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Flow field visualization of sediment-laden flow using ultrasonic imaging

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Abstract

This investigation concerns the application of particle image velocimetry (PIV) to ultrasonic images of sediment-laden flow in order to obtain accurate, quantitative, two dimensional vector maps of the flow field within the sediment suspension. Experiments were carried out using a medical ultrasound scanner to obtain ultrasonic images in a kaolin/salt water suspension of mean concentration 16 g/l and to compare results obtained with the ultrasound scanner in clear water with those from established measurement techniques. Measurements of mud were obtained, and the comparison with established methods indicated that the application of PIV to the analysis of ultrasound images yields velocity information accurate to within $\pm 15\%$. This measurement technique will be of great value in furthering the understanding of the behavior of sediment-laden flows.

Keywords: Flow field visualization; Sediment-laden flow; Ultrasonic imaging

1. Introduction

The movement of suspensions of mud in ports, harbors, estuaries and coastal regions is important both economically and environmentally. However, many of the physical processes governing the erosion, suspension, transport, flocculation, settlement and consolidation of mud remain poorly understood, largely due to the difficulty in obtaining accurate measurements of these processes in a controlled environment.

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This paper describes a novel technique for obtaining accurate maps of the instantaneous flow velocities of a two-dimensional flow field within a suspension of mud in salt water. This method is based on applying the processing techniques of particle image velocimetry (PIV) to ultrasonic tomographs of the mud flow.

2. Objective

The objective of this investigation is to determine whether and within what limits useful data on estuarine mud behavior can be obtained using PIV on ultrasonic tomographs obtained in the laboratory.

3. Background

3.1. PIV

PIV is a well understood measuring method capable of giving an accurate map of the instantaneous flow velocities of a two-dimensional flow field. In its conventional application to hydrodynamic problems, clear fluid such as water is seeded with small tracer particles such as conifer pollen. Photographs or video recordings of the flowing fluid are then made, and flow velocities determined from the movement between one video or photo frame and the next. This allows a two-dimensional vector map of flow velocity over the whole area of the image at a given instant to be produced without the need for intrusive measurement.

This technique has been successfully applied to liquid, gas and two-phase flows over a wide range of speeds and scales. In the area of hydrodynamics, recent work at Edinburgh has included the measurement of kinematics of breaking waves Gray and Bruce, 1995, wave shoaling Earnshaw et al., 1994 and kinematics of breaking wave impacts on breakwaters Bruce and Vicinanza, 1998. The principal limitation of PIV as used to date is that it can only operate in clear fluids which allow photographic or video images to be recorded. This clearly precludes its use on opaque materials such as suspensions of estuarine mud.

3.2. Tomography

Tomography is a method of building up a quasi-photographic image using a method not reliant on visible light. Ultrasonic tomography is widely used in medical applications, particularly for obstetric purposes, where images of the fetus in the womb can be obtained quickly and safely with a refresh rate similar to standard video techniques. Ultrasound is also used in cardio-vascular imaging and other medical contexts. Various other forms of process tomography exist and are used in industry; for example, electrical resistivity maps are used to examine various chemical industry processes (e.g., Williams and Beck, 1995).

4. Experiments

Experiments were carried out to obtain velocity information in dense suspensions of mud using an ultrasound scanner and to compare results obtained with the ultrasound scanner in clear water with those from established measurement techniques.

Fig. 1. Sonarscan Prisma ultrasound scanner.

4.1. Ultrasound scanner

Tests were carried using a Diagnostic Sonar Sonarscan Prisma ultrasound scanner with a 3.5 MHz probe (Figs. 1 and 2). This was mounted at the water surface of a small mud flume and enabled a region of interest approximately 10 cm from the probe to be monitored. The probe was fixed in line with the main flow axis in the flume, so the major movement of fluid was across the recorded image, from left to right in Fig. 3. The real time B-scan image of the area of interest was recorded on SVHS video for later analysis.

4.2. Video camera

For comparison purposes, video recordings of the flow in clear water were obtained using a CCD SVHS camera. This was oriented through the perspex side of the flume, with illumination being provided from above. The camera was arranged to record the same area as the ultrasound probe.

