A Phase Locked High Speed Real-time Interferometry System for Large Amplitude Unsteady Flows

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ABSTRACT

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Summary

A high speed phase locked interferometry system has been designed and developed for real-time measurements of the dynamic stall flow over a pitching airfoil. Point diffraction interferograms of incipient flow separation over a sinusoidally oscillating airfoil have been obtained at rates of up to 20 KHz and for free stream Mach numbers of 0.3 and 0.45. The images were recorded on ASA 125 and ASA 400 film using a drum camera. Special electronic timing and synchronizing circuits were developed to trigger the laser light source from the camera and to initiate acquisition of the interferogram sequence from any desired phase angle of oscillation. The airfoil instantaneous angle of attack data provided by an

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optical encoder was recorded via a FIFO and an EPROM into a microcomputer. The interferograms have been analyzed using software developed in-house to get quantitative flow density and pressure distributions.

1. Introduction

Research on compressibility effects on dynamic stall of pitching airfoils is on-going at the U.S. Navy-NASA Joint Institute of Aeronautics and is being conducted in the Fluid Mechanics Laboratory of NASA Ames Research Center. The phenomenon of dynamic stall pertains to the production of lift at angles of attack well beyond the static stall angle of attack by rapidly pitching an airfoil. The problem is of interest to helicopters and fighter aircraft. Dynamic stall occurs on the retreating blade of a helicopter as it is pitched to high angles of attack during the portion of the blade revolution when it is moving with the wind. A fighter aircraft performing a rapid maneuver also experiences dynamic stall. The process is characterized by the formation of a large vortex at the leading edge (known as the dynamic stall vortex) whose vorticity is responsible for the enhanced lift. However, its convection over the airfoil upper surface needs to be avoided since it produces strong pitching moment variations. which are destructive to the aircraft. This flow feature has been responsible for the phenomenon remaining unexploited thus far. Another characteristic feature of the flow is the large flow accelerations around the leading edge, resulting in the onset of compressibility effects at a very low free stream Mach number of 0.2 -0.3[1,2]. The local flow could become supersonic and form a series of shocks[3]. The various fine scale events of the flow that are present for the different flow conditions need to be properly understood before an effective means of controlling the flow can be devised.

As part of this study, a real-time interferometry method known as point diffraction interferometry(PDI) has been developed[4,5] to map the instantaneous global flow details. This effort has been successful in delivering sharp. high-contrast interferograms of the flow for all the conditions of the experiment. The interferograms are obtained as conditionally sampled images and have provided the first insight into the many flow details. However.

capturing the full flow sequence takes several cycles of motion. The rapid changes that occur in the flow, especially the details of the dynamic stall vortex formation and the shock/boundary layer interactions leading to possible premature flow separation do not repeat perfectly from cycle to cycle. Thus, there is a need to obtain the flow details in just one pitching cycle, as they occur. It is this need that prompted the design and development of the very high speed interferogram recording system being presented in this paper.

2. Design Specifications

The studies are being conducted on a NACA 0012 airfoil with a chord length of 7.62cm in the Compressible Dynamic Stall Facility(CDSF). Two different drive systems could be used in the CDSF to produce either an oscillatory pitching motion or a constant rate transient pitching motion of the airfoil. The angle of attack variation in the former case is given by $\alpha = \alpha_0 + \alpha_m \sin \omega t$ with the mean angle of attack α_0 and the amplitude α_m variable from $0^0 - 15^0$ and $2^0 - 10^0$ respectively. The maximum frequency of oscillation is 100 Hz. The constant rate pitch drive produces a rapid change of angle of attack from $0^0 - 60^0$ at rates as high as 3600 degrees/sec. Earlier work [5] has shown that the events of dynamic stall onset occur rapidly over a small angle of attack range of about 0.5 to 1.0 degree. Thus, in order to have a resolution of 0.1 degree or better at the limits of operation of either drive system, a camera speed of 36 KHz or more is necessary.

The very large flow acceleration (and concomitant density variations around the airfoil leading edge could create as many as 60 fringes/millimeter at the airfoil) and the rapidity of the development of the dynamic stall vortex or the shock induced flow events, result in interference fringes that evolve and move at very high frequency ($O(KHz)$). This necessitates the use of extremely short light pulse duration, typically nanoseconds. These challenges require the use of a laser that produces the necessary energy for each exposure and is externally controllable at the high camera rates.

