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Sensor Development Programs at NASA Ames Research Center

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ABSTRACT

This paper presents a brief description of two sensor development programs at the Fluid Mechanics Laboratory, NASA Ames Research Center, one in progress and the other being initiated. The ongoing programs involve digital image velocimetry for velocity field measurements of time-dependent flows. The new program involves advanced acoustic sensors for wind tunnel applications.

1. DIGITAL IMAGE VELOCIMETRY

Digital image velocimetry (DIV) is a new technique which is currently being developed for real-time measurements of instantaneous velocity fields of time-dependent flows or of a collection of objects moving with varying velocities.[1] Such measurements will yield information not possible to obtain using conventional point-measurement methods such as hot-wire anemometry and laser Doppler velocimetry. This new information will provide a greater understanding of time-dependent flows or of objects moving with varying velocities.

Recently, fluid dynamicists have exploited modern computer and optics technologies to develop methods for measuring instantaneous velocity fields, including particle image velocimetry (PIV) and laser speckle velocimetry (LSV). With these methods, multiply exposed images of seed particles embedded in the flow or of moving objects are captured on a photographic film. The object travel distances between exposures are obtained from the image separations of the same seed particles or objects. The velocities are then determined by dividing the travel distances with the time interval between the exposures. These methods are, however, subject to some serious restrictions, such as limited dynamic range of the velocity measurements, ambiguity of the direction of the velocity vectors to be determined, and difficulties of development into a real-time measurement capability.

DIV, which is designed to eliminate these restrictions, exploits high-speed video photography, image processing, and digital Fourier transformation. With this technique, a time sequence of images of seed particles or moving objects are captured using a high-speed video camera, with each frame containing a single-exposure image. A finite number of single-exposure images are sampled with a certain separation time. The sampled images are then digitized on the image processor, enhanced, and linearly superposed to construct an image. This process is illustrated in Figure 1.

The superposed image is equivalent to the multiple-exposure image used in LSV/PIV. However, there exists a subtle but important difference between the superposed image and the multiple-exposure image, especially with high concentrations of seed particles as in cases where a detailed determination of velocity fields is required. With a high concentration of seed particles, the different-time exposure images of individual objects can easily overlap. On the multiple-exposure image in LSV or PIV, the intensity in the overlapped region may not differ much from that in the nonoverlapping images. Such overlapping will suppress the correlation between the images of the same objects, resulting in an increase of the uncertainty of the velocity determination. In contrast, on the linearly superposed image in DIV, the intensity of the image overlap is equal to the arithmetic sum of the intensities of the individual images, and thus the correlation between the images of the same objects is preserved. (See Figure 2.)

The velocities are determined from the image separations recaptured on the superposed image. A single-exposure image is used to eliminate the uncertainty effects that are due to the finite image sizes and some interference effects caused by undesirable distributions of the seed particles or the objects. An example of this procedure, in which a Fourier-transform technique is used, is shown in Figures 3-5. The fringes shown in the figures are directly related to the magnitude and the orientation of the velocity. The direction of the velocity vector can be determined unambiguously using a single-exposure image, since this image contains information on the time history.

It should be emphasized that the single-exposure images are not available in, nor can they be isolated from, the multiple-exposure image with the photographic film technique used in LSV or PIV.

2. ADVANCED ACOUSTIC SENSORS FOR WIND TUNNEL APPLICATIONS

Acoustic measurements in wind tunnels are subject to certain interference effects not found in anechoic chambers. Such effects include wind noise, flow-sensor interaction noise, flow-induced sensor vibration, deflection of acoustic waves by sensor-induced boundary layers, and reflections from facility and sensor support components. Furthermore, it is often desirable to investigate specific source regions on the models being studied. Currently existing acoustic sensor techniques are not adequate to cope with these problems.