4.3. PIV analysis

PIV analysis was carried out by grabbing successive video frames (either videos of the real time ultrasonic tomograph or those taken by the camera) and storing them as

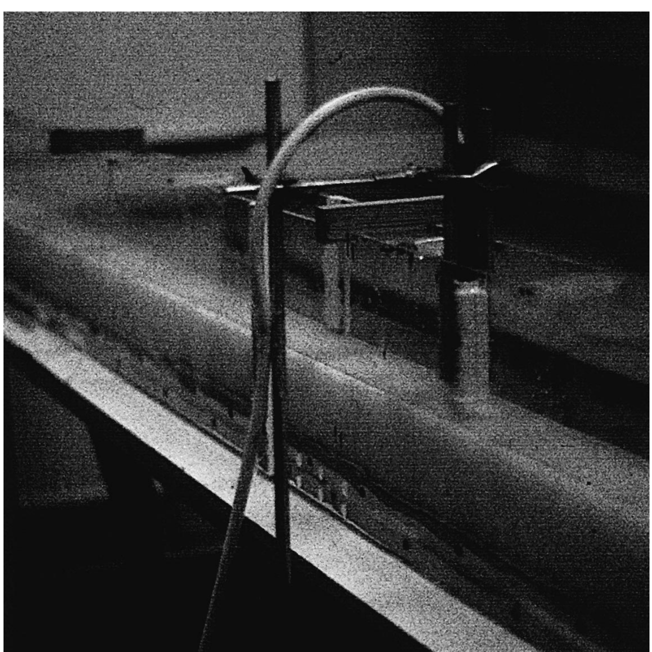

Fig. 2. 3.5 Mhz probe mounted in the flume.

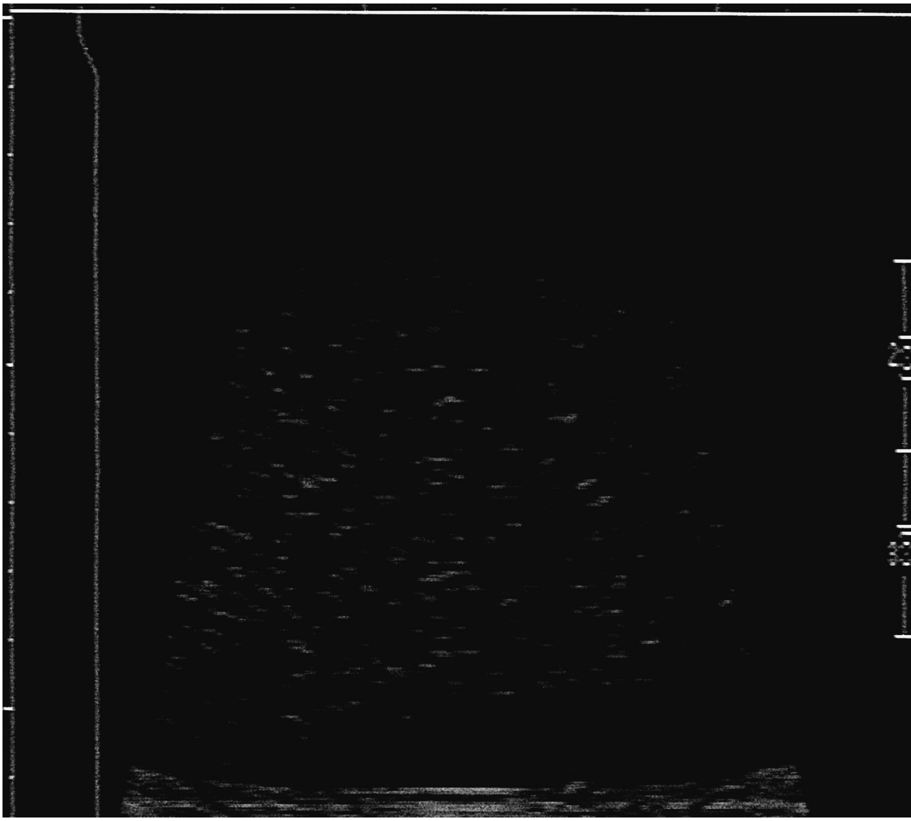

Fig. 3. Typical tomograph obtained from the ultrasound scanner.

bitmaps. These were then analyzed using the VidPIV analysis software VidPIV, 1994. The time interval was determined either from the frame refresh rate of one frame every 40 ms or where possible from stopwatch times recorded onto the video tape. Cross-correlation was used, in which the movement between successive frames is analyzed. The frame is subdivided into a grid of small cells, and the velocity vector in each is determined by assessing the directional and distance offset between the images at which the highest degree of correlation is obtained. For quality control purposes, the software allows the correlation function to be examined before a particular vector is stored.

