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FLOW VELOCITY MEASUREMENTS BY IMAGE PROCESSING OF OPTICALLY ACTIVATED TRACERS

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ABSTRACT

A computerized flow visualization technique capable of quantifying the flow field automatically has been developed. This technique uses afterglowing effect of optically activated phosphorescent particles to retrieve vectorial information on each trace. By using this information, in conjunction with computer image processing, the flow field of a free surface transient vortex was investigated.

INTRODUCTION

Advances in fluid mechanics have been closely linked to the correct interpretation of qualitative *information that can be obtained from flow* visualization pictures. To confirm the validity of such qualitative interpretation, quantitative methods such as hot wire or laser doppler velocimetry are used. The latter two techniques are typically limited to simultaneous sampling at few spatial locations. In this respect, a quantitative flow visualization technique is required because it can provide simultaneous spatial and temporal information. Earlier attempts to obtain such information has been made by tracing the path of small particles suspended in fluid(1,2,3). However, this conventional particle tracing technique with uniform intensity traces, suffers from two major drawbacks (a) ambiguity in flow direction on each trace (the information regarding flow direction is usually lost during unbiased uniform illumination of particles), and (b) unacceptable amount of manual work required to obtain velocity vector field for a large number of traces. Attempts to reduce the amount of the manual work, by using computer image digitizing and processing techniques, have failed because of the problem of flow direction ambiguity(1,2,3). The lack of vectorial information requires the final judgement of an operator who should bear in mind the flow direction and assign a local velocity vector to <u>each</u> *individual trace*. This is usually done during the digitization process and requires both manual labor and a priori knowledge of the direction of the flow field under investigation.

But for many unsteady flows, lack of such a priori knowledge necessitates a new technique that eliminates both the flow direction ambiguity and required manual labor. This paper will attempt to introduce such a technique based on afterglow property of optically activated phosphorescent particles via digital image analysis. The technique was applied to a simple free surface transient vortex and is the subject of this paper.

PARTICLE TRACING BY PHOSPHORESCENT PARTICLES

The present technique employs particles that are coated with phosphorescent materials to retrieve the vectorial information. Once the particle that follows the flow is illuminated by a short intense light pulse, the phosphorescent crystals re-emit the absorbed energy via electronic transition and crystal's lattice vibration. The former, which has a short period ($\sim 10^{-5}$s) and is associated with the fluorescent properties of the crystal, marks the image by a bright spot. The electronic transition will be followed by crystal's lattice vibration period (phosphorescence) which has a longer period (~100 ms) and permits the generation of a trace over the distance that the particle has traveled with the flow. During the phosphorescence period the emission intensity decays with time and consequently with distance. Since the decay direction is always similar to that of the flow, one can use this property to infer the velocity vector (see Figure 3). However, such information cannot be obtained from a uniform intensity trace shown in Figure 2.

It should be mentioned that luminescent materials have been used before for the flow visualization purposes(4,5), but to our knowledge no investigator has used the afterglowing effect of the individual particles to generate traces with variable *intensity. In our automated technique*, we strictly rely on this property to make particle tracing technique less laborious.

EXPERIMENTAL SET UP

The experiment was carried out on the free surface of a round water container of 12.5 cm diameter (Figure 1). Provisions were made to have a small propeller at the bottom of the container to induce circulation in the tank. The propeller was rotated by a variable speed motor.

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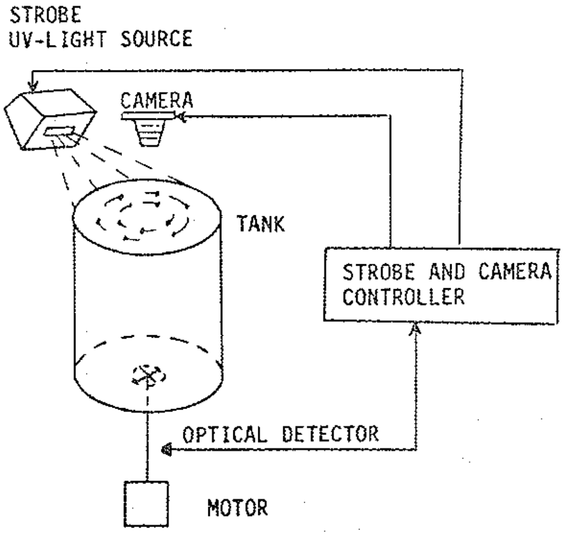