The high framing rates, the short duration of the light pulse, and the low light levels preclude the use of video cameras or similar recording devices, limiting the choice to film cameras. Possible blurring of the images due to flow changes eliminates choices such as streak cameras.

It is also necessary to record the airfoil angle of attack corresponding to the frames on the film. Further, the system should be controllable in order to generate an interferogram sequence starting at any desired angle of attack.

3. Details of the Camera, Laser Control and Recording Systems

A Qunatronix Series 100 CW/pumped Nd:YAG laser, capable of operating from DC to 50Khz was used in the experiments. It can be externally triggered without any detectable delay at all the rates. The pulse duration and the energy output varied nonlinearly from 85ns and 0.14mJ at 500Hz, 420ns and 25μJ at 40KHz and 100ns and 11μJ at 50KHz. At the rates used for the high speed interferometry experiments being reported, the corresponding numbers were: 140ns and 65μJ at 10KHz and 240ns and 17μJ at 20KHz, at nearly full current settings. The energy density in the laser at 10 KHz rate was adequate to give proper exposure on ASA 100 T-MAX film. ASA 400 film was necessary at 20 KHz.

A 35 mm. variable speed Cordin drum camera (DYNAFAX Model 350) was used for image recording. A rotating 8 faceted mirror in the camera reflects the incoming light beam onto the film which is rotating in the same direction in the camera drum. Effective shutter times of 1.3μsec can be achieved at 40 KHz framing rate. At 20 KHz, this time was 2.6μsec. Two rows of images were obtained on the film strip, with subsequent exposures being recorded alternately in each row, but displaced 16 frames.

The laser was triggered by the TTL pulses emitted by custom built (in-house) circuitry installed on the camera. Tuning the camera required aligning the mirror facet with the incident light beam. An infrared light emitter diode and corresponding IR photo detector were installed in the camera (see Fig. 1) to detect the mirror facet location. For tuning purposes, two additional photo detectors were installed, one at each frame position. The tuning procedure involved adjusting two delay times: T_1, the delay between detecting a mirror facet and emitting the first pulse and T_2, the time between the two TTL pulses. The delay times T_1 and T_2 were adjusted to maximize the laser light detected by the frame photo diodes. Once tuning was properly completed, the photo diodes were moved from the field of view to permit laser light to reach the film plane. The short effective shutter times and the high framing speeds required a careful design of the electronic system that included schemes for proper attenuation of noise.

A Nikon 55mm macro. f/2.8 lens was used in the camera. Aligning the camera along the optical axis of the interferometry system required very accurate adjustment.

Both unsteady motion producing drives referred to in section 2 are equipped with an optical encoder that produces 800 counts/cycle of motion (one oscillation cycle or one pitch-up from 0-60 degrees). It is an incremental encoder that produces a quadrature pulse train which is in turn processed by an oscillating airfoil position interface(OAPI) for phase locking and recording by the data acquisition system. The OAPI could be preset to produce a TTL event pulse (or pulse repetitively) at any desired phase angle by a series of front panel BCD switches. The TTL output pulse was used to trigger the opening of a laser safety shutter and also to initiate encoder data transfer to memory. As shown in Fig. 2. the laser is enabled by the first TTL pulse from the OAPI. However, recording the encoder outputs was enabled from the next pulse. The data was recorded in a 512 word first-in-first-out(FIFO) buffer for each camera pulse. The number of frames acquired by the camera could be controlled from 0 to 224 (camera maximum) by the external electronics built for enabling the handshake between the various devices. Typically, 200 frames of point diffraction interferograms were obtained and the phase angles corresponding for each of the frames were recorded into the FIFO which were later downloaded into a microVAX II computer through an EPROM.