4.4. Seeding techniques

Materials such as conifer pollen and aluminum sulfate particles are commonly used as seeding to provide tracer particles for standard, clear-water PIV using photographic or video techniques. These materials are readily visible; they also absorb fluid and become neutrally buoyant, thereby following the flow with no significant inertial or gravitational effects and giving an accurate representation of hydrodynamic properties.

Ultrasound reflects best from sharp density interfaces such as liquid/gas interfaces. For this reason, ultrasound reflectors are often hollow, gas-filled spheres with the size of the cavity being balanced against the shell thickness in order to give a neutrally buoyant particle. Unfortunately, no such particles were available for this investigation, so the performance of the standard optical seeding materials was assessed for use with ultrasound. These tests were initially carried out in clear water. The best results were obtained with conifer pollen, which was first mixed with water in a beaker and added to the flow some distance upstream of the measuring section.

The apparent size of the seeding particles as shown in an ultrasonic image is affected by their effective cross-sectional area and their speed and direction of motion within the scan plane. In our tests, this resulted in an apparent enhancement of seeding particle size, rendering it extremely easy to follow the motion of individual particles. The number of individual particles that could be resolved in each image was however somewhat limited, resulting in a restricted spatial resolution compared with photographic or video based PIV measurements. Nevertheless, this seeding methodology gave sufficient clear reflections in a given scan area to allow the general flow pattern to be followed extremely clearly.

Following the establishment of this technique for seeding clear water, the seeding of mud suspensions was investigated. It was found that at mean flow speeds above 0.005 m/s, particle motions following the expected pattern of flow could be resolved from the mud/water suspension alone, without any artificial seeding. However, it was impossible to determine exactly what particles within the mud suspension were acting as ultrasound reflectors or what their buoyant and inertial properties were.

At mean flow speeds below 0.005 m/s, however, settling effects became significant, and mud particles settling under gravity, rather than following the expected flow pattern, were resolved. This suggests that the mud particles resolved by the ultrasound scanner were not good reflectors for PIV measurements of flow conditions.

Mud suspensions were then tested with conifer pollen seeding in the same way as clear water. At speeds above 0.005 m/s, there was no discernible difference on the scan between the motion of the conifer pollen seeding and that of the reflectors already present in the mud, and the pollen could only be identified from knowledge of when and where it was added, which allowed the evolution of the ‘cloud’ of pollen to be followed. Nevertheless, it was decided to use pollen seeding in all tests since the buoyant and inertial properties of this material were known with certainty. Thus, for each test, sufficient pollen seeding was added to make it possible to assume that the majority of the images appearing on the ultrasound scan were due to conifer pollen, but with extra reflections from particles naturally present in the mud.

Care had to be taken to minimize air bubbles in the flow since these, also, gave rise to ultrasound images. Air bubbles are clearly not neutrally buoyant in water and would thus give rise to incorrect results.

4.5. Flow conditions

Flow conditions tested consisted of straight, unobstructed flow, flow through a narrow gap beneath a baffle (Fig. 4) and flow around a small obstruction placed in the