Ames Research Center is initiating a program to develop advanced acoustic sensors to eliminate or minimize these interference restrictions. The program is based on new concepts for adaptive arrays using optical fibers as acoustic sensor elements. An adaptive array is a system composed of a number of geometrically configured sensor elements and a real-time signal processor.[2] The signal processor is designed to automatically adjust the array sensitivity for enhancing the directivity and the spectral response for the acoustic signal. The directional properties of such a system allows discrimination against unwanted sound coming from directions other than the acoustic source under study. A proper adjustment of the spectral response discriminates noise of frequencies different from the signal frequencies. Another significant advantage of an adaptive array can be derived from the real-time manipulation of the correlation of signals detected by various sensor elements. Such a manipulation can be used to discriminate random noise or pressure fluctuations generated locally on individual sensor elements.

The technology of fiber-optic acoustic sensors has matured in underwater acoustics applications, and is readily available for implementation to aero-acoustics.[3] Fiber-optic acoustic sensors offer a number of advantages. The sensor element package can be very compact, thus reducing flow-sensor interactions. The optical fibers are geometrically versatile and can therefore be configured with great flexibility as extended (or distributed) sensor elements. Such configurations would generate a great variety of array sensitivity patterns. Furthermore, the optical fibers can be molded on the surface of a solid body. With the sensor elements molded on an aerodynamically smooth body, the flow interaction can be made negligible, the aerodynamically induced vibration will be minimized, and effects of the boundary layer will be made more tractable.

An adaptive array with fiber-optic interferometric acoustic sensors is schematically displayed in Figure 6. The system is composed of three elements: a light source, fiber optic interferometric sensor elements, and a photodetector interfaced with a signal processor. Light, transmitted from the light source into the optical fiber (waveguide), will be split at the first coupling branch. One part will propagate through the reference arm without experiencing any external effect. The other part, which will propagate through the sensing arm, will be affected by the external acoustic signals. The exertion of the acoustic pressure, Δp, on the optical fiber will result in the phase shift, $\Delta\phi$, of the light (or the optical wave). In other words, the acoustic signal modulates the phase of the optical wave. The phase-modulated optical wave will be combined with the unaffected reference light at the second coupling branch. The interference will then be recorded on the photodetector, and processed on the signal processor to extract information on the acoustic signal.

3. REFERENCES

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[2] R. A. Monzingo and T. M. Miller, *Introduction to Adaptive Arrays*, John Wiley & Sons, New York (1980).
[3] T. G. Giallorenz, J. A. Bucaro, A. Dandridge, G. H. Sigel, Jr., J. H. Cole, S. C. Rashleigh, and R. G. Priest, "Optical fiber sensor technology," IEEE J. Quantum Electronics, QE-18, 626-665 (1982).