Figure 1. Experimental Set-up

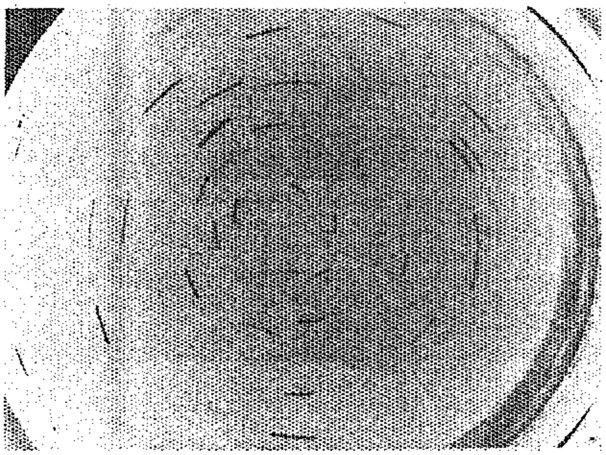

Figure 2. Conventional Particle Traces

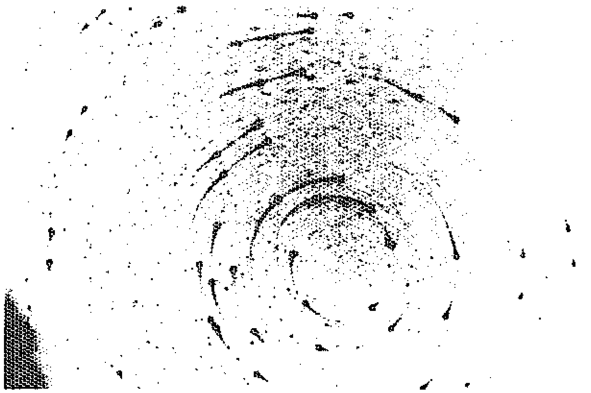

Figure 3. Double Pulsed After Glowing Traces

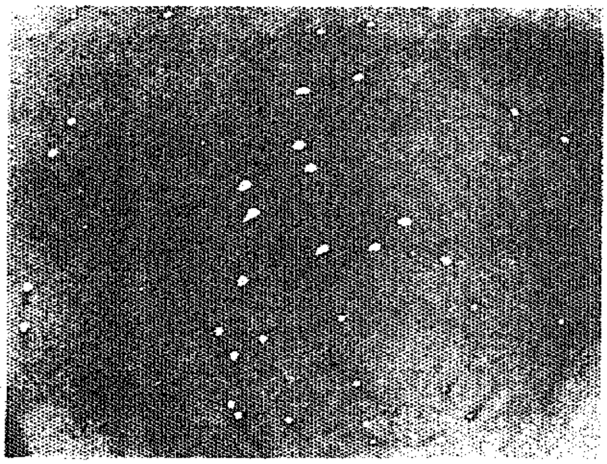

Figure 4. Spot Isolation

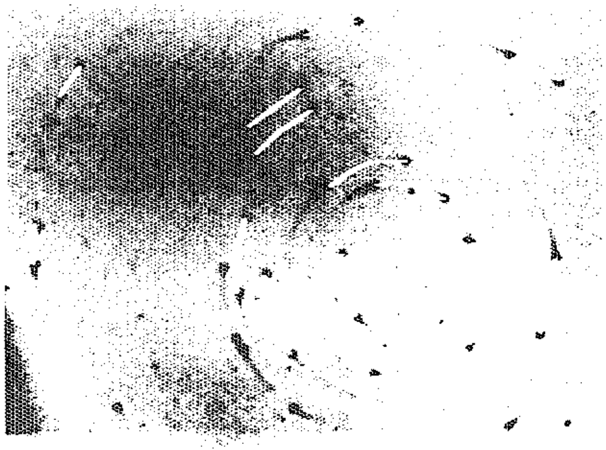

Figure 5. Trace Construction

The free surface was seeded by 200 μm polystyrene particles coated with submicron size zinc sulfate (ZnS:Cu) crystals. These particles have maximum absorption and emission wavelengths in the range of 400 nm and 530 nm respectively. For illumination purposes, a strobe light was used. The light source was filtered to allow only wavelength smaller than 420 nm to pass.