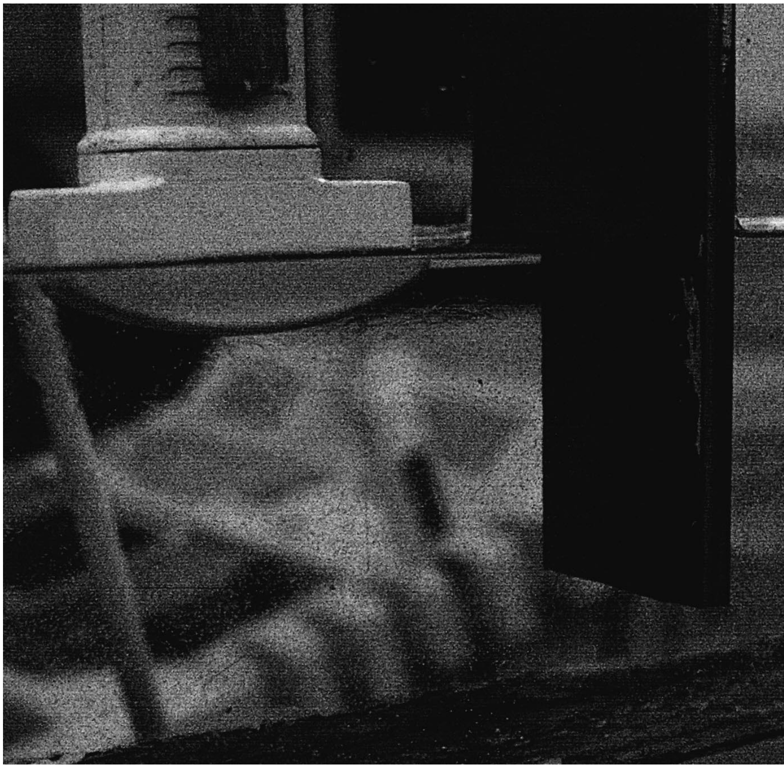

Fig. 4. Baffle used to introduce eddy patterns into the flow.

flow. Comparison of the ultrasonic readings with standard video camera PIV took place using clear, fresh water. However, as the initial target application for this instrumentation technique is the examination of dense suspensions of flocculated estuarine mud, the main experiments were carried out using a kaolin/salt water suspension of average concentration 16 g/l, intended to approximate a natural estuarine mud. The salt was first added and the flume run to allow it to dissolve, producing saline water of bulk density 1019 kg/m^3, this corresponding to a typical value for a UK estuary. The kaolin was then added and the flume run for a further period to allow flocculation to take place. No information on the particle or floc size distribution was recorded during these tests.

4.6. Flow speeds

The flume used could generate mean longitudinal flows ranging from zero to 0.09 m/s. Speeds below 0.005 m/s were not used due to the settling effects of the mud flocs discussed previously. It would be possible to use lower speeds than this if seeding material that were readily distinguishable from mud particles were available. At speeds above 0.06 m/s, the particle movement between successive video images was too great to allow analysis. This limit could be extended by use of an increased scan rate and digital image storage, such as would be available on a more advanced ultrasound instrument. This would allow a much shorter time interval between frames than is possible with video tape.

Analysis was also difficult where there is a large range of velocities within a single set of images, such as what occurred with flow under the baffle, where there was a relatively high velocity in the lower region of the flume. In this case, the offset between particles on successive video frames was much larger for the rapid flow area than for the slower eddy motion above, so analysis had to be carried out separately for each region.

5. Results

5.1. Vector maps obtained in mud

Ultrasonic tomographs and corresponding scaled vector maps obtained in a kaolin/salt water suspension of average concentration 16 g/l are shown in Figs. 5 and 6. Fig. 5 shows straight, uninterrupted flow, whilst Fig. 6 shows flow in the wake of a narrow obstruction; the disturbance produced by the obstruction can be clearly seen.

Table 1 shows typical quantitative results obtained. Each mean velocity value is the result of an average over 150 to 200 vectors distributed across the area of a single image. The mean flow speed in the flume is derived from a measurement of discharge at the flume outlet. Mean vertical velocities are small, as would be expected given the