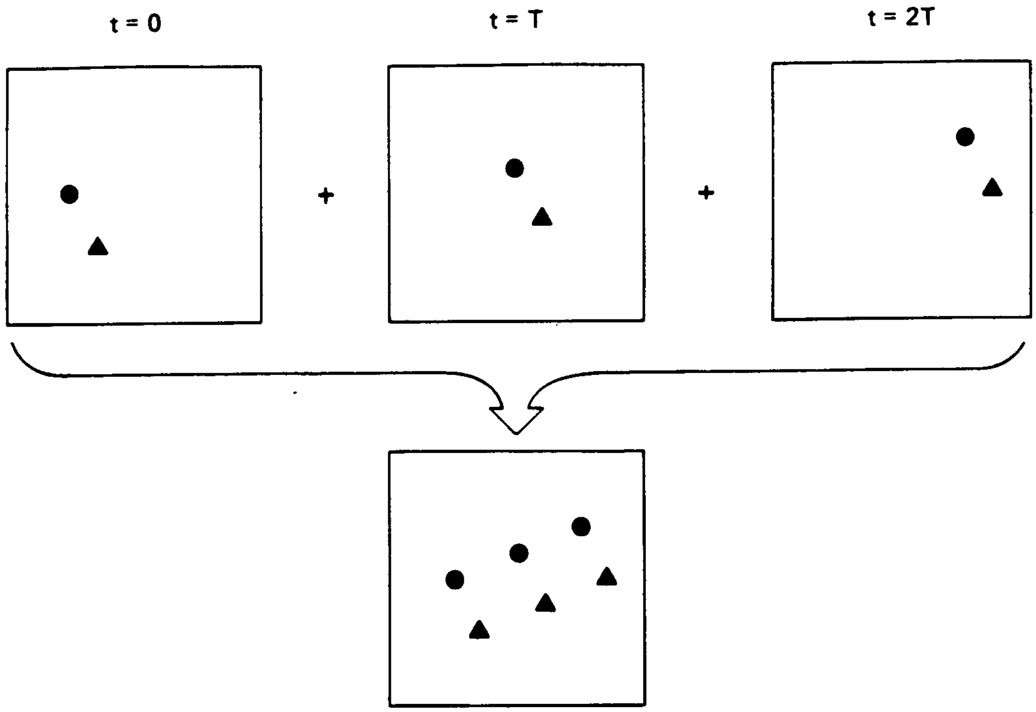


Figure 1. Construction of a multiple-exposure image as a superposition of single-exposure images.