4. Operation

The interframe pulse delay was tuned to the desired rate and the actual rate of the camera obtained was measured using a frequency counter. The data to be reported were obtained at 11.56 KHz and 19.62KHz. The desired initial phase angle for the interferogram sequence was set using the BCD switches on the OAPI front panel. Before the images were acquired. the laser was constantly triggered by an external pulse train at a 40KHz rate. This was necessary to protect the laser crystal from the giant pulse that is normally generated when the laser is pulsed after a short lapse time. The electronic circuit then inhibited the laser pulsing when the OAPI TTL event was output and until the laser shutter was opened (see Fig. 1 and 2). The shutter opening time was about 1 millisecond. necessitating a delay before enabling the laser again. After the shutter was fully open. which was ensured by an AND gate. the laser was enabled on the next OAPI TTL event output pulse. The laser was actually pulsed from the next camera pulse. at which time the encoder was latched and recorded in the FIFO. A frame counter started at this event. permitted capturing the angles corresponding to the 200 images that were recorded on film. The short elapsed time between the laser enabling and its subsequent firing resulted in a "small" giant-pulse. which over exposed the first frame. This frame served to determine the first image on the film strip: thus. it was possible to accurately match the interferogram images with the phase angle of motion and to correlate the values in the FIFO buffer. Following the completion of the imaging, the shutter was closed and the laser returned to the constant 40KHz external triggering. The camera alignment was verified by taking test sequences on a Polapan ASA 125 film and the data was obtained on a higher resolution T-MAX 400 film.

Fig. 3 shows a schematic of the PDI optics and its implementation in the dynamic stall facility. The details of the PDI technique has been described in Ref. 3 and 4. It uses one single pass of the laser beam through the test section and depends upon the ability of a pin-hole created *in-situ* in a semi-transparent plate to produce the reference beam. The signal beam passes around this pin-hole to produce interference fringes in real-time. In the experiment, the PDI spot was created with no-flow in the test section and once it was determined to be satisfactory (from still polaroid pictures), the movies were obtained.

5. Results and Discussion

Fig. 4a and Fig.4b show typical interferograms obtained using the high speed recording system at $\alpha = 9.8^0$ and $\alpha = 14.37^0$ respectively. Fig. 4c and 4d show the corresponding images from a single realization of the event (and hence for different cycles) recorded on Polaroid film. The free stream Mach number of the flow was 0.3. The camera framing rate was 11.56 KHz. (At the time of writing, copies of selected frames from the films obtained at 19.62 KHz rate at free stream Mach numbers of 0.3 and 0.45 are still being printed). The triangles seen in the images are registration markers on the glass windows of the facility which are used to determine the airfoil profile during image processing. The dark bulge seen near the leading edge region is due to the light beam being bent away from the leading edge due to the very large local density gradients. The agreement between Fig. 4a and 4c is very good. The figures show a laminar separation bubble that forms over the airfoil for this angle of attack. Figures 4b and 4d show qualitative agreement at $\alpha = 14.37^0$, in that the dynamic stall process has begun in both (the set of vertical fringes seen correspond to the dynamic stall vortex as it forms) but it is clear that the process has progressed more in Fig. 4b. More results along with the appropriate pressure distributions (obtained by image processing) will be presented at the conference.

The image size on the film was 3.5mm in diameter and the images shown in Fig. 4a and 4b have been magnified by nearly 1000 times. Despite the large magnification factor, the quality of the images is very good. Attempts to enlarge the original size of the image (using extension rings) in the camera met with partial success owing to the long focal length of the mirrors and the fact that the laser beam has a small divergence angle, as opposed to white light. This situation also made the task of aligning the camera with the optical axis of the PDI system challenging.

Yet another concern in the use of the system was the ability of the PDI spot to withstand the rapid exposure to the laser energy during high speed imaging. In the experiment at 20 KHz the PDI spot was exposed to a total of 3.4mJ in 10 milliseconds. At such large energy levels, there was a possibility that the PDI spot could get enlarged or even damaged, thus creating inaccurate interferograms. However, the robustness of the holographic plate film coating material used for the purpose prevented this from happening.

It is worth commenting that acquisition of high speed interferograms using white light has been reported in the literature[6]. However, the key differences in the present study are the requirements of phase locking, controlling the laser from the camera pulses, the need to precisely record the phase angle for each pulse (since the flow undergoes significant changes in a very small angle of attack range), and the very short duration of the pitching motion - all of which preclude the use other measurement methods.

6. Conclusions

A novel system for acquiring real-time phase locked interferograms has been developed for use in unsteady separated flows. The rapid nature of the flow changes and the extremely high gradients around the leading edge of an airfoil experiencing dynamic stall requires the use of such a measurement technique. The system uses a laser that can be pulsed at high rates to produce interferograms and record these on film at rates of up to 40KHz. To date interferograms have been obtained at 20 KHz rate and the system has been tested at 40 KHz. Proper electronic interlocking has enabled precise control of the experiment. The use of the laser giant pulse permits correlating the angle of attack information with the individual frames accurately by clearly marking the first frame.