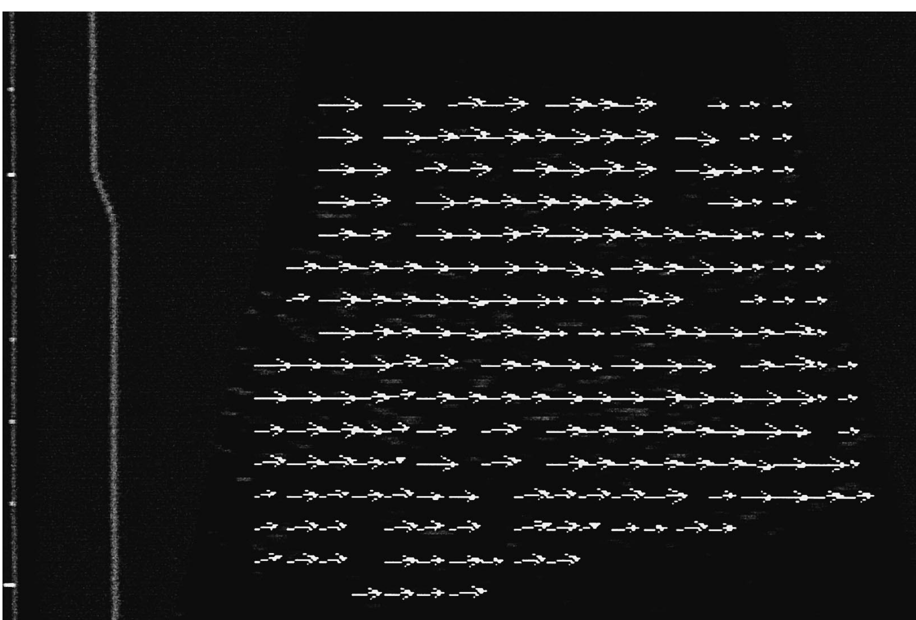

Fig. 5. Tomograph with superimposed vector map; uninterrupted flow in kaolin/salt water suspension.

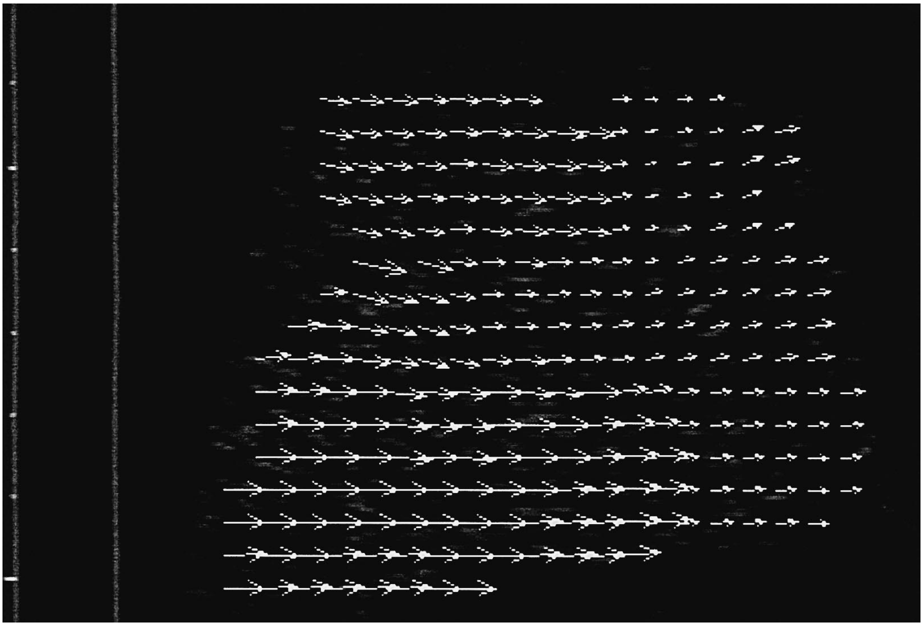

Fig. 6. Tomograph with superimposed vector map; flow in the wake of an obstruction in kaolin/salt water suspension.

experimental situation in which the only vertical motions were due to eddying effects at localized points within the scanned area.

5.2. Comparison with video camera PIV

The graph in Fig. 7 shows the comparison between results obtained using ultrasonic imaging and standard video camera PIV (see also Table 2). Again, results are averaged

Table 1
Results obtained from ultrasonic tomograph in kaolin/salt water suspension

Test number	Flow condition	Mean flow speed in flume (m/s)	Mean longitudinal velocity (m/s)	Mean vertical velocity (m/s)	RMS fluctuating longitudinal velocity (m/s)	RMS fluctuating vertical velocity (m/s)
1	Straight	0.006	0.0087	−0.0002	0.0056	−0.0014
2	Straight	0.016	0.0115	−0.0003	0.0113	−0.0024
3	Straight	0.030	0.0271	0.0005	0.0109	−0.0042
4	Straight	0.043	0.0584	0.0011	0.0088	−0.0061
5	Obstructed	0.006	0.0111	0.0001	0.0064	−0.0023
6	Obstructed	0.016	0.0221	0.0030	0.0088	−0.0055
7	Obstructed	0.026	0.0259	0.0044	0.0120	−0.111
8	Obstructed	0.042	0.0465	−0.0011	0.0158	−0.049

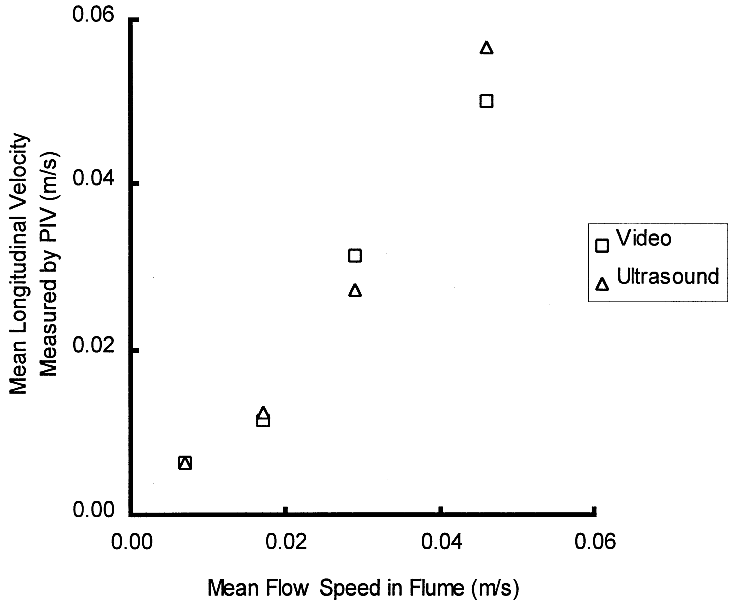

Fig. 7. Graph of mean longitudinal velocity measured by ultrasonic and video PIV against mean flow speed in flume.

over 150 to 200 vectors distributed over the whole area of an image, with mean vertical velocities being extremely small. Straight, longitudinal flow results show an agreement between ultrasound and video results to within $\pm 15\%$. The graph suggests that agreement is better for lower velocities. This is to be expected as the images become increasingly streaked for higher velocities resulting in the peak in the cross-correlation function (from which the movement of the images from the first to subsequent video frame is derived) becoming stretched in the flow direction. This, in turn, degrades the

Table 2
Comparison between results obtained from ultrasonic tomograph and those obtained from video camera, clear water

Test number	Flow condition	Mean flow speed in flume (m/s)	Mean longitudinal velocity (m/s)		Mean vertical velocity (m/s)	
			Video	Ultrasound	Video	Ultrasound
9	Straight	0.007	0.0063	0.0064	0.0003	0.0002
10	Straight	0.017	0.0115	0.0123	0.0045	−0.0003
11	Straight	0.029	0.0314	0.0273	0.0003	−0.0007
12	Straight	0.046	0.0500	0.0567	0.0000	−0.0012
13	Obstructed	0.007	0.0450	0.0690	0.0001	0.0003
14	Obstructed	0.017	0.0142	0.0157	0.0002	−0.0001
15	Obstructed	0.027	0.0287	0.0327	0.0002	0.0012
16	Obstructed	0.044	0.0419	0.0607	0.0007	−0.0013