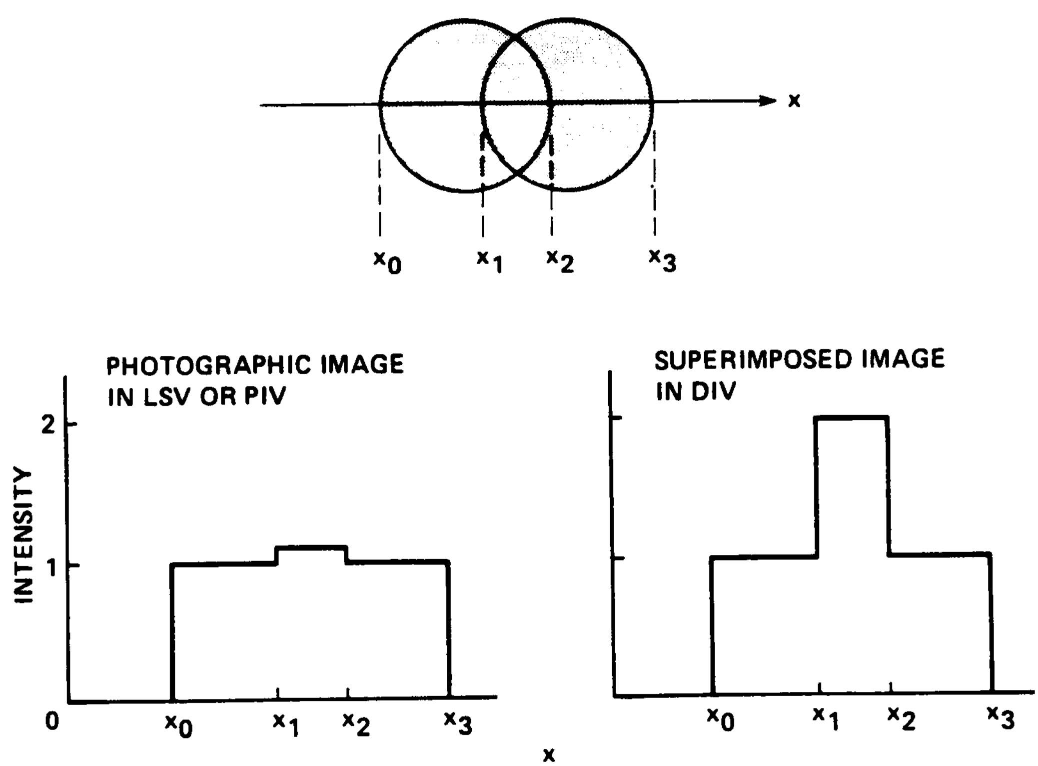
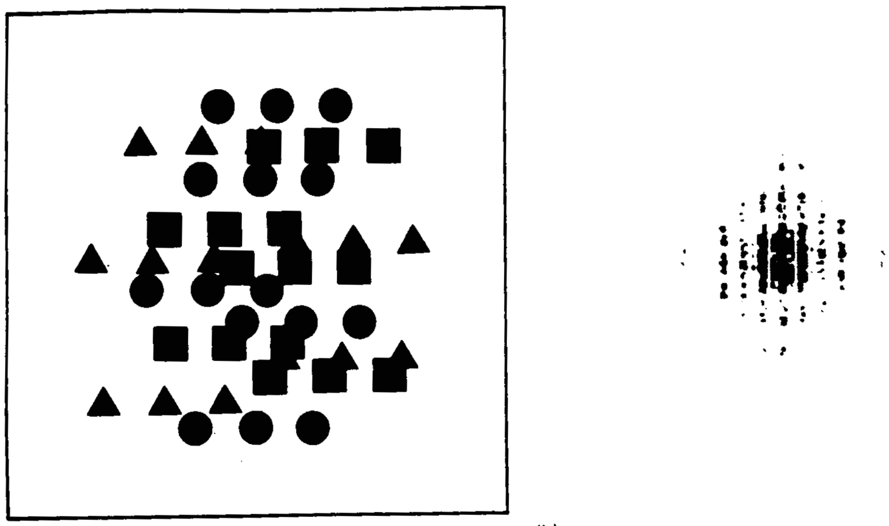
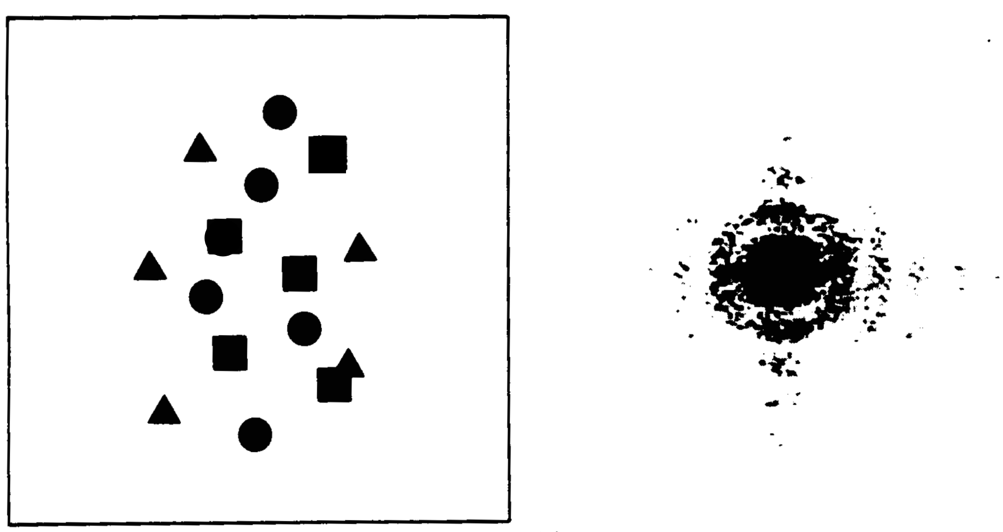


Figure 2. Intensity of multiple-exposure images in overlap region.



(a) (b)

Figure 3. (a) Triple-exposure image and (b) the modulus of the Fourier transformed image.



(a) (b)

Figure 4. (a) Single-exposure image which is contained in the image in Figure 3(a) as a component detected at the initial exposure and (b) the modulus of the Fourier-transformed image.