7. References

1. McCroskey, W.J., "The Phenomenon of Dynamic Stall", NASA TM-81264, March 1981.

2. M.S.Chandrasekhara and L.W.Carr, "Flow Visualization Studies of the Mach Number Effects on the Dynamic Stall of Oscillating Airfoils", *AIAA Jl. of Aircraft*, Vol. 27, No. 6, pp. 516-522, June 1990.

3. M.S.Chandrasekhara, L.W.Carr and M.C.Wilder, "Interferometric Investigations of Compressible Dynamic Stall Over a Transiently Pitching Airfoil", *AIAA Paper 93-0211*, To appear in *AIAA Journal*

4. N.Brock, M.S.Chandrasekhara and L.W.Carr, "A Real-Time Interferometry System for Unsteady Flow Measurements", *ICIASF'91 RECORD, IEEE Publication 91CH3028-8*, pp. 423-430.

5. L.W.Carr, M.S.Chandrasekhara, S.Ahmed and N.Brock, "A Study of Dynamic Stall Using Real-Time Interferometry", *AIAA Paper 91-0007*, To appear in *AIAA Journal of Aircraft*.

6. J.M.Desse and J.C.Pegneaux, "Direct Measurement of the Density Field Using High Speed Differential Interferometry", *Experiments in Fluids*, 15, 452-458, Oct. 1993.