To measure velocity of each particle, length of each trace for a given traveling time should be measured. There were two options to measure traveling time. First, to use shutter's opening time. Second, to double pulse the strobe light at certain pulse increments. We used the second technique, because the pulse intervals with greater precision could be measured than the shutter's opening time. The double pulse time interval (T_D) should be selected in such a way that the trace of the first pulse sees the second spot somewhere along its length before its intensity diminishes. Thus, the first requirement for selecting T_D, time between pulses will be

$$T_D < T_p$$

where T_p is the nominal phosphorescent lifetime of the particle. T_p is 400 ms for the type of particles used in this experiment.

The particles in the high speed region of the flow will travel a relatively long distance. Due to the finite amount of the emitted power during afterglowing period, these high speed particles will have a reduced trace brightness compared to those that travel shorter distances for the given time increment. The final value of T_D is therefore decided by the flow velocity, the optical quality of the image recording system, and the threshold sensitivity of the film. In the present experiment with a maximum particle velocity of 5 cm/sec, a typical 250 ms pulse interval was found to be sufficient to generate traces that visually connect two spots. Each pulse was of 20 μs duration.

When the propeller started to rotate at 3 rps, an optical detector activated a programable control box. The control box then triggered the camera, and with shutter opened sent two pulses to the strobe light. The time between pulses was set at 250 ms, and the camera was triggered every 3 seconds. During each measurement period a total of 36 pictures were taken.

IMAGE DIGITIZATION AND SOFTWARE STRUCTURE

Each photographic negative (Figure 3) is digitized by a vidicon camera, and image digitizer. This process is controlled by a host computer and the photographic plate is digitized into a 512 x 512 matrix with 256 gray levels resolution. The first step in the analysis of the digital picture is detection of the spots. Each individual spot can be isolated from the background via local high pass filtering and thresholding (see Figure 4). Once these spots have been isolated, the next step is to label them as starting or ending points. This is done by comparing the region around each spot with eight different square masks which are centered on the spots. Each mask represents a certain direction (Figure 6). We structured the following criterion in order to distinguish the starting from the ending point: starting point has only one neighboring trace while an ending point has two neighboring traces (Figure 3). Therefore, a starting point shows a good correlation only with one mask while an ending point shows two good correlations (Figure 7). This criterion enables the computer to label each point. This process also identifies the next neighboring pixel on the trace.

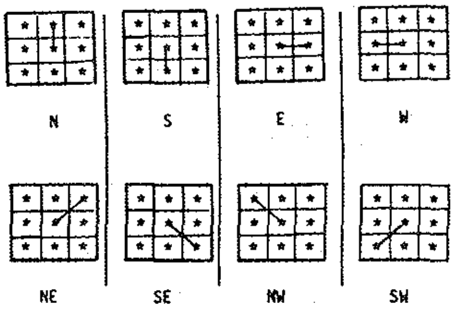

Figure 6. Mask Patterns

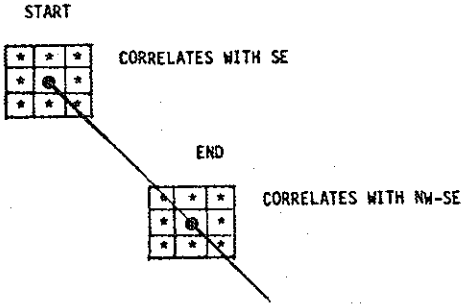

Figure 7. Spot Labeling

The labeling process is only applied to the points which are recognized as spots and not to the whole image. Trace-following-algorithms is applied to connect the starting point to the ending point. The process is as follows: with points labeled, the same masking comparison is done for the next neighboring pixel of the starting point. This process continues until an end point is identified and the connecting trace is constructed (Figure 5). At this point the computer measures the number of pixels between points on the trace and calculates the velocity by knowing T_D and the calibration factor. Several complications might arise due to local trace crossing or overlaps. At this point, the software halts the process and asks for operator's assistance. In the present experiment, traces with a spot diameter to trace length less than 10 were considered for velocity calculations.