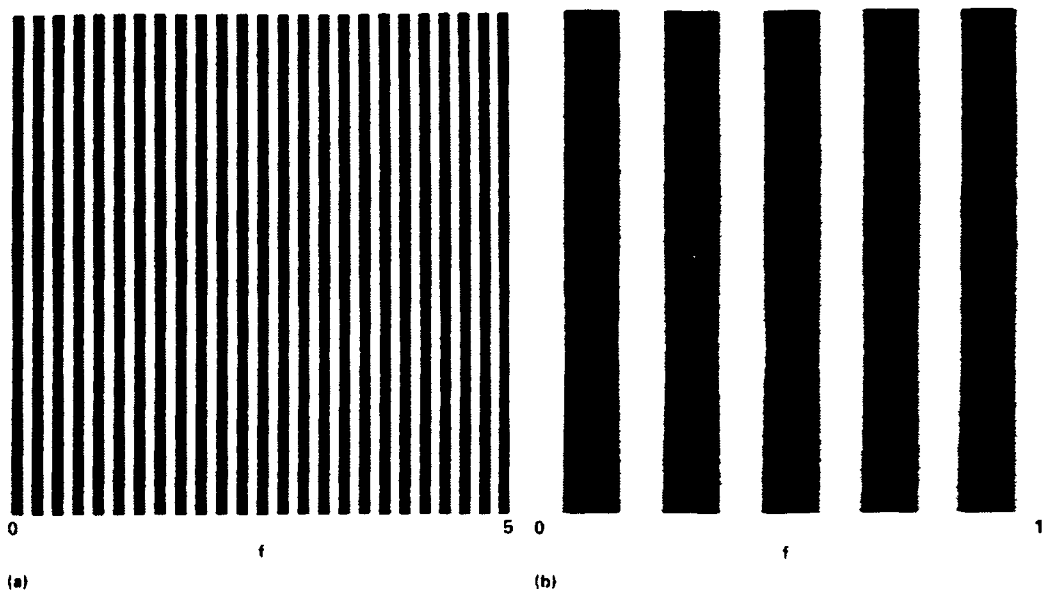


Figure 5. (a) Fringe pattern, which is obtained by dividing the Fourier-transformed image in Figure 3(b) with that in Figure 4(b); and (b) magnified fringe pattern.

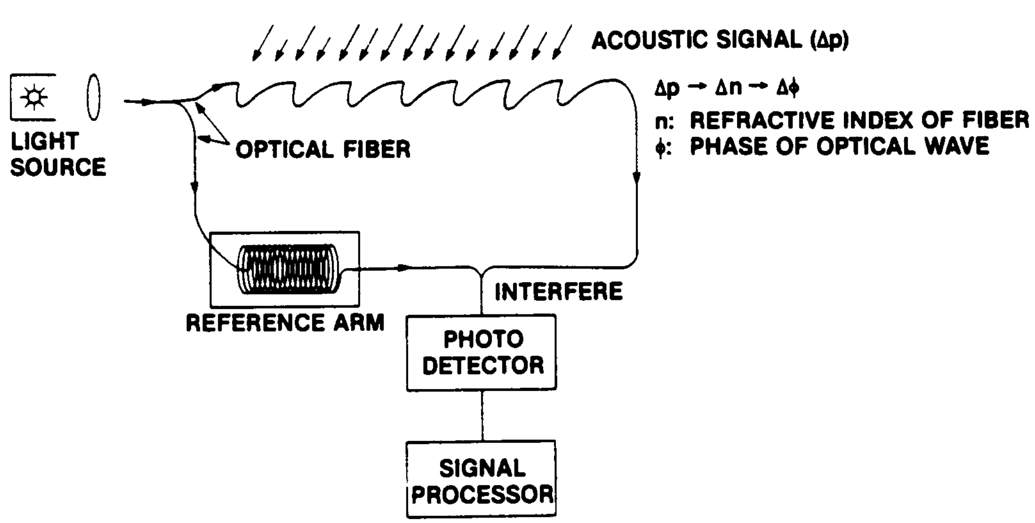


Figure 6. Schematic of an adaptive array with fiber-optic interferometric sensor elements.

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