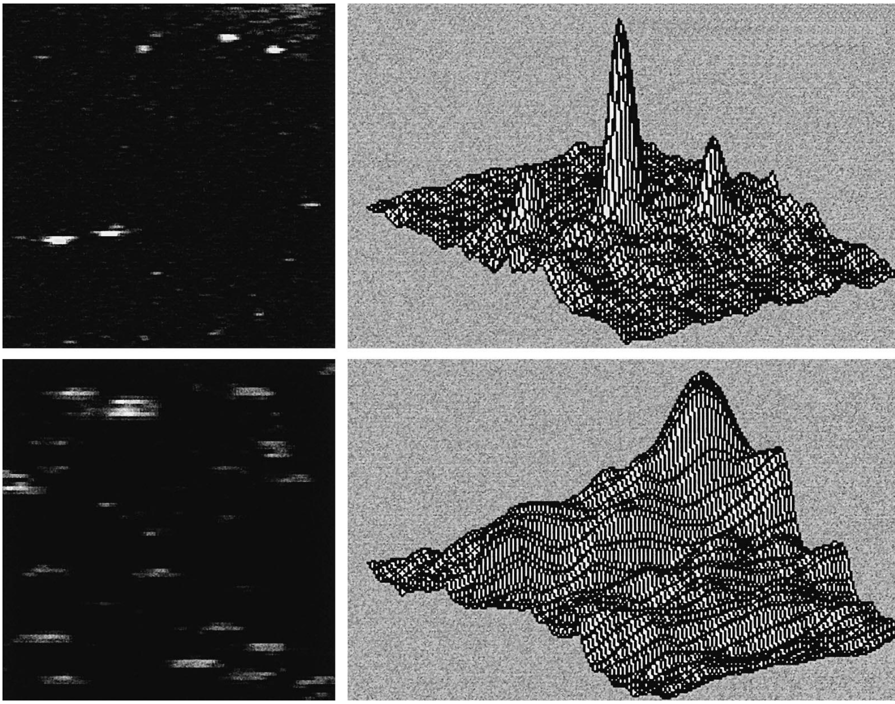

Fig. 8. An illustration of the effect of image streaking (lower, left) due to higher flow velocities, and (lower, right) the effect of the image streaking upon the cross-correlation function compared with the case for less streaked images (upper figures).

accuracy of the determination of the distance moved and thus the local flow velocity. This degradation of data quality is illustrated in Fig. 8. The upper figures show a portion of a tomograph taken at low velocity, and the form of the cross-correlation function for images of good sharpness. The lower figures are more typical of the data at the upper end of the range of velocities studied, and illustrate the streaking of the images and the resultant stretching of the peak in the autocorrelation function. As the method is developed, attention will be paid to reducing the influence of streaking upon data quality through a combination of improved hardware and the application of image processing methods such as morphological transforms to sharpen the images.

The obstructed flow results are not a good basis for comparison, since the temporal variation in flow caused by eddying behind the obstruction gave rise to variations in the flow structure at timescales beyond those to which ultrasound and camera measurements could be synchronized.

5.3. RMS fluctuating velocity values

The VidPIV software allows RMS fluctuating velocity to be determined, this being based on the difference between local velocity at each interrogation point and the mean velocity over the whole image. This facility gives statistical information regarding the spatial variations in flow over the image area. In a uniform flow, these variations will be related to fluid turbulence.

RMS values obtained in a mud suspension using ultrasonic imaging are included in Table 1. At present, spatial resolution is not sufficient to give information on small scale structures in the flow, and these results may be interpreted only as giving information about general non-uniformity of the flow field. With increased spatial resolution, it would be possible to investigate the interaction of sediment and turbulence. It is expected that such improved resolution would be obtained by combining a more advanced instrument with hollow sphere seeding particles, which are likely to be much better ultrasound reflectors than the conifer pollen used and will allow far more particles to be resolved in each image than was the case in these experiments.

6. Conclusions

Accurate, two-dimensional maps of the flow field in a suspension of flocculated mud in salt water have been obtained using PIV techniques in conjunction with ultrasonic imaging. RMS values of the flow have also been determined.

Comparison of results obtained in clear water using the ultrasonic method with those from standard video camera PIV indicate that the ultrasonic method is accurate to within $\pm 15\%$ of the widely accepted video camera technique.

The application of this instrumentation method will enable advances to be made in the understanding of mud process important in coastal engineering and the environmental management of estuaries and coastlines.

7. Further work

The authors now propose to extend this work to carry out quantitative analysis on the entrainment of dense near-bed layers of mud by the breaking of internal waves and to increase the spatial resolution of the measurements so that the interaction of sediment and turbulence may be examined. These objectives will require additional equipment including a more sophisticated ultrasound scanner.

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