PHOTOGRAMMETRY FOR THE NON-INVASIVE MEASUREMENT OF VOID FRACTION AND VELOCITY IN TWO PHASE FLOW

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Abstract
The presence of air and liquid, or two phase flow, in gas turbine oil or fuel systems poses performance analysis problems. Conventional instrumentation is invasive and, by its presence, changes the nature of the downstream flow. To analyse a complete system a non-invasive technique is preferable. Photogrammetry has been chosen for this task.

An Image Acquisition System has been constructed based on a 300 nanosecond pulsed argon spark source, double pulsing being used for velocity measurement, together with a pair of Nikon 'F' 35mm non-metric cameras. The Image Analysis system uses a Ross SFS-3 Stereocomparator coupled to a Commodore PET 8032 microcomputer and peripherals. Computer programs have been developed for measurement of gas volumes in the flow. The experimental work is described, error sources considered, the results discussed and future developments of the technique suggested.

Introduction
Previous workers applying stereoscopic measurement or photogrammetric techniques were Nedderman (1961) (1) who used plastic balls to trace the flow & Wilkes and Nedderman (1962) (2) who measured velocities in thin films of liquids. In 1962 Mann (3) used stereo photogrammetry for hydraulic analogue studies of unsteady gas flow. In 1965 Stewart (4) used the technique for the study of cavitation in high speed pump inducers using half frame Nikon F cameras. In 1969 Reddy, van Wijk and Pel (5) applied the technique to an investigation of the flow of solid particles in a gas. Between 1966-68 Moffit (6) (7) used photogrammetry to define wave surfaces and wave surface configurations. This work was followed by Faig (8) (9) (10) who studied hydraulic surfaces. In 1971 Cook and Clarke (11) determined velocity profiles in smooth falling liquid films and in 1974 Azzopardi and Lacey (12) used similar techniques for determining the structures of complex film flows.

Ofsti (1975) (13) and Ofsti and Svenberg (1976) (14) used photogrammetry to determine the distribution and thickness of cavitation on ships propellors and similar work has been described by Oshima (1976) (15) in Japan. In 1975 Praturi (16) carried out a stereoscopic visual study of coherent structures in turbulent shear flow, later with Brodkey (1978) (17). In 1981 Gorashi and Brodkey (18) used simultaneous stereoscopic visual and anemometer instrumentation to study turbulent shear flows. In 1978 Azzopardi, Freeman and Whalley (19) used photographic methods to measure drop sizes in annular two phase flow at Harwell.

At the Technical University of Denmark, Jacobi 1979 (20) investigated photogrammetry to track the saltation of a particle in running water.

This technique was later used by Sumer and Oguz (1978) (21) and Sumer & Deigaard (1981) (22), to study particle motions near the bottom in turbulent flow in an open channel.

Methodology
From the literature, photogrammetry has not been used to measure two phase flow structures. The present instrumentation is bulky and modifies the parameters it is required to measure. The objective of this work was to determine the feasibility of non-invasively measuring two phase fluid flow parameters using visible light photogrammetry.

The study also investigated the problems, accuracies and sources of error inherent in such a measurement technique due to the nature of the flow. Void fraction measurement was carried out from a prior knowledge of pipe volume and summing the volumes of bubbles in the flow. Velocities were determined using a double pulsed spark source of known duration and time interval.

Experimental Apparatus

The photogrammetric system is shown in Fig 1. The Image acquisition system Fig 2 comprised a Pulse Photonics double argon spark source of 2.5 joules energy and 300 nanoseconds duration. The flashes were triggered by bubble passing pressure disturbances, either simultaneously or sequenced with a time delay for velocity determination. The observation section comprised a central pyrex tube through which the two phase flow passes. To reduce distortion it is surrounded by a flatsided perspex box filled with oil. To reduce flare from the flash a blanking plate was butted to each side of the pyrex tube. One plate had a section removed to insert a transparent graduated scale. On each plate metal was cut out in the shape of a cross to provide six reference points. A set of 3 lead balls was provided above and below the flow section to provide Z axis control. The cameras used were two, non-metric, 35mm Nikon F. For image optimisation they were mounted with the format long axis parallel to the flow section. Power winders were used to improve image acquisition rate. Due to their bulkiness it was necessary to fold the optics, the pair of front silvered mirrors being inclined at 45° to each other and the cameras facing each other on the same axis. The films used were Ektachrome Professional Daylight 135-136 processed in Kodak E-6 Developer to achieve an ASA Rating of 200.

The Image Analysis System (Fig 3) comprised a Ross Instruments SFS-3 stereo comparator interfaced to a CBM 8032 microcomputer with matched baud rates, a CBM 8050 dual drive floppy disk storage and a CBM 8026 printer.

Instrumentation measurements of flow parameters were merged with photogrammetric data to provide complete experimental results.

The flow rig is as shown in Fig 4. Nitrogen was mixed with oil to produce bubble, plug, churn, annular or mist flow regimes for the photography.

Photogrammetric Considerations

The cameras used were a Nikon FM (85mm f2.0 Nikkor set at f 8) and a Nikon FE (85mm f 1.8 Nikkor HC at f 8). To overcome problems due to varying focus before the lens calibration was carried out, the cameras were installed on the rig, focussed on the test section with the correct geometry and the lens position locked. The correct lens aperture f 8 was also set before calibration as this determined the area of lens used.

The cameras and lenses were calibrated by Dr Peter Scott of the Photogrammetry Department of University College, London to determine the radial or symmetric lens distortion parameters and the decentring comprised of asymmetric and tangential lens distortion parameters.

The interior orientation was determined using the method of steel rules described by Scott (1976) (23) and Scott and Georgopoulos (1979) (24). A fully co-ordinated small test field was set up and due to the short object distance a steel rule was used, the target being the graduations.

A further calibration required was the recovery of the Principal point, to do this, an exposure was made of the flow section including the two T-shaped control patterns with both cameras. This allowed the corners of the negative to be referred to the images of the T-shaped control patterns permitting the recovery of the principal point from the controls.

The exterior orientation determination was carried out at the end of the test after the photogrammetric geometry had been optimised.

Due to the lack of control points on the front face of the clear perspex block of the flow section, a piece of drafting film with control marks was placed on the front of the block and photographed to produce a calibration. Twelve control marks were used (eg A, B, C, D.........) their X, Y, co-ordinates being known. They are assumed to have a constant Z value (the front face of the perspex flow section block is the plane Z=0.)

Images of the control marks on each of the pictures allowed a space resection for the two cameras to be obtained and gave the X, Y, Z co-ordinates of the lens in space relative to plane Z=0 and the perspective centres for each camera. This also gave the rotational attitude of the camera axes and the image X Y axes in relation to the ray normal to the plane Z of the perspex flow section and the X, Y axes of the drafting film control marks.

Photogrammetric Data Processing

There were three computer programmes associated with the photogrammetry:-

(A) Data Compilation and Storage Programme

This programme wrote stereocomparator data to disk.

The transparences on the comparator were identified, checked for parallelism and scale and using the X Y Z motions to observe 5 control points photograph origin was established.

The bubbles were observed, if spherical, two diametral measurements were taken. If axisymmetric, then readings were taken on one side of the bubble to establish surface of revolution. If asymmetric then 'n' sections were recorded. If random then 30 points were observed on the random shape.

(B) Programme to calibrate the photogrammetric system and correct the readings

This programme was supplied by Dr Scott of the Department of Photogrammetry and Surveying, University College, London.

The photography of 12 control points ensured that the scale and planarity were correct. The normals of the measured versus the actual dimensions between the control points were compared and residual errors were examined in an attempt to ensure that their algebraic sum approached zero. The coefficients in the equations were obtained through a best mean fit. The end product of this work was a transformation of measured data to actual data.

The analytic ray tracing started from the image in the stereocomparator where readings were taken from the file defining a bubble. The stereocomparator co-ordinates were converted to the co-ordinates in the plane of the photographic film on the picture point or the Principal point origin using Cholesky's method. The interior orientation was dealt with and radial and decentring distortion corrections applied for the camera lens. The direction cosines were determined of rays leaving the camera towards the test section via the surface silvered mirrors. It was in fact assumed that the cameras were positioned further back on the acquisition system centreline.

The intersections of two rays with the front face of the perspex test section wall were next calculated and the direction cosines of refracted rays inside the perspex and pyrex on the basis of Snells Law. Finally the bubble co-ordinates were calculated.

(C) Programme for the calculation of bubble volumes

Three types of bubbles were recognised.

- For the first type, the spherical bubble, the co-ordinates of two diametrally opposite points define the bubble radius and the volume of the bubble.

- For the second type, the axisymmetric bubble, the calculation of bubble volume is in three stages. Firstly the axis of bubble symmetry is defined. Secondly the co-ordinates of 'n' points along the line of intersection of the bubble with the axisymmetric plane are measured in the fixed co-ordinate system and transferred to bubble system co-ordinates. Thirdly the volume of the bubble was calculated from:

$$V = \pi \sum_{i=1}^{N=1} \left[(x_{i+1} + x_i)/2 \right]^2 (y_{i+1} - y_i) \text{ ------ } (1)$$

This formula assumed that the shape of the bubble between two consecutive measuring points Xi + (Xi + 1) can be treated as a cylinder with a radius equal to the mean and height the difference between the co-ordinates of the two points.

- For the third type, irregular shape, the volume is divided into J.sections. Each section has an area Ai and a centre of gravity Ci. The volume between section Ai and Ai + 1 is given as the product of the mean of the two areas times the distance between the two centres of gravity Ci and Ci + 1. The two end volumes were assumed to be cones with base A1 and AJ and height the distance CoC1 and CJCJ + 1 respectively. The volumes are then a third of the product area times height.

Sources of Error in the Photogrammetric System

There were a number of potential sources of error inherent in the Photogrammetric system as follows:-

- A large principal distance coupled with a small format (35mm) gave a poor angle determination at the perspective centre.
- A very small base to distance ratio (41/890) made for an extremely weak intersection angle at the bubble surface.
- Because it was necessary to cut the films to mount them in slides the corners were lost which would have served as fiducial markers. This was recovered for the calibration by making photographs using the 12 control points but assumptions have to be made that on all the previous photographs the geometries were unchanged.
- The control points in the plane of the bubbles all lay within the uncertain medium of oil and perspex, except for calibration there were no external controls.
- The bubble surfaces were not truly stereoscopic - what was seen was a pattern of shadows and reflections which may not have been the same to each camera. The operator may have seen different highlights and falsely fused them. In practice this did not happen.
- The non-homogeneous refractive index of perspex and the small differences between the indices of perspex and oil resulted in pairs of rays not intersecting. The perspex was not optically flat - this may have had some residual effect on the refraction assumptions.
- The calibration of the stereocomparator showed it to have performed well within the 10μm specification. Any errors are therefore neglected

Residuals and their assignment in the Photogrammetric System

(a) The camera calibration was not very satisfactory because of the limited depth of the object - However, the maximum radial distance used on the photographs was 7mm which, with the principal distance of 95mm, meant that to achieve an accuracy of ± 10μm in the picture co-ordinates, the principal distance had to be known to ±135μm. To that limit, the camera calibration could be assumed to have yielded constant principal distances of 95.6 and 95.8mm. The origins of symmetry in relation to the fiducial origin (the intersection of the lines joining the corners of the format) were as follows.

Shifts from F to OS (Fiducial Centre or origin centre to origin of symmetry),

Camera A y = +0,72 x = +0,35
Camera B y = +0,17 x = -0,12

(b) For interior orientation calibration because no fiducials were available, the camera was orientated on the exterior controls a, b, e, f, g, h in the flow section. Therefore any change in the exterior orientation resulted in a shift of a, b etc and a consequent shift in the assumed principal point.

Fluid dynamics results from the photogrammetric analysis

In the photogrammetric analysis of the flow structure images, 617 stereo pairs of images were inspected from the photography of the flow matrix.

A list was then made of 263 images from which measurements of scientific value could be made. These were carefully considered in conjunction with a selection of 34 images visually displaying interesting or new fluid dynamic structures, the number of measurements was reduced to 150.

Measurements of Bubble Configuration and Volumes

- Two Dimensional measurements
  - Gas volumes - Void fraction measurements
    Volumes of spherical bubbles, spherical and elliptical caps, axisymmetric bubbles and the summing of volumes of bubbles in a flow field.
  - Fluid Dynamics measurements of medium/long plugs and Taylor bubbles
    Measurement of nose radii, shape and cone angles. Buckling and notches on plug noses, deformities and shear angles.
    Variations in diameters on long plug.
    Shear angles at base of plugs, trailing gas skirts and studies of tail breakup including matching lengths of detached sections against the length of detachment cavity.
    Studies of wakes, measurement of angular distribution of small bubbles aligned in Taylor Bubble wakes. Measurement of other wake features lengths of filamentary bubbles.
  - Rotational Instability Structures - shear angle and pitch measurement.
  - Churn Flow - churn cell length and diameter.
  - Froth and Annular Flow - film thickness measurement
- Three Dimensional measurements
  - Volumes of irregularly shaped bubbles
  - Exploration of structures in base of bubbles and rotational instabilities.

- Exploration of the nature of collapsing bubbles.
- Measurements and determinations of existence of concavities or convexities on bubbles not obtainable from a single photograph
- Spatial distributions of bubbles and relationships in a flow field.
- Spatial movements of bubbles on one transparency superimposed by two flashes of known time separation to determine velocity vectors. Due to problems with equipment only 9 velocities were measured.

CONCLUSIONS

- Determination of Fluid Dynamic Parameters by Photogrammetry
  Tables were produced from the photogrammetric analysis of the photographic images giving Bubble diameter, velocity, volume, Reynolds Number based on the bubble diameter and the equivalent bubble diameter. The values of the two Eotvos numbers for bubble and equivalent bubble diameters were obtained, together with the Morton number for the fluid.

- Feasibility of the use of Photogrammetry for void fraction measurement
  It was found possible to obtain accurate measurement of bubble and plug volumes and from knowledge of the pipe volume the instantaneous gas and liquid fractions were measured. Smaller spherical bubble volume determination was limited by the size of the floating point in the stereocomparator of 0.05mm diameter. The minimum bubble size that could be measured was double the size of the floating point i.e. 0.1mm diameter.

  The volumes of large numbers of bubbles in a flow field could be measured, and the third computer programme had the facility for adding up the void fractions, however it would have been very time consuming.

  Rotational instability structures were measured and, to a certain extent, churn. Froth and Annular void fractions were not easily obtained.

  It was not possible to compare the accuracies of conventional versus photogrammetric systems as conventional void fraction and velocity measurement instrumentation were not available.

- Feasibility of the use of Photogrammetry for velocity measurement
  Due to constraints of the timing system and the time cycles of the Nikon camera powerwinders, the number of velocity measurement images was small. However, from the images obtained in the two flash mode, linear velocity was readily available and rotational velocity was also possible. From the linear velocities obtained, it was possible to determine a modification to the work of Nicklin, Wilkes and Davidson (25) (1962), (27) (1983).

- Area of the Flow Matrix accessible to Photogrammetric Measurement
  Measurement was relatively easy with stable plugs and plugs with tail break up. In the rotational instability regime, measurement was possible. However, in the churn, churn-annular, annular and froth flow regimes, measurement using visible light was not possible due to the opacity of the flow.

In considering the original objectives of the work, it is concluded:-

- The feasibility of using visible light photogrammetry for the non-invasive measurement of fluid flow structures has been proven.

- Subsequent photogrammetry will be improved by better control points at the plane of the flow axis and by increasing the baseline distance. This may be achieved by converging the cameras or the use of a Nikon Perspective Control Lens.
- Using Torlegard's technique (26) it may be possible to provide mirrors in the arrangement of the blanking plates to permit both sides of the flow channel to appear on the image and be measured. Stratified lighting may give interesting results.
- It was not possible during the course of the work to quantify the magnitudes of the errors and accuracies absolutely, but sources of error and the nature of inaccuracies were identified. It is believed that 90-95% of the width of the flow section is distortion free due to the matching of the refractive indices and it is considered by the photogrammetrist that accuracies in the X and Y directions may be as good as 20 microns with 40 microns in the Z direction.
- It is concluded that photogrammetry is a valuable tool for the non-invasive measurement of two phase flow.

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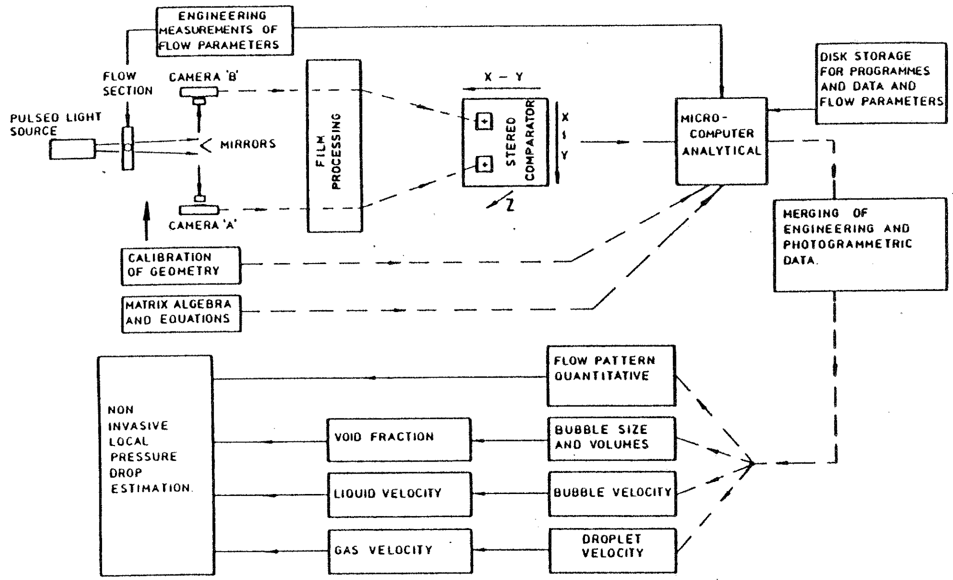
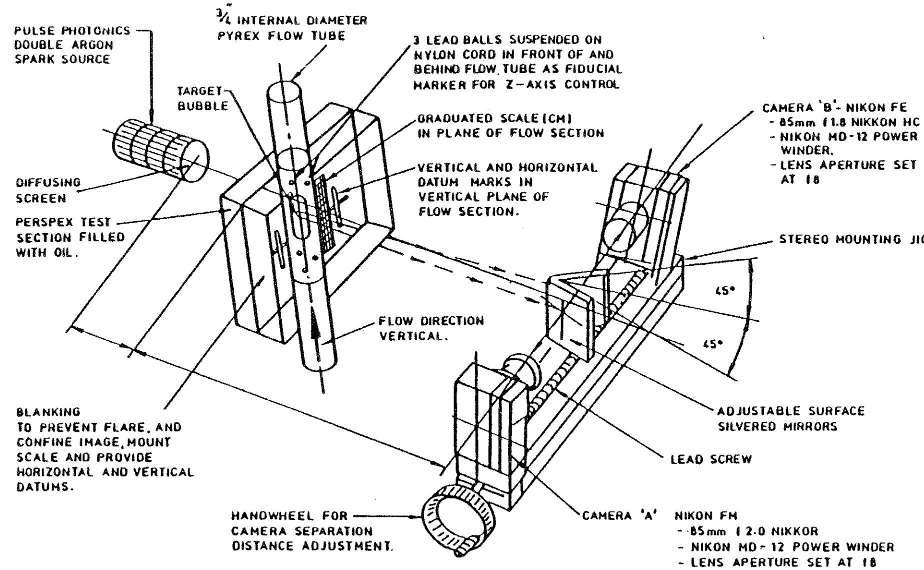


FIG. Nº 1 THE PHOTOGRAMMETRIC SYSTEM

FIG. Nº 2 LAYOUT OF PHOTOGRAMMETRIC IMAGE ACQUISITION SYSTEM FOR TWO PHASE FLOW STUDIES.



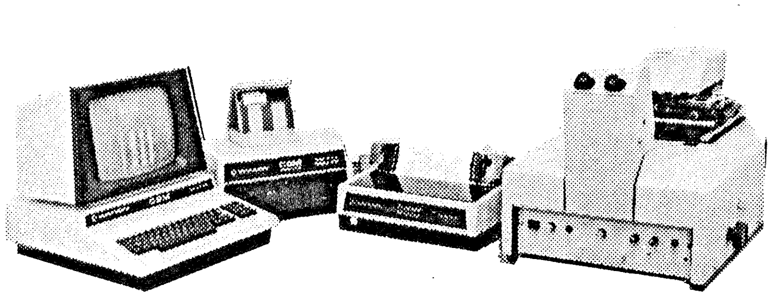


Fig. 3 IMAGE ANALYSIS SYSTEM

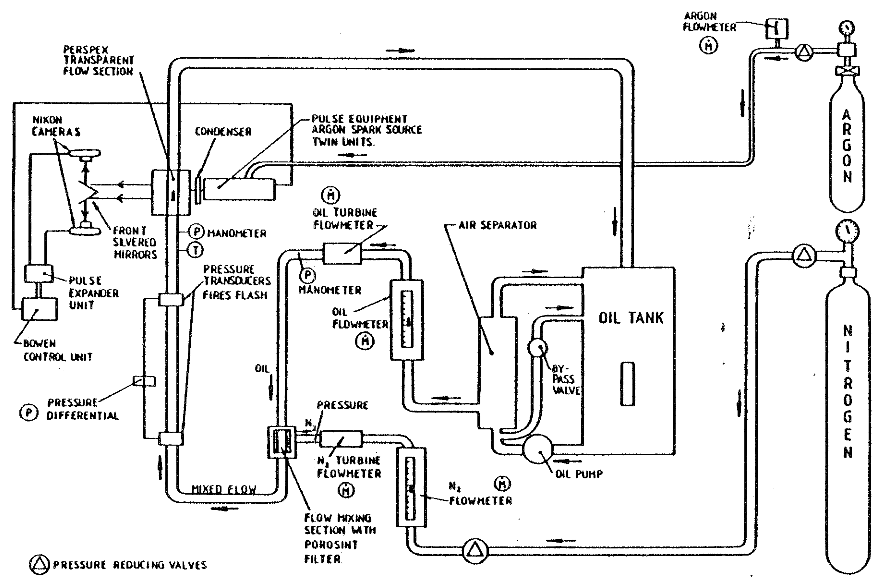


Fig. 4 EXPERIMENTAL APPARATUS FOR TWO PHASE FLOW