THREE DIMENSIONAL HOLOGRAPHIC FLOW VISUALIZATION

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A description has been made of the theory, method and application of holographic flow visualization to a rotating transonic cascade. The objective of the technique being to spatially locate the leading shock wave as experienced by the first stage compressor fan in a typical commercial axial gas turbine aero engine. Previous similar holographic approaches to this problem have also been discussed.

INTRODUCTION

Holographic interferometry records the density distribution within the flow. In two dimensional cascades it gives quantitative measurements of the density field (Ref. 1) and in the three dimensional flow it can show the positions of major features such as shocks, vortices, wakes, boundary layers and flow separation.

The application of holographic interferometry to three dimensional visualization of flow fields has to be approached differently depending on the requirements of the experiments. For slowly changing continuously variable flows a tomographic method of analysis has been considered the most applicable (Ref.2). Whereas for the discrete changes associated with a shock front more direct techniques using pulse laser holography have been applied (Ref.3).

In the last few years the quality, stability and power of ruby pulse lasers have improved, (Ref.4). This has aided the use of optically simpler and more rugged approaches to the problem. Coupled with this the increasing requirement of the turbomachinery research engineer to compare calculation with interpassage measurement has provided a driving force for the development of non-intrusive optical measurement techniques (Ref. 5 to 7).

In recent work completed at Rolls Royce holographic interferometry has been developed to the state where it is considered to be a technique which can be used routinely in fan research and development (Ref. 5). The application at present being the three dimensional location of the leading edge shock on a first stage compressor fan.

A holographic system is now also being developed at the Engineering Department Cambridge University to visualize the flow structure in a non-rotating annular cascade.

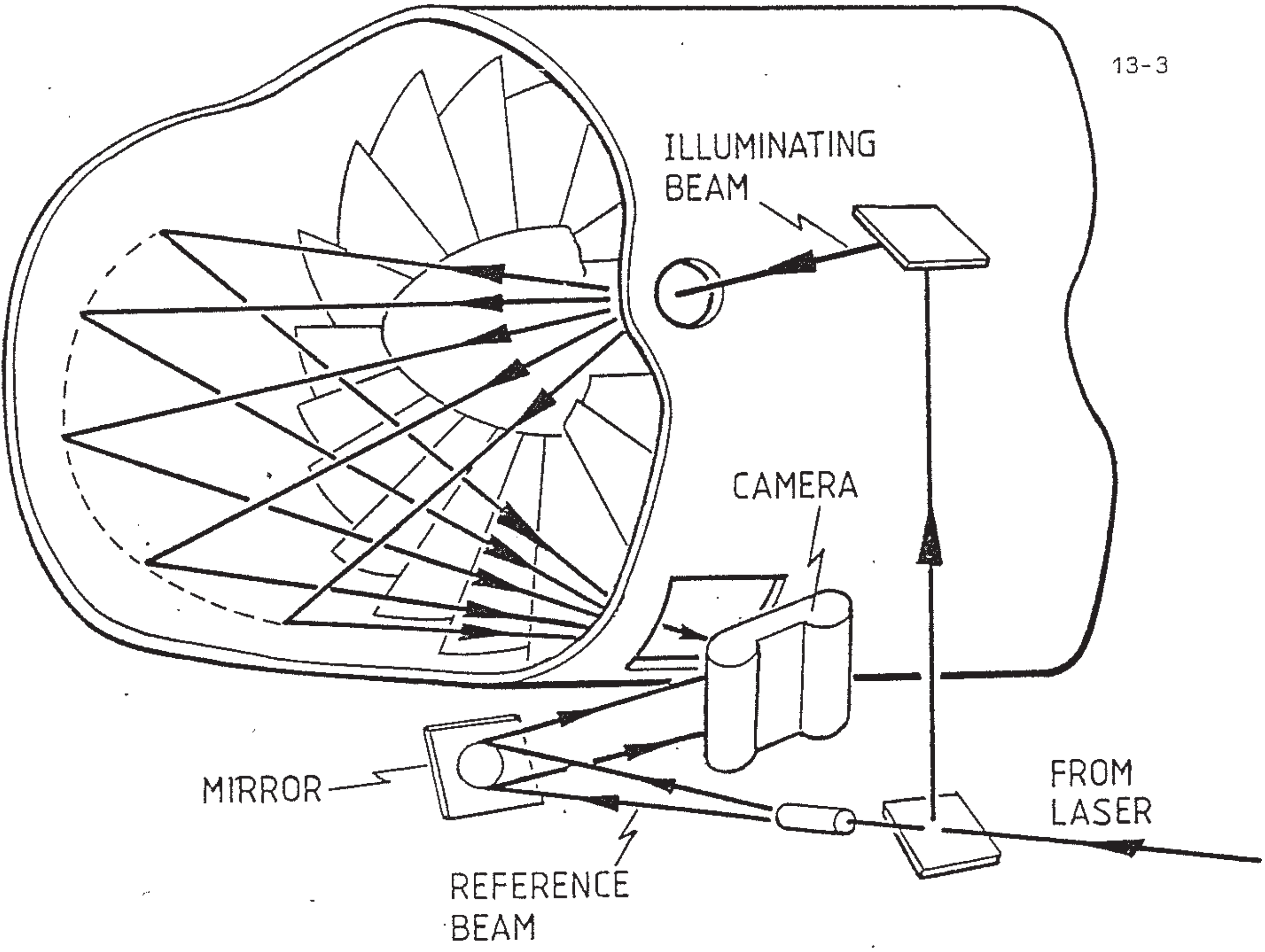


Fig. 1. Reflection Holographic System

HOLOGRAPHIC PRINCIPLES

The method by which two beams interfere to form a holographic image is described in (Ref. 8). The essential requirement is that a laser be used as a source of illumination and a sensitive photographic plate is used to record the information. In most holographic set-ups the output beam from the laser is divided into two parts. The first or main beam is known as the sample beam, the remainder being termed the reference beam. Conventionally in pulse holography two short duration pulses are produced using a Q switched rub pulse laser (100 m. sec FWHM). The separation between these pulses being variable from 1 μ sec. The resulting holograms when reconstructed show interferometrically the changes which have occurred between the two pulses. There are two main methods of producing such interferograms. The first being commonly called reflection holography, simply the sample beam is reflected from the test object onto the holographic plate. This method has been used extensively in the modal analysis of bladed assemblies (Ref. 9). The alternative method to this is known as transmission holography.Ref.(5). This technique requires that the test object is optically transparent, and the changes observed are related to changes in the density of the medium between pulses. (Ref. 1).

The technique applied to a fan is a combination of both reflection and transmission holography. The initial beam is first expanded onto and reflected off the internal surface of the engine casing. By painting the surface with white emulsion paint the light is scattered approximately evenly over an angle of 90°. A fraction of this reflected light is in the correct direction to pass through a viewing port onto a holographic plate (Fig. 1). Appendix 1.

Due to the short pulse separation required, 1 μ sec to 10 μ sec, all the components in the system can be considered as static except for the rotating blade row.

For a pulse separation of 5 μ secs, the blade tip moves 2.2 mm. This represents a rotation of the air between the blades. Hence the first pulse from the laser travels through one part of the flow and the second travels through the same air displaced by rotation. As a result of this any large disturbance in the air density is visualised interferometrically. The problem of interpreting such data is difficult as the density information is three dimensional and is not, as with reflection holograms, located in a single plane on the object surface.

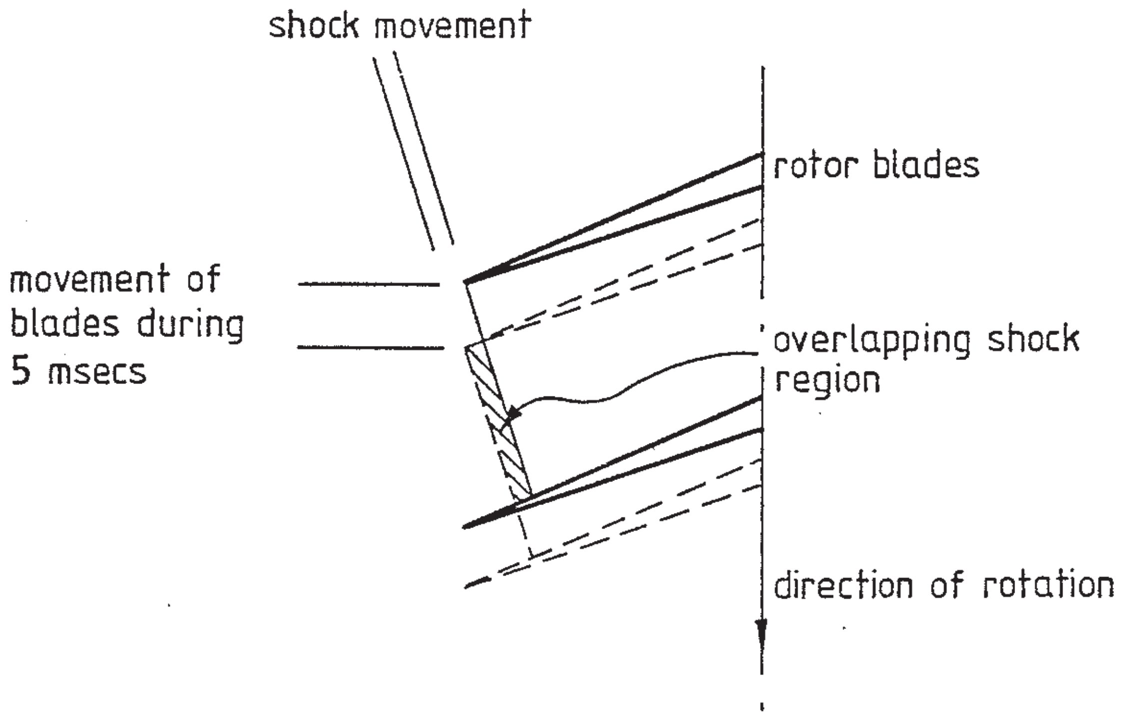
In the case of a non-rotating cascade two approaches are being developed. Here it has been found possible to locate the shock by allowing a much longer pulse separation. Shock oscillations produce the changes in pathlength required to form interferometric fringe information. A similar effect can be achieved by applying small variations to the throat of a cascade.

It is noted that these approaches unlike the presently applied reflection system are very much at the research stage of development.

HOLOGRAPHIC SYSTEM

In the 'reflection' system, i.e. where the laser pulse is reflected off the casing all the optical components are located on one side of the of the compressor, as shown diagramatically in Fig. (1). Ref. (5) The 5 mm diamete 1.2 J ruby pulse laser beam was first expanded through a highly divergent negative lens: (a positive lens would focus the light beam and ionize the air), which was mounted immediately upstream of the rotor. The expanded beam was then projected across the compressor casing and scattered from the white painted surface, as previously described. The holographic plate viewed the interblade passage against a bright background formed by the casing. The area of casing illuminated was approximately 0.5m in diameter. The objective of the scattering surface, a technique introduced by Leith and Upatnieks Ref. (11), was to allow multiple angles of view through the foreground object, i.e. the shock front. It is this ability which allows the shock front to be spatially locatable, either by paralax, (which is how the human eye guages depth), or by focusing a large aperture lens through the object Ref. (12). In the special case of a holographic image there is a third method which uses a conguate or 'real' image projection Ref. (13) to reconstruct the object.

The position of the holographic plate relative to the blade passing position and the area of illuminated casing has been found critical in the visualization of the shock front. The light intensity from the sample beam of 1.2 J was found just sufficient to expose the holographic plate (Appendix 1), which was situated 0.25 m outside the casing and 1 m from the reflective surface.



Movement of a normal shock between two pulses with a 5 msecs separation.

Fig. 2.

HOLOGRAPHIC FRINGE INTERPRETATION

Interferometric fringes are formed by the superposition of two holograms of the flow recorded on the holographic plate. A 5μsec pulse separation represents a 2 mm movement of the rotor blades past the viewing window (Fig. 2).

In the holograms formed there is an overlapping region between the two exposures of pre and post shock densities.

For example

If ρ_{pre} (pre shock inlet density) = 1.o kg/m³

and ρ_{pt} (post shock exit density) = 1.95 kg/m³

Then the change in density in the overlapping region of the two holographic exposure

$$\Delta\rho = \rho_{pt} - \rho_{pr} = 0.95 \text{ kg/m}^3$$

The relationship between interferometric fringe formation and density change is given by the relationship

$$n\lambda = RC\Delta\rho \qquad \text{Equation (1)}$$

where n is the fringe order

λ is the wavelength g light (ruby) 0.694310^{-6} m

C is the Gladstone-Dale constant $2.24\ 10^{-4} m^3/kg$

R is the optical pathlength over which the density change $\Delta\rho$ has occurred in.

For a 5 µsec pulse separation the rotor moves approximately 2 mm; as shown in (Fig. 2) this is equivalent to a displacement of a shock normal to the blade of 1 mm (d).

The path length R over which the interferometric fringe information is formed

$R \simeq \frac{d}{\sin\theta}$ where θ is the compound angle which the laser projects from the casing between the rotor blades and through the exit port onto the holographic plate.

Thus rewriting equation (1)

$$n\lambda = \frac{d}{\sin\theta} c\ \Delta\rho$$

and solving for the case of minimum fringe formation where $n = \frac{1}{2}$

$$\sin\theta = \frac{dc\Delta\rho}{n\lambda}$$

$$= \frac{10^{-3},\ 2.2410^{-4}0.95}{0.5\ 0.6943\ 10^{-6}}$$

$$\theta \simeq 37°$$

In terms of a rotating cascade both the shock strength and its relative displacement with respect to the holographic plate are related to the radial height of the blade. To visualize a part span shock a more acute viewing angle is required. For example, for a normal shock at $^3/_4$ span this angle is reduced to 10°.

This calculation represents the largest viewing angle for which interferometric fringe information can be formed. Clearly, as has been found in the non-rotating case, a shallower angle of view allows either a much weaker density change to be detected or a shorter pulse separation to be used. In the limit, looking directly along the shock its non-planar characteristics i.e. shock curvature, determines the maximum possible path difference available.

RESULTS

Holographic flow visualization has been applied to several rotating cascades at Rolls Royce, Derby. The operation of the system and its function as a complement to laser anemometry has been discussed in a previous publication (Ref.5). The objective of the holographic system was to visualize the leading edge interpassage shock structure associated with the first stage of a compressor fan. Having achieved this, various parameters which determine the position of the shock, and hence the efficiency of the fan, have been varied. These were:-

1. Individual blade to blade variations within a blade set at constant conditions
2. The speed of the rotor
3. The pressure ratio across the fan

It has also been found possible to visualize the overtip leakage with its associated vortex structure and the formation of a lambda foot produced by the interaction of a normal interpassage shock with the suction surface boundary layer

The results of these tests have been presented in Ref.(5). An illustration of the type of information which can be obtained from holographic flow visualization has been presented in (Fig.3). Here the leading edge shock at the blade tip can be seen to be expelled from the blade leading edge. The over tip vortex can also be seen in the passage, generated from the lower blade leading edge.

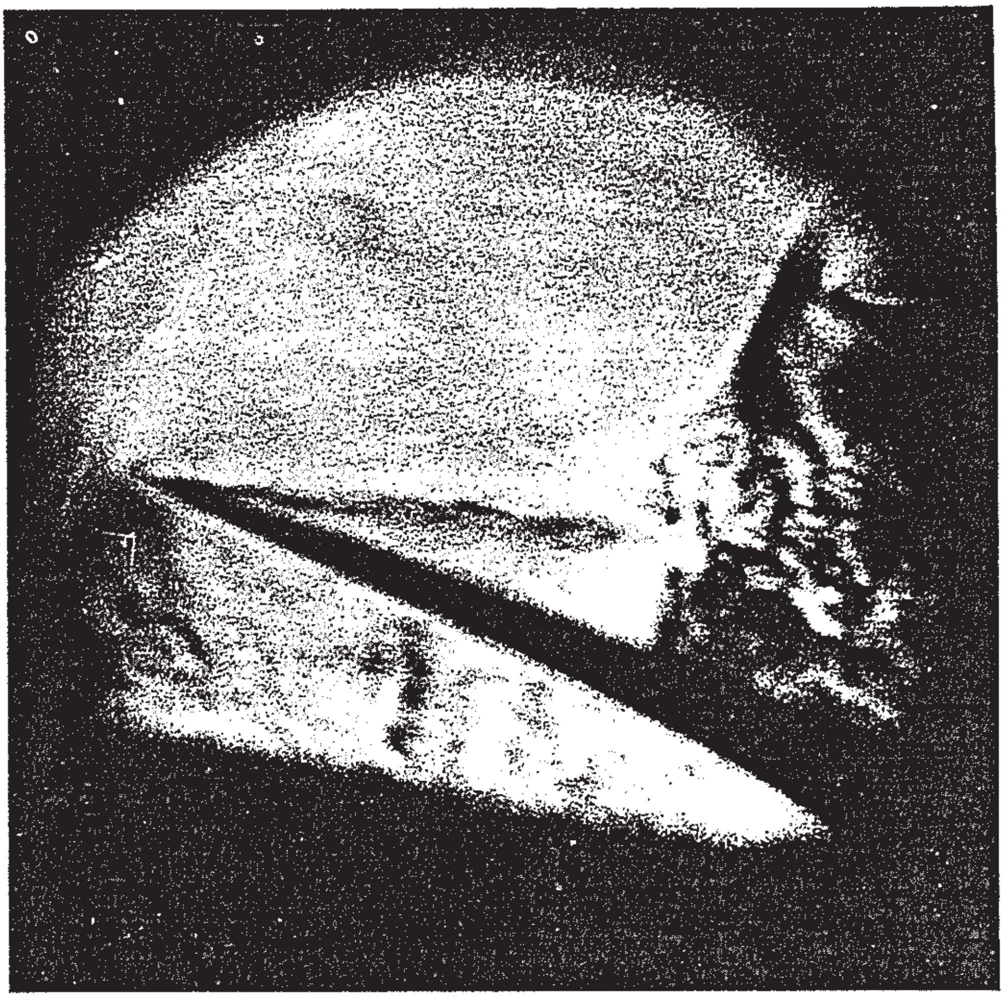


Fig.3 Reconstruction made from a hologram showing the shock structure in a rotating flow.

A REVIEW OF OTHER HOLOGRAPHIC FLOW VISUALIZATION EXPERIMENTS MADE ON ROTATING CASCADES

There have been several attempts to visualize holographically the interblade shock structure. One of the earliest a 'transmission system Ref (3) was applied to a compressor with a particularly high pre shock tip speed. M = 1.9. The resulting density change across the shock was approximately 1.5 times stronger than commercial fan of current interest. This allowed a larger shock viewing angle and made the problem of finding the necessary line of sight between the rotor blades to visualize the shock simple. Another experiment of the same period used a 'reflection' approach Ref.(10). Here the pressure ratio across the rotor was in the region of 2.3, whereas that reported in Ref.(5) was in the order of 1.8. In a more recent experiment using a 'transmission' approach Ref.(14), where a comparison of holographic and anemometry measurements are made with a numerical solution; it is reported that a tip speed of M = 1.4 only the tip shock could be visualized. This is confirmed in a Rolls Royce comparison made between the 'transmission' system described in REf.(3) and the 'reflection' system Ref.(5). The present Rolls Royce reflection approach by careful choice of the line of sight through the blade passage allows visualization of the part span interpassage shock at commercial operating conditions.

HOLOGRAPHIC FLOW VISUALIZATION IN NON-ROTATING CASCADES

The holographic limitations experienced on rotating cascades are considerably relaxed with respect to non-rotating cascades, Ref.(15), Appendix 2. Recent developments Ref.(16) in the use of volume holography show how measurements can be made without the use of either a pulse laser or an isolated rigid framework. Due to the high sensitivity of interferometric measurements however an accurate support and location system is still a necessity; and in the area of flow visualization a pulse laser is required to 'freeze' the high frequency fluctuations in the flow Ref. (17 and 18).

For a two-dimensional cascade it is also possible to compare interferometric information with detailed numerical solutions. Ref.(18). In the three-dimensional (annular) case shock front location, flow separation, the extent of secondary flow into the field and probe/shock interaction become the main areas of interest.

At present at Cambridge University, an annular turbine cascade is being developed to operate as a transient running facility in the Aero Laboratory. Research also is continuing into the fringe localization and measurement of three dimensional density disturbances Ref. (19).

CONCLUSION

An analysis of the holographic flow visualization of the leading edge shock structure associated with a commercial first stage compressor fan has been presented.

The present Rolls Royce reflection holographic system has been described, other similar experiments have been reviewed.

The future application of holographic flow visualization to a non-rotating cascade has been discussed.

APPENDIX 1

Attenuation of light path due to the use of a partial Lambertian scattering surface.

An estimate has been made of the attenuation of the sample beam as it propagates onto and from a Lambertian scattering surface. The initial output power of the JK ruby pulse laser is 0.5 J per pulse. Each pulse has a duration of 100 μ secs. It was assumed that a 50% loss in the power occurred in projecting the beam through a 12 mm negative lens and onto the surface. As a scattering surface the casing was not expected to be totally uniform but 25% efficient at an off axis angle of 12°.

Thus of the original 0.5 J of energy the amount in terms of J/cm^2 of energy reaching the photographic plate has been calculated as:

0.5 J	initial power
50%	loss due to projection system
25%	efficiency of scattering surface
2%	amount of light which exits through viewing port onto the photographic plate of the total scattered light.
	$\simeq 6\ \mu J/cm^2$

The sensitivity of Agfa Holo test film(10E75) is 3 μ J/cm^2

APPENDIX 2. FORMATION OF A HOLOGRAPHIC IMAGE

General Theory

As a background to this appendix reference (12) may be found useful. The subject of holographic fringe formation can be difficult to understand without the necessary background in optics. To simplify this it may be useful to establish a few well known factors.

Associated with any scattering surface illuminated with coherent light (normally a laser source) is a unique speckle pattern. The speckle pattern consists of a series of bright points of light created by the mutual interference of the light as it is randomly reflected. The size of each speckle point is dependent on how it is viewed, and is defined by the diffraction limit of the aperture presented to it. In the case when it is imaged using a lens, the size of each speckle σ in the image plane of the lens is defined as

$$\sigma = \lambda F 1.21$$

where σ is the speckle size
F is the f No. of the lens   focal length/decimeter
λ is the wavelength of light.

Typically for a $F = 10$ and $\lambda = 0.694310^{-6}$ m

$$\sigma \simeq .7 \times 10^{-5} \text{ m.}$$

$$7 \ \mu\text{m.}$$

Alternatively if the speckle is observed directly on a photographic plate then the speckle size is given by $1.21 \frac{z}{d} \lambda$ where z is the distance of the plane and d is the diameter of the reflecting surface.

To form a holographic image of any object the speckle pattern observed on the holographic plate must be static to within 1/10th of the speckle pattern size. If the speckle pattern moves then multiple decorrelated images will form and the resulting hologram degraded. There are three approaches to overcome this problem, one is to use a pulse laser; the exposure of the laser is in the order of 50nsecs and freezes an instantaneous picture of speckle pattern. Another approach is to allow both the sample and reference beams to move together. (Ref. 16). This second approach allows the use of a continuous wave laser and exposures over relatively long periods; up to 4 minutes exposure periods are possible (Ref. 19). Finally there is the method traditionally associated with holographic system from vibration for the duration of the exposure. Typically a large stable mass such as a machine bed isolated by a damping system is required to achieve wavelength stability over such long periods. For flow visualization work a pulse laser is preferable because it records an instantaneous picture of the flow field (Ref. 1), where localized disturbance can occur with frequencies in the region of 100 kHz (Ref. 18).

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