled to 0°C, are loaded by internal pressures of 5 to 10 atm and then forced to break by impact loading), double-pulse holography was chosen for the experiments.

The source of the crack has some typical characteristics, that does not depend upon the methods of the crack initiation at experimental test conditions or in case of real accident. After being initiated by internal pressure (or with externally applied force) the crack grows almost linearly and then after a while starts to oscillate or to branch. Also quite typical is its propagation kinetics: ordinarily, the crack initiates at critical point, grows stepwise (slow) and becomes unstable (fast), when a certain dimension is reached. This failure mechanism is not reproducible in laboratory tests. The stepwise growth of the crack, by creep tests on pipes, either at room or at higher temperatures, is observed in laboratories. Nevertheless, crack propagation is exceptional. Probably, because of the test conditions : internal water pressure, limited pipe length, temperature interval from 20°C up to about a 95°C. Moreover, the fact that the hydraulic pressure tests are stopped when leakage occurs, avoids the growth of the crack.

Except for plastics materials with a macroscopic defect as crack starter, little literature is available about crack initiation. As far as laboratory tests are considered, it can be shown that the real stress may exceed up to 100% the hoop stress, taking into account : errors in dimensions, test temperature, variations in diameter, thickness, residual stresses, etc. In pipelines, additional stresses are set up by ground pressure and bending. This means that accidentally the real stress, set up by a given internal pressure, can locally exceed the calculated stresses by more than a 100%. The above mentioned errors are only important if failure is of a brittle type. They have little influence if the crack is preceeded by a certain amount of plastic deformation.

Experimental RCP testing.

For experimental investigation of RCP the test procedure and the specimen geometry should be based on the following principles: the test has to be carried out on the pipes of a minimum length of 7 ϕ, pressurized at a certain temperature; in one part of the pipe a brittle fracture has to be initiated by combination of low temperature, notch effect and high strain rate (impact). The initiated crack has to enter the zone under test conditions. Both the crack length and the crack speed must be measured and compared with the limits imposed to the type of PE material.

Several methods, that fulfill the above discussed conditions, have been developed. Modified Robertson tests[10-12], the S4 (Small Scale Steady State)[13], the S5 (Small Scale Steady State Scum[4]) as well as the Full Scale and Modified Full Scale are well recognized and practically used as pipe testing techniques. More detailed description of those can be found in[4,9]. In our experiments, to avoid the disadvantages related to fast decompression of the pressurized pipe, the S4 and the S5 tests have been used for RCP study.

In the S4 test (figure 4) the crack is initiated by the impact of a gas-gun fired projectile (sharp knife) on a well-supported and non-pressurized zone, to achieve embrittlement by strain rate alone. This fast crack is injected into a propagation zone in which internal baffles, and external containment against flaring, prevent decompression and provide a controlled local environment.

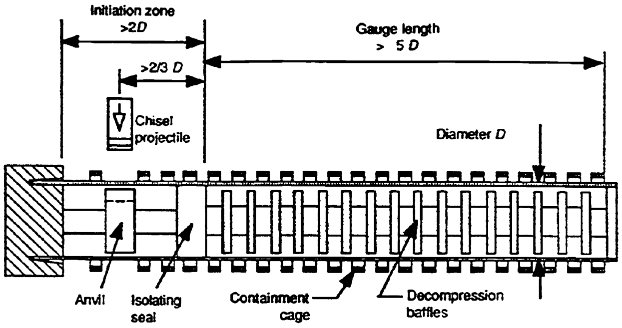

Fig. 4: Typical system for the S4 test.

The propagation zone contains a series of disc baffles, slightly smaller in diameter than the not- pressurized pipe bore and spaced at $\phi/3$ intervals, to restrain axial decompression waves. The decompression baffles are not less than 0.94 ϕ_{min} and not more than 0.96 ϕ_{max} in diameter. A supplementary feature here is a containment cage consisting of a series of rings, at $\phi/3$ intervals, separated from the pressurized pipe outside diameter by a small clearance. These rings bear no stress prior to fracture, but severely restrict radial expansion of the pipe thereafter, delaying decompression by radial gas escape (and serving to contain ejected fragments). The internal volume of pressurized air within the gauge length, which can expand without restriction to drive the pipe wall radial outwards, is at least 75% of the total internal volume.

Instead of using the decompression disc baffles, which already strongly damp axial decompression waves, it was suggested to modify the S4 test (for S5) by inserting a soft compressible foam (scum) into the pipe bore. This foam theoretically acts as an infinitesimal number of discs, spaced at zero intervals, having no thickness at all. In the S5 test the internal volume of pressurized air, that can expand to drive the pipe wall outwards, is more than 85% of the interval volume. All other specification of the S4 test remain unchanged.

The S5 test is now carried out by four European research centers, and is currently the focus of interest from several resin suppliers, as this test shows the good performance of the newly developed third generation polyethylene (MDPE and HDPE). Furthermore the S5 test reveals the minimum pressure for brittle pipe failure mode : the critical pressure, below which steady state RCP cannot be sustained.

Holographic investigation of stress fields associated with the different RCP testing methods.

In order to gain some insight in the stresses associated with running cracks at different test conditions, and in subsidiary order to get some information about crack oscillation and branching, a series of holographic experiments have been conducted on a number of pipes in different experimental conditions. Due to the rapidity of the RCP phenomena, double-pulsed holographic interferometry was the only possibility for recording the interferograms. Methods based on phase shifting, with multiple reference and/or multiple "deformed" recording, are not applicable here as the large-size specimen can be strongly distorted (with respect to interferometric sensitivity) between the successive exposures.

Reflection geometry holographic NDT experiments.

At the first stage, to localize the stress distribution in the simplest way, the holographic recording scheme based on the Denisyuk reflection geometry was used. The scheme was designed with pontwise (Alexandrov-Bonch Bruevich)[17] interrogation for collecting the raw displacement data. Although this technique seems to be quite cumbersome and might give rise to some uncertainties in describing the direction of the different displacements, it has the advantage that it yields the orthogonal displacement components.

The set-up for the reflection hologram recording (Figure 5) involves a double-pulse ruby laser (1 Joule HLS2 JK Lasers - now Lumonics). Due to local circumstances, the optical path between the laser room and test facilities (about 50 m) had to be passed, using four front surface mirrors, the last one resting on a ladder on top of the specimen. The recording medium was placed at about 50 mm distance from the top side of the pipe on a 25 mm thick perspex plate, separated from the tube surface. This was made in order to avoid the effects connected with the shock waves or propagation of sound and/or air pressure differences, at the moment of crack opening and propagation along the pipe. AGFA 8E75 HD film was used as the light-sensitive material in these experiments for hologram recording. Chemical processing technique was similar to that described in [14].

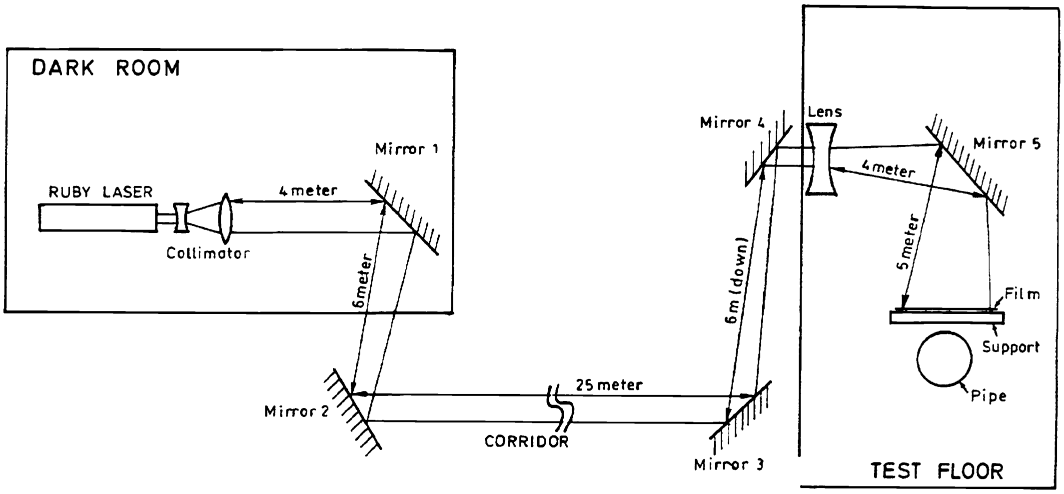

Fig. 5: Setup for recording Denisyuk holograms.

An holographic interference pattern typical for these experiments is shown on Figure 6, for the test conducted on the ϕ250mm PE pipe with wall thickness 22 mm. In this particular case laser pulses were triggered by a crack gauge located at 150 mm from the initiation point; the hologram center was located at 150mm "downstream" from the trigger wire. Interval between pulses was regulated to 3 μsecs; typical with a jitters of about 0.03 μs. The light beam travelled a relatively complicated path through the lab and the dependances to the test site outside; of course, the tests had to be effectuated at night to avoid white-light over-exposure of the film (figure 6).

Fig. 6: Typical fringe pattern for reflection recording setup.

Out-of-plane displacements can be directly derived from the photograph of the fringes; in-plane displacements from point-to-point fringes counting measurements. From such measurements, the displacement "surfaces" can be obtained using cubic-spline approximation. Then, combining the results of derivatives of these surfaces one finally can find strain fields and, using Hooke's equations, stresses along the pipe. For more correct explanation of the fringe/displacement structure the obtained data should be "convoluted" with the kinetic of crack tip propagation phenomena[13] to explain the stress behavior at a point of the material. On the other hand, one can see some kind of asymmetry in the displacement field, as shown on figure 6, that seems to be related to the crack oscillation.

The hologram represents the stress distribution around the tip of the crack and the structure of the crack in the area of the observation. However, we had to recognize that viewing zone in these experiments was relatively narrow, what is one of the restrictions of reflection geometry in the case when the distance between the object and recording material is relatively small[16]. This limitation made it rather difficult to observe the stress distribution along the whole pipe at the test process. It is, however, the only way to get three-dimensional information about displacements (apart from using three different lasers). As the results of those measurements seem to indicate mainly hoop stresses are relatively important, we turned over to a set of experiments with transmission hologram recording geometry was performed.

Transmission geometry HNDT experiments.

In this case (figure 7a) the outgoing laser emission was split on the two beams to illuminate the pipe and recording material, that was again AGFA GEVAERT film (10 x 10 sq.cm). It was placed on 2m distance from the object. To minimize the losses of the light energy reflected from the pipe its surface was painted with retro-reflective paint (3M Scotchlite 831). At S4-test conditions a ϕ 160 mm SDR11-type PE pipe was cooled to the temperature of 0°C and then installed in testing facilities and pressurized internally to the level of P=5bar. The trigger system of laser pulses was the same, and the interval between two laser pulses was again 3 μsecs.

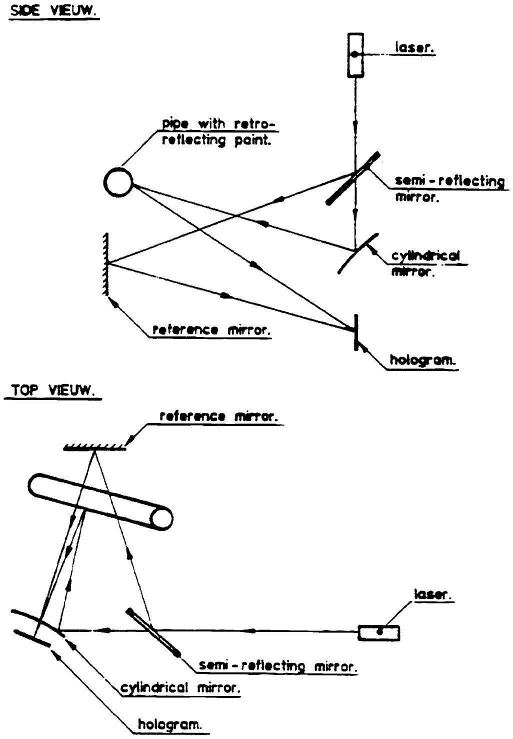

Figure 7a:
Setup for transmission holograms

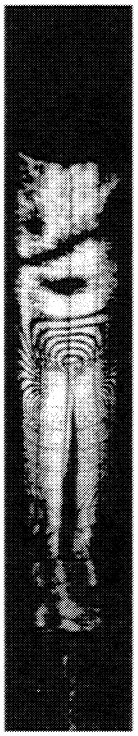

Fig. 7b:
Fringe patterns obtained by transmission holography.

A typical example of the interferogram, obtained from the experiments with transmission holography, is shown on Figure 7b. This figure proves clearly that with transmission recording geometry the whole pipe body became visible. Moreover, what is of primary importance for better analysis of the situation, one can see not only the crack tip and field of stresses around this area, but also the distribution (both linear and oscillating parts) and structure of the opening of the crack all over the pipe and also can get distribution of the displacement surfaces along the whole pipe. It is also interesting to note that the "hills" of the interference fringes on this figure are related to the oscillating propagation mode of the crack during the testing process.

Another interesting aspect, that needs further clarification, is the interaction of the stress field due to the running crack and displacement due to the vibration modes introduced by the crack initiating instrument. It is indeed possible that these vibrations induce another stress field, and that the interaction between the two give rise to the typical sinusoidal oscillating crack propagation. This can also be observed in steel pipes, in ductile fractures of rubber hose pipes and even in some cracks propagating from the hull of ice breaking ships in the larger Russian lakes. It is our feeling that the oscillating nature of those cracks is related to the varying biaxial stress field and for better understanding of this phenomena the vibration modal analysis[7] is of importance. This aspect will be treated in the next paper of this Conference.

4. CONCLUSIONS

Investigations on the displacement behavior of complex pressurized vessels and of plastics pipes subjected to rapid crack propagation and their interpretations, have been presented. Some experimental details need optimisation to yield quantitative results useful for common practice; most stringent is probably the time constraint. Nevertheless, the holographic technique allows one to see phenomena that otherwise would have been unnoticed; on the other hand, some indications about displacement, stress and strain fields associated with the most stressed zones and with RCP are gathered.

5. ACKNOWLEDGMENTS

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