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Final Report to the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
on

SELF-SYNCHRONIZING SCHLIEREN PHOTOGRAPHY AND INTERFEROMETRY FOR THE VISUALIZATION OF UNSTEADY TRANSONIC FLOWS

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SUMMARY

This final report gives an account of the experimental research supported by NASA Grant NSG-2128 to investigate the use of self-synchronizing stroboscopic schlieren and laser interferometer systems for the study of unsteady periodic transonic flows. The performance objective of these systems is to obtain quantitative space-time measurements of distinguished flow surfaces, steakline patterns, and the density field of two-dimensional flows that exhibit a periodic content. The technique allows the experimentalist to stroboscopically stop the periodic motion at any intermediate phase by driving the pulsed light source with an electronically processed synchronizing signal that is derived by measuring a periodic flow variable with a convenient transducer.

During this grant period we have made significant progress toward our performance objective by completing the design and construction of a large field single-path stroboscopic schlieren system and successfully applying this system to visualize four periodic flows: near-wake behind an oscillating airfoil; edge ton sound sound generation; 2-D planar wall jet; and axisymmetric pulsed sonic jet. We have found that this visualization technique provides an extraordinarily effective means of studying quasi-periodic flows in real time. Based on the applications described, our experience indicates that this visualization system allows the experimentalist to examine patterns of a quasi-periodic motion at any phase in a cycle while the experiment is in progress. Secondly, the image on the viewing screen is a spatial signal average of the coherent periodic motion rather than a single realization, and this record results in a much higher signal-to-noise ratio since random components of the image cancel in the averaging process. Finally, the high-speed motion of a quasi-periodic flow can be reconstructed by recording photographs of the flow at different fixed time delays in one cycle.

We also completed the preliminary design and construction of a self-synchronizing stroboscopic laser interferometer with a modified Mach-Zehnder optical system. Initial results for the study of an axisymmetric pulsed sonic jet demonstrate the feasibility of this technique, however, interferograms of propagating weak shock waves obtained were of poor quality and limited spatial extent. The interferometer optics should be modified by incorporating high quality, large aperture optics, such as off-axis parabolic mirrors, in the test leg of the interferometer. This system could then first be tested

by studying the unsteady transonic flow in a two-dimensional diffuser exhibiting periodic shock oscillations, and finally adapted to the transonic wind tunnel facility at NASA Ames Research Center and conducting a series of experiments on the shock-induced separation problem in unsteady transonic aerodynamics.

1. INTRODUCTION

Unsteady aerodynamics includes many examples of fundamental interest having the common characteristic that the flow variables change periodically with time over a large spacial region of the flow but often with a frequency that drifts; that is, the flow is quasi-periodic. In some cases this periodicity is the consequence of rotating or oscillating surfaces in the flow. Representatives of this class occur in the aerodynamