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COMPUTER CONTROLLED, PULSED LIGHT SHEET/IMAGE ACQUISITION SYSTEMS FOR USE IN TURBULENT FLOW.

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Summary.

In the majority of flows of practical aeronautical interest the presence of turbulence may lead to unsteady effects such as flow reversal and separation. The measurement of such transient motion by pulsed laser velocimetry (PLV) and visualisation by light-sheet techniques has contributed much to our understanding of the nature of unsteady flows. A difficulty encountered in using this type of measurement systems is the need for synchronisation of light source and image grabbing hardware with flow features. Laser pulse opimisation is also required.

The present paper reviews the area of PLV and describes work by the authors in developing a computer control system to allow automated data collection by pulsed light sheet techniques. The behaviour of a YAG:Nd laser is optimised and the output power of consecutive pulses controlled. The algorithms allow the regular pulse train to be interrupted in order to provide the recorded laser flash sequence at an arbitrary time determined by dynamic events in the flow.

This system is illustrated by two application examples. In the first, procedures adopted in a spinning wind-turbine experiment are described while the second discusses a tow-tank experiment involving a moving ship model with spinning propellers. In these examples a standard film camera was used with the electronic shutter synchronised by computer control.

The various analysis strategies currently favoured for the interpretation of such flow following imagery techniques are described with a discussion of their optimum application.

Introduction.

Laser sheet flow velocimetry methods have developed rapidly over the last fifteen years, being now a mature and powerful branch of measurement science. Pulsed laser velocimetry is the generic term given to the method of flow measurement which infers fluid velocity from the motion of flow following particles or seeds. In application, the method is often refereed to as Particle Image Velocimetry (PIV) or Particle Tracking Velocimetry (PTV) (1). The light, usually laser light, is shaped into a two dimensional plane region (sheet) and used to stroboscopically illuminate the particle motion. The event is either recorded photographically by film camera or directly to computer frame board by a CCD camera. Knowing the laser flash rate and the magnification between experiment and image allows the velocity of the flow following particles to be obtained using image processing methods (2, 3). These two references illustrate different approaches to data reduction which are described in more detail in the section "Current Development Work in Flow Image Analysis" below. A useful classification of the nuances of the technique can be found in the paper(4).

In many industrial and aeronautical flows of importance there is a periodicity or other time signature with which data capture need to be synchronised. Examples include rotating turbomachinery, bursting turbulence and aircraft or projectile passage. In synchronising with these events the properties of the laser light source and the data capture methods need to be taken into account. The laser light source will either be CW (continuous), in which case the camera needs to act as the *gate* , or pulsed in which case the laser will need to be integrated into a control system to make synchronised data capture reliable. The pulsed laser may require an initialising time during which energy is stored then released in a small number of flashes, typically two or four (this is the mode of operation of the Ruby laser). A second commonly used pulsed laser type operates most efficiently when it runs continually at a pulse rate of approximately 10hz (this is typical of the mode of operation of the Nd:Yag laser). The operation of the Nd;YAG under computer control is described in the present paper. Details of the operation of the Ruby laser is described in a second paper in this conference volume (5).

Turbine Aerodynamic Studies Using a Computer Controlled Nd:Yag Laser.

Wind turbine aerodynamics is an environment where rotating aerofoils are exposed to a cross wind and produce a periodic wake in which there will be turbulent effects and, depending on the incident wind conditions, unsteadiness. The authors have been developing pulsed laser sheet methods for application to turbines for a number of years (6, 7). The emphasis has been on determining circulation on the moving rotor blades and velocity mapping of the spiralling vorticity in the turbulent wake. Recently the laser sheet methods have been applied out-of-doors in site measurements (7).

The choice of the light source was influenced by several factors, the most important being the requirement for high intensity illumination and a light pulse length and rate compatible with the fluid velocity. In aerodynamic studies this generally results in a pulsed laser source being chosen. The ease with which the light sheet can be formed and manipulated was also relevant. Portability was also a requirement since the work program was to be extended to field measurements when sufficient experience had been obtained in wind tunnel tests. The YAG laser met these criterion.

The frequency doubled Yag laser had a wavelength of 532 nm (green) with an output energy of about 135 mJ. The very short pulse width of about 6 ns resulted in very sharp particle images. For example, a 60 micron seed particle moving at 10 m/s travelled less than 0.1% of its diameter during the pulse.

Laser Control.

The laser operated via a remote controller which connected to the power supply unit. The output energy, pulse repetition frequency and Q-switch operation mode could be adjusted manually. The Q-switch, or Pockels Cell, was a very important part of the laser which allowed the shortening of the pulse duration and increase in peak power. The Q-switch "enabled" position was adjusted relative to the flash lamp (pumped) phase to affect the laser output energy. It was required to open at the instant when that the laser reached the maximum gain, or had the highest population inversion. If it opened too early the pumped energy was not fully used. Late opening meant that many pumped Nd ions had decayed to their ground state with the available energy again reduced. For PIV the repetition rate of this laser is too slow for high speed flows. A second, high voltage producing, device called a Max-Bank, was therefore added to our laser system. This could be triggered by a second signal and applied to the Pockels Cell to produce another laser pulse within one cycle of the flash pump. A delay box can be used to produce this pulse synchronously. By carefully adjusting the Q-switch times, double pulses were produced from each flash lamp cycle. The energy for the double pulses was balanced by the Q-switch, in the open position, when the lamps triggered. A periodic laser pulse train was produced in this way.

The operation of the laser, when manually adjusted, suffered poor repetition with consequent power loss. It was also difficult to synchronise the laser with outside events when manually adjusted. The external input ports of the flash lamp and Q-switch triggering signal on the Nd:YAG laser power supply unit made it possible to control the laser operation externally. A PC was used to supply the triggering pulses which the laser needed to work in the different modes. The parameters were set digitally and the pulses sent out from the computer via its parallel port thus optimised the laser performance.

A portable PC delivered a repetitive control signal to the laser which activated the flash lamps at the optimum rate of 10hz. The PC also delivered a second signal to the laser which was used to control the Q-switch circuit of the laser. This later function allowed the production of two discrete light pulses within the energy envelope as described above. The position of the pulses within the envelope was critical since it determined the ration of the intensities of the two pulsed. This in turn could be used to determine the flow direction since different brightness or size distinguished the components of the pulse pair.

The signal from an optical switch mounted on the spinning hub of the wind turbine was used by the PC to monitor rotor phase. The signal was passed through a delay unit prior to being monitored by the PC. Image capture mode was enabled by keyboard prompt which signalled the PC to interrupt the regular 10hz pulse train and re-initiate, after receiving the next hub trigger pulse, at a time calculated from the rotor speed. After re-starting the second pulse (pair) was timed at the instant a rotor blade passed the field of view. The camera also required to be automatically triggered.

Experimental Geometry.

The Yag laser was located on the wind tunnel roof with the beam being projected down into the working section. Suitable optical arrangements were used to produce a fan shaped light sheet of approximate thickness 1cm. Figure 1 shows the wind generator and laser in the wind tunnel.

The flow around an individual blade was examined by positioning the laser sheet to intercept a horizontal blade at the selected blade radius. The laser sheet was positioned on the rotor centre-line for study of the near wake region. The control arrangements for laser control are shown in Figure 2.

Image Recording and Analysis.

The image was photographed on 35 mm film using a standard single lens reflex camera. For the wind tunnel work a Nikon 105 mm macro lens at an approximate magnification of 0.25 was used. For outdoor work, Ilford HP5 film (400 ASA) was generally used with the Yag laser, being a good compromise between grain size (and hence resolution) and sensitivity. A shutter speed was selected to encompass the pulse separation time.

The low seeding and image densities used in the studies meant that particle tracking techniques were particularly effective in the analysis of the images. The analysis of the photographic images was conducted automatically using a PC based image scanning and analysis system.

The software used the statistical approach described by Grant and Liu (3) which allowed the efficient calculation of flow velocities. Software to allow averaging, interpolation and the calculation of derived quantities, such as vorticity and circulation, was also available.

Flow Around an Individual Blade.

A typical example of flow conditions around a blade is shown in Figure 3. The data was interpolated onto a regular grid before plotting. As flow conditions in the tunnel are steady, flow fields calculated from a number of images can be ensemble averaged. Ten images have been averaged in this way to give Figure 3. The length of the vector gives the magnitude of the in-plane component. The disturbance caused by the blade is visible but it was more informative to transform the frame of reference to either that of the blade or that of the fluid. Figure 4 shows the same data set after subtraction of the free stream velocity from the measurement set.

Further details of the experiment and discussion can be found elsewhere (7).

Spinning Propeller-Ship Wake Studies.

The wake of a ship is a region of highly turbulent flow. The wake characteristics are dependent on hull shape and propeller performance. In order to progress hull design and maximise vessel performance detailed measurements of the flow are required in this difficult region.

PIV measurements of the turbulent flow in the wake of a model ship were made using the computer controlled, pulsed Nd:YAG laser illumination system. The experiments were conducted in a 25 m towing tank with a 1:97 model destroyer (Figure 5). The laser beam entered the tank via a periscope. Observations were made using a second periscope viewing arrangement (Figure 6). During the experiment the YAG laser was fully controlled by computer to optimise the output and to control the distribution of energy between pulses. The optimised operational repeat rate of this laser was 10 Hz and a similar PC based control strategy was used as described in the wind turbine experiments. The camera operation was also controlled by computer. Two optical sensors were fitted to the side of the channel to indicate the position of the moving ship. The computer switched the laser on and off and controlled the camera, taking the PIV pictures at specific ship positions and with a pre-determined exposure. Further details of the experimental arrangement can be found in (8).

Experimental Procedure.

The cross-section of the wake of the model ship one ship length behind the model was examined. Two periscopes were used in this experiment. One had a glass rod in the front of bottom laser "delivery" mirror producing an illuminating laser sheet across the channel. The other laser had a camera fixed on the top (viewing position) to allow the capturing of under-water wake images. The geometry of the tow did not allow the orienting of the camera normal to the light sheet. The angle of view meant that a correction had to be applied to the velocity estimates obtained during analysis of the images (9).

The first optical sensor was used to begin the laser pulse train and the second sensor was used to trigger the camera shutter then switch off the laser. The position of the second sensor was determined by the laser sheet and model ship position. The first sensor was fixed in a position so that the laser would have enough time to warm up to a stable condition at the optimum pulse rate of 10 Hz prior to image capture.

The laser pulses were manipulated by the control software so that "tagged" images were produced. That is, the timing of the pulses was varied in order to obtain different intensities for the two pulses in order to determine direction (9). The test area was approximately 300mm wide and 150 mm deep. The PIV seeding particles with a specific gravity of 0.98-1.02 and an average diameter of 60mm were introduced into the measurement area. Kodak T-Max 400 black and white film was the recording medium. The film was "push" developed for maximum sensitivity. All the images were processed using statistical windowing techniques (3, 10). Figures 7 (a) and (b) show some typical instantaneous flow pattern of the wake. The data were interpolated into a 9 mm square grid using a distance weighting method.

Current Development Work in Flow Image Analysis.

In order to give an up-to date summary of development work in flow image analysis in the pulsed laser light sheet domain it is necessary first to review work and methods to date.

The multiply exposed image, be it a film or digital image, is processed by determining the spacing between the successive images of the same target particle. Two methods have been traditionally used in this process.

The fringe method (2) obtains a Fourier transform of the particle motion image as a fringe pattern whose interpretation gives the particle displacement properties. In early procedures an analogue transform was obtained by passing a low powered interrogating laser beam through a local portion of the image. The resulting interference pattern, Young's fringes, was then examined and based on the slope and spacing of the fringes the particle displacements were obtained. This approach was best suited to very densely seeded experiments.

In larger facilities where sparse seeding is more practical, and for flow interference reasons, more desirable, particle tracking analysis has been favoured. In this approach a statistical windowing procedure is used to obtain particle image grouping directly (3, 10).

Much effort is being given to developing methods of obtaining the transformation of the fringe pattern. This transformation takes the form of a correlation function whose two first order lobes give a direct measure of the particle spacing in the original image. Two approaches have been taken to obtaining the correlation function. The first is digital and favours the use of high specification computing facilities (11). The second is analogue, and various attempts have been made to use photosensitive element arrays in this context (12).

The direct analysis approach, most suited to low image density, has recently seen a number of interesting developments. The implicitly temporal (and thus directional) ambiguity of the particle motion images has been resolved using pulse coding (10) and image shifting methods (13). The variable and complex nature of many practical flows has meant that new developments in processing methodology have found immediate application. One of the most interesting innovations has been the use of self learning filtering and feature recognition methods based on neural networks (14).

References.

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Figures.

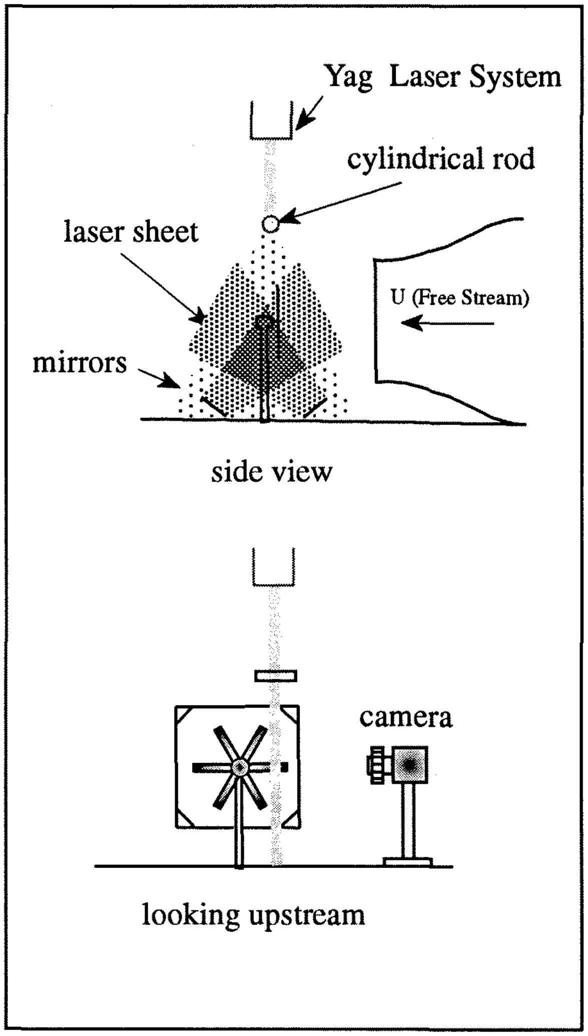

Figure 1. The Wind Turbine and YAG Laser in the Wind Tunnel.

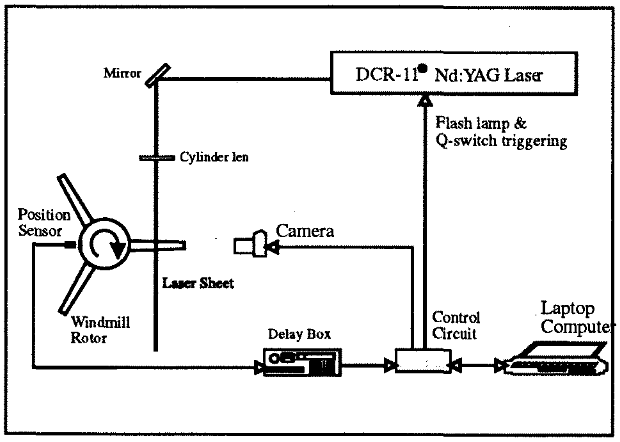

Figure 2. Schematic Diagram Showing the Control System for the YAG laser.

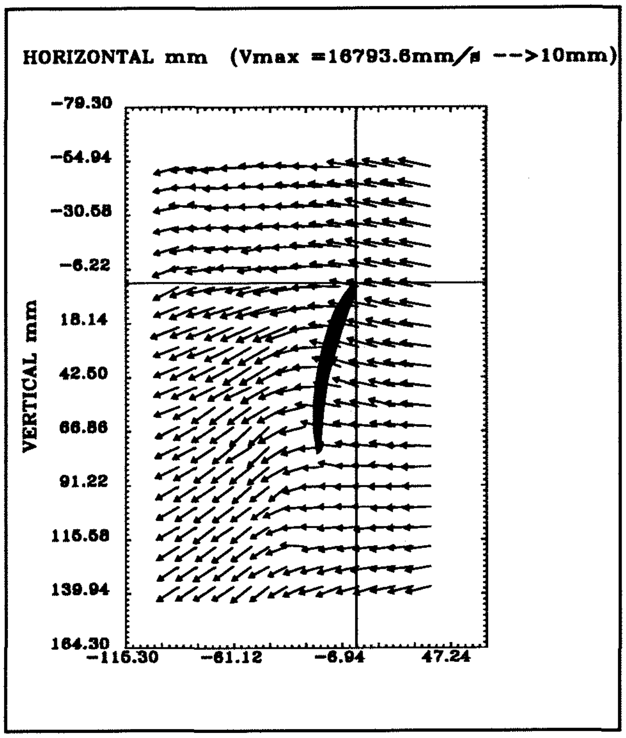

Figure 3. Typical Flow Measurements Around a Turbine Blade While in Motion.

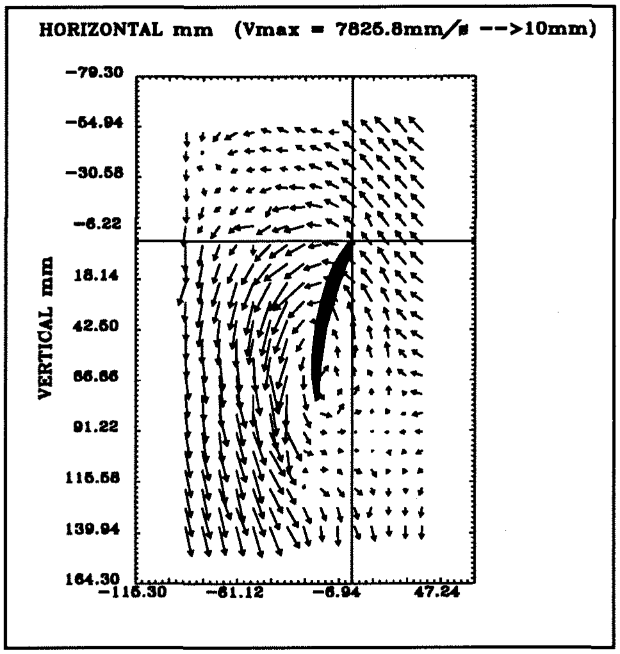

Figure 4. Typical Flow Measurements Around a Turbine Blade While in Motion Seen From the Frame of Refernce of the FreeStream Flow.

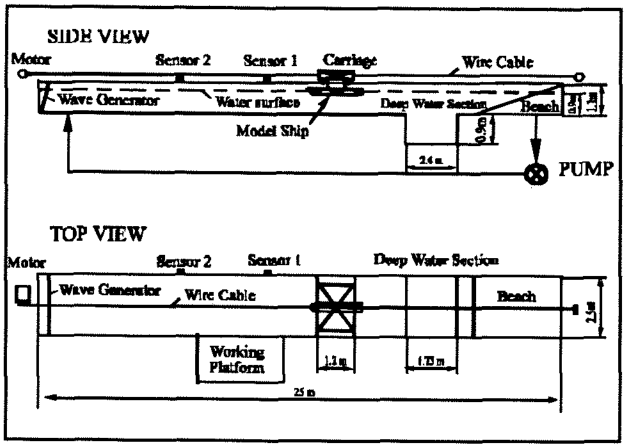

Figure 5. The Towing Tank.

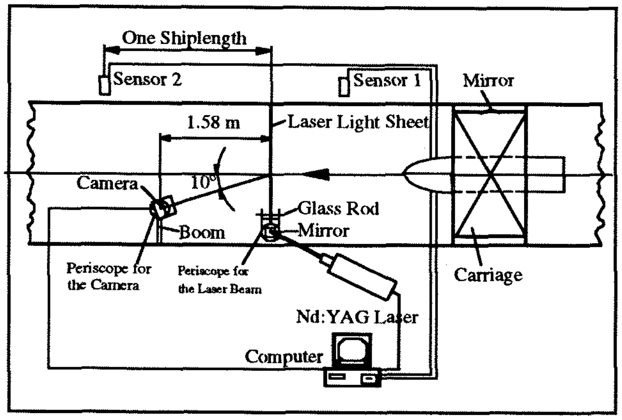

Figure 6. The Experimental Arrangements for the Laser Image Capture

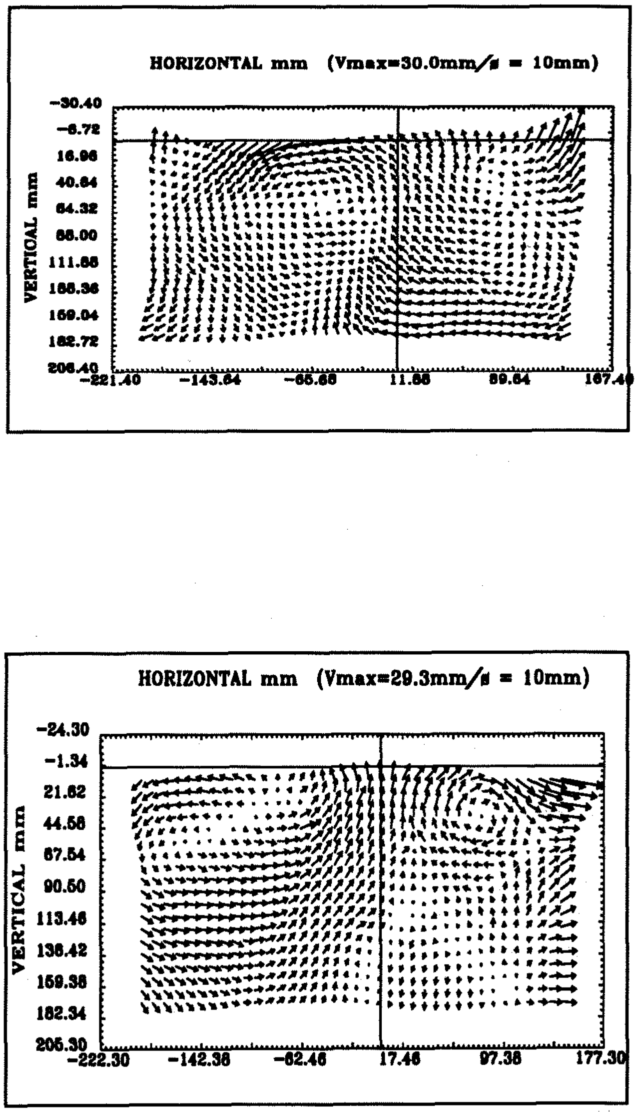

Figure 7 (a) and (b).
Example Flow Measurements in the Wake Cross Section.