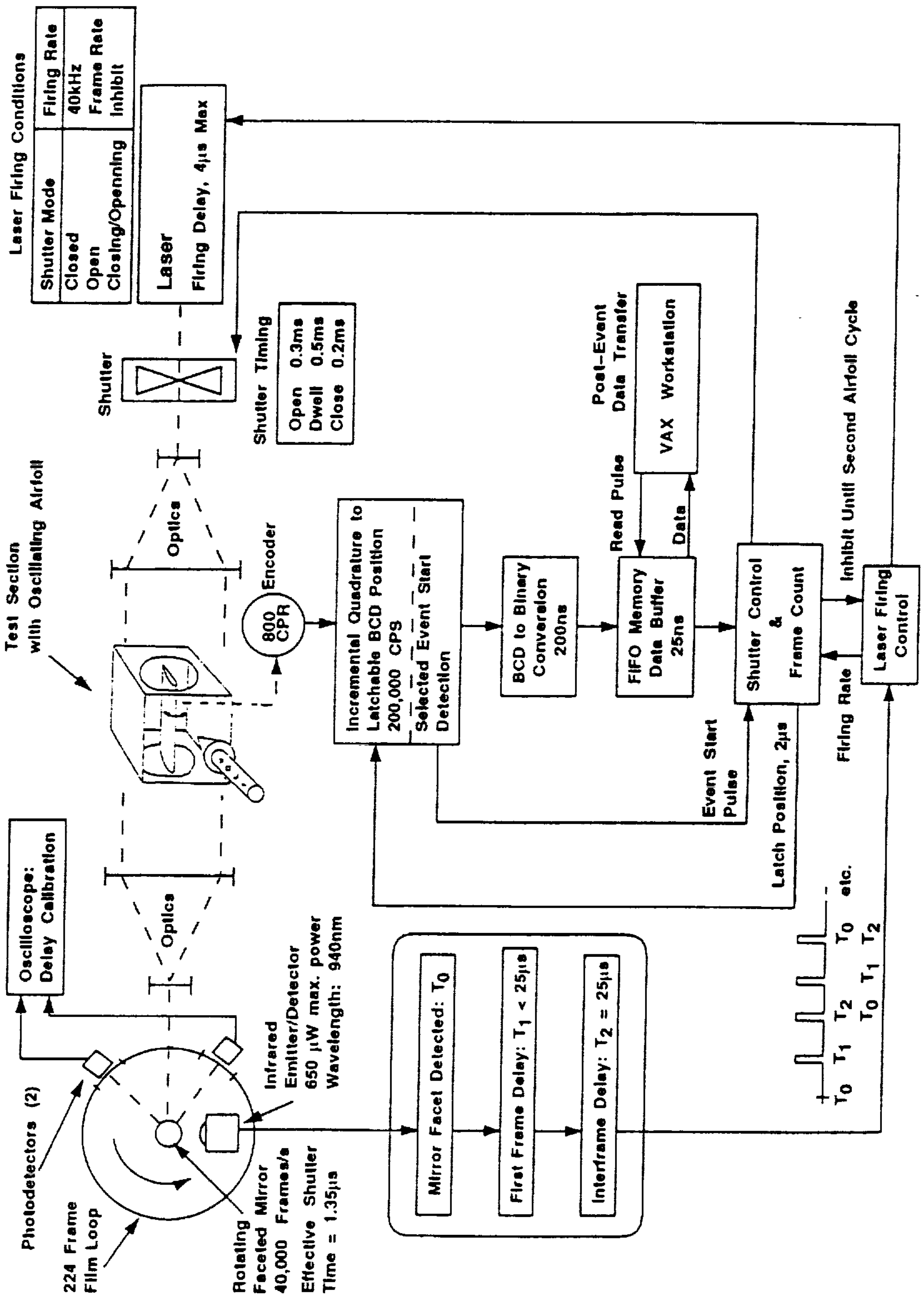

Figure 1. Timing Sequence of Phase-Locked High-Speed Interferometry System.

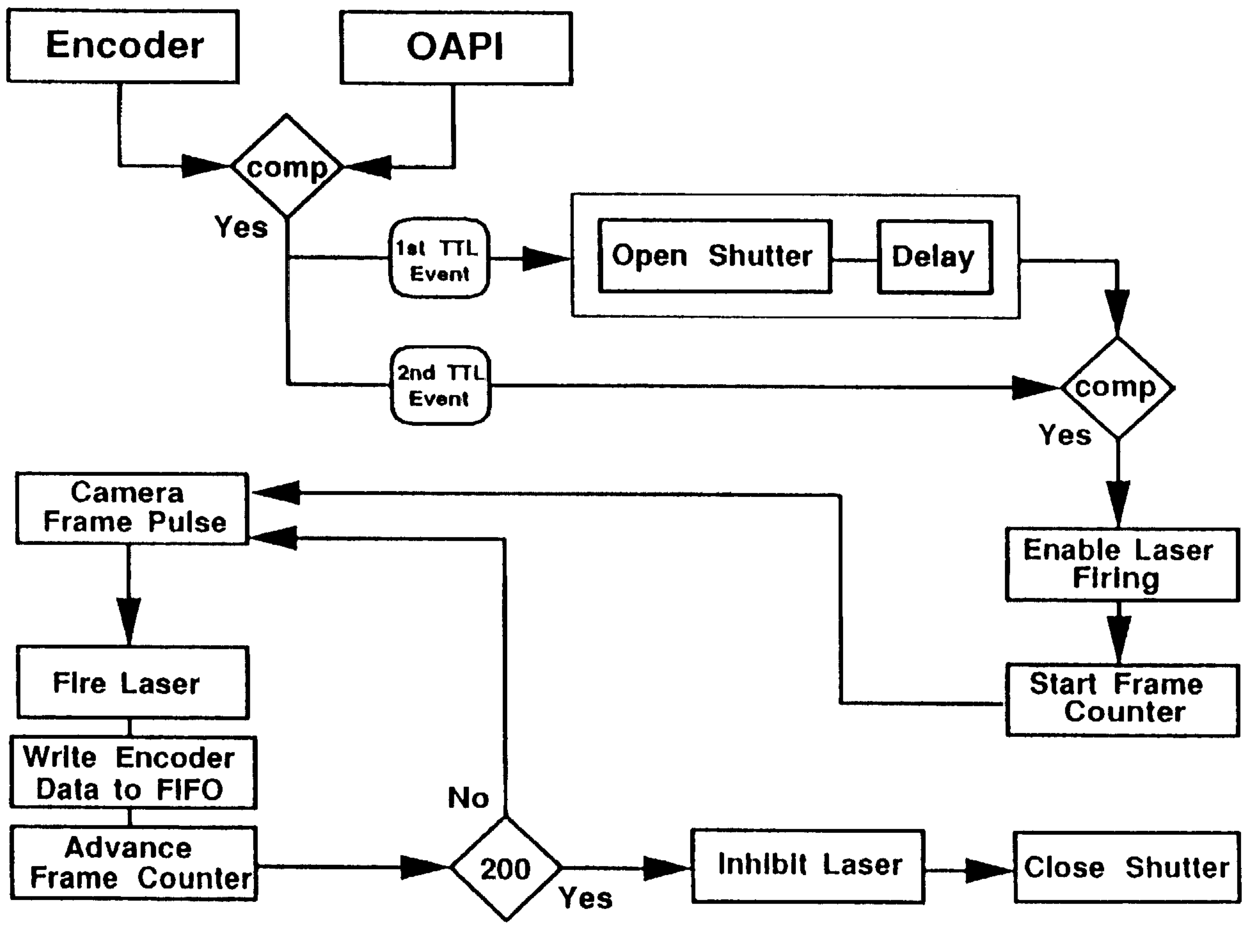

Figure 2. Instrumentation Interlocking Sequence for High-Speed Interferometry System.

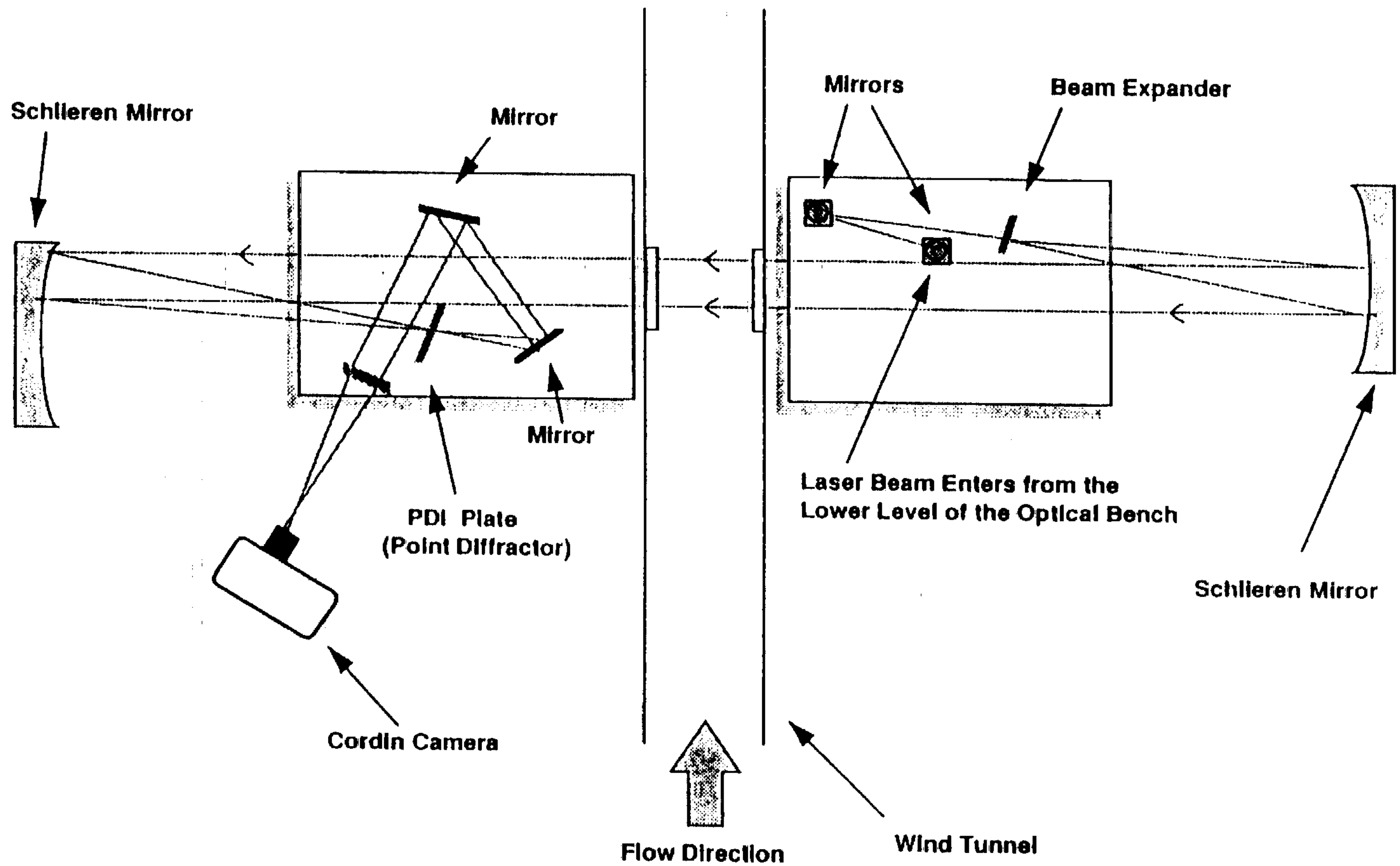

Figure 3. Schematic of the Point Diffraction Interferometry Setup.