RESULTS AND DISCUSSION

Figures 8a through 8f represent selected sequences of instantaneous azimuthal velocity distribution of a free surface vortex. Initial spin-up of the free surface is characterized by a rapid azimuthal velocity increase in a broad area close to R = 20 mm (Figure 8a through 8d). Figure 9f presents two superimposed velocity profiles at time = 63 sec and T = 69 sec. It can be seen that for T

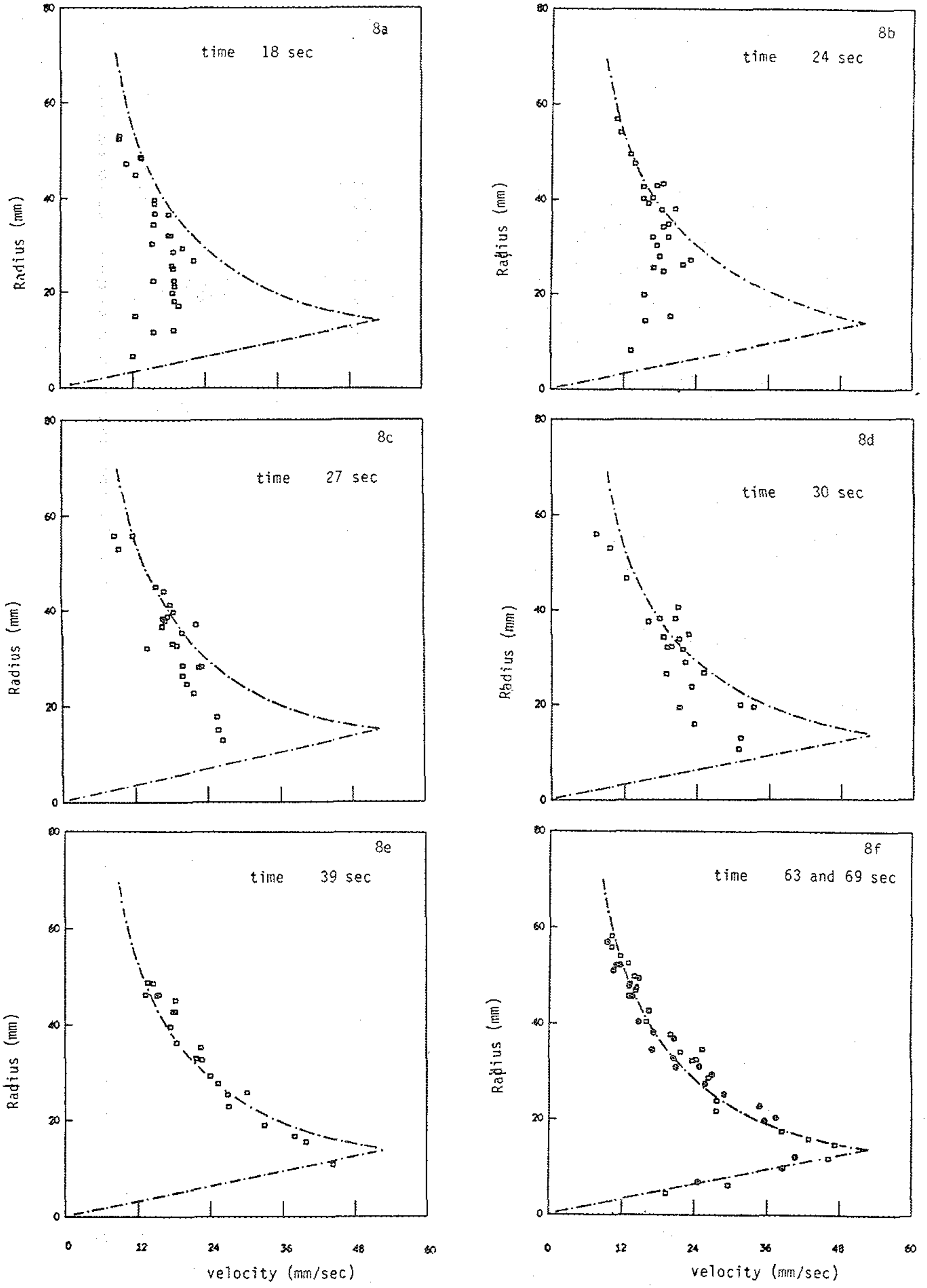

Figure 8. Free Surface Vortex Velocity Distribution as a Function of Time

> 39, the velocity profile has reached a steady state and does not change with time. The azimuthal velocity (U_θ) increases as the radial distance from the core increases. After a maximum is reached at R = 14 mm, the velocity decreases toward the outer edge of the free surface.

We can understand this observation by assuming that the flow is irrotational outside a circle (with a finite radius R_0) that encloses the core. This means that all of the vorticity is contained in the interior of this circular region. Therefore, it can be assumed that circulation is constant for the area exterior to the circular region and its value can be determined by the following relation

$$\Gamma = 2\pi R U_\theta ,$$

where Γ is the circulation, R is the radial distance. The dashed curve in Figure 8f represents the relation

$$U_\theta = \frac{\Gamma o}{2\pi R} ,$$

which is determined by assuming a constant circulation value (Γo) at R_0. It can be seen that this curve can satisfactorily represent the experimental points in the outer region.

Another observation is that the azimuthal velocity component increases linearly in the inner region of the velocity distribution. Therefore, the inner velocity distribution is same as that of a rotating solid body with uniform vorticity distribution. The intersection of a fitted straight line through the inner region and that of the outer region can be used to define a reference radius (R_0) for the core. For example, in the present experiment, the value of R_0 was found to be 14 mm. For comparison purposes, the Rankine model is superimposed on the figures that represent the transient phase of the flow (Figures 8a -8f). It can be concluded that the steady phase of the present flow can be successfully represented by the Rankine vortex model. It should be pointed out that the interface between inner and outer regions has seen a rapid velocity increase during the transient phase.

CONCLUDING REMARKS

The above results provide credence to the applicability of optically activated traces via digital image analysis as a quantitative flow visualization technique. It can be applied to complicated flow problems where single point measurements or laborious conventional particle tracing techniques cannot be considered feasible.

Much needs to be done regarding perfection of the software in handling trace crossing and trace overlap which are expected to occur in complex flows. Generation of particles with the right density and size to resolve different spatial and temporal scales is required for future work. Direct optical and electronic image recording is required to reduce the total time needed to obtain velocity information from the flow field.

Experiments are underway to apply the current technique to the internal structure of transient vortex flows by selectively illuminating regions of the flow by an intense pulsed laser or strobe sheet (see Figure 9). Particles that are excited by the light sheet generate traces in the flow and can be photographed from two angles (x-y and z-y plane) to obtain three dimensional velocity vector. Findings of these experiments will be reported elsewhere.

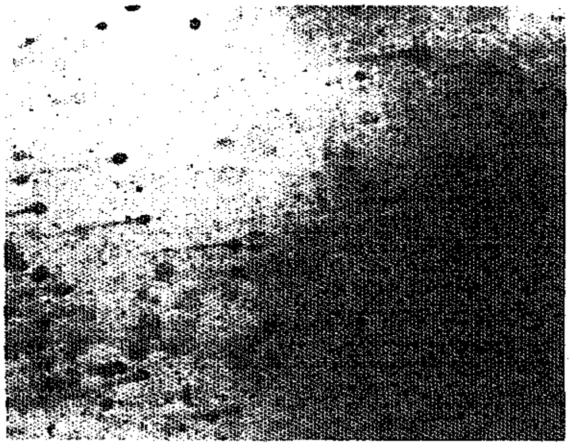

Fig. 9. Internal Flow Visualization

The authors would like to mention that the present technique can be applied for fast multi-point analysis of the flow. In this respect it can be considered as the only counterpart to multi-point numerical methods for studying fluid mechanics problems.

ACKNOWLEDGEMENTS

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