(a) (b) (c) (d)

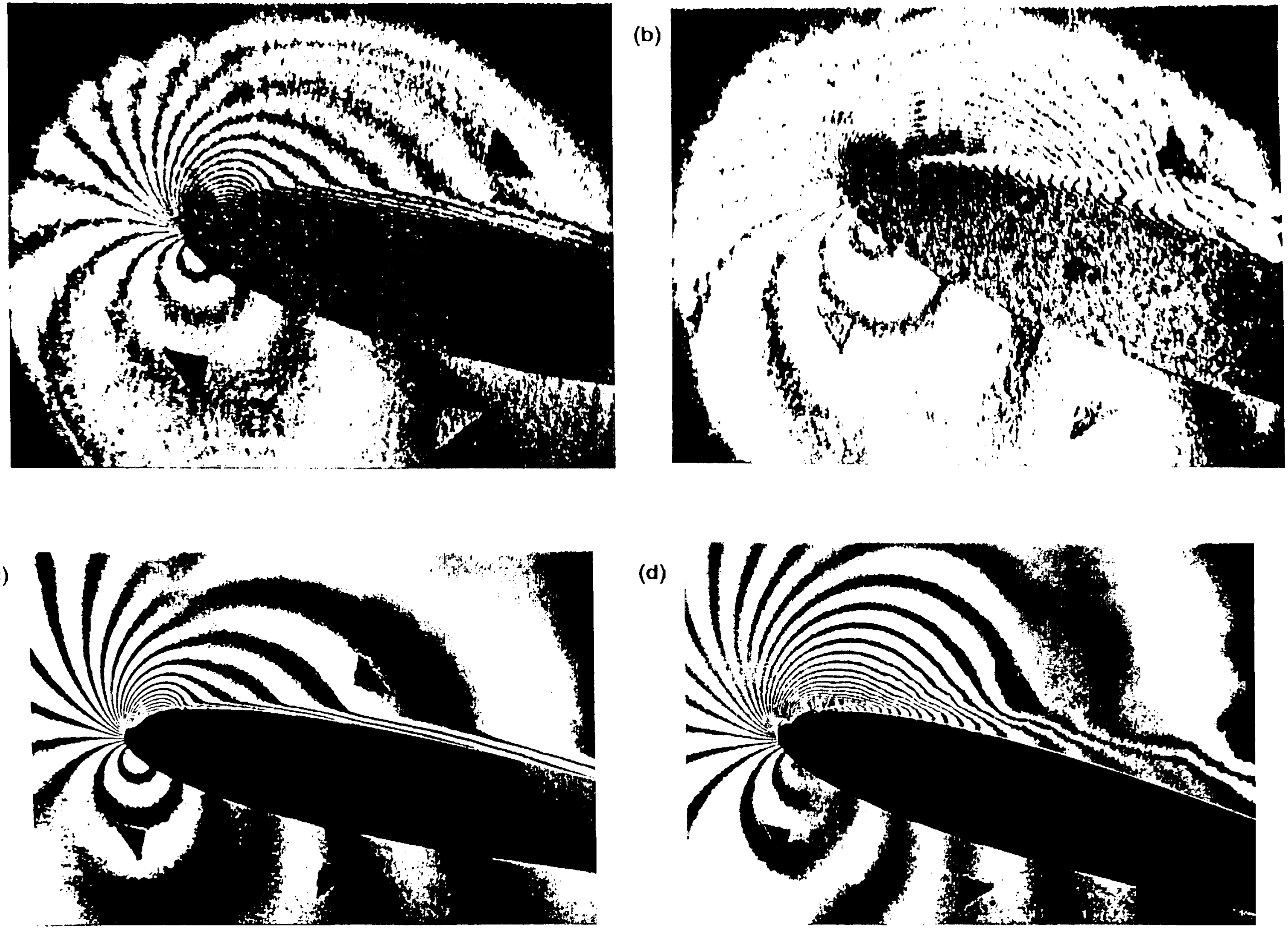

Figure 4. Representative Interferograms of the Flow Field, M = 0.3, k = 0.05 (a) $\alpha = 9.8^o$, High-speed Image. (b) $\alpha = 14.37^o$, High-speed Image. (c) $\alpha = 9.8^o$, Static Image. (d) $\alpha = 14.37^o$, Static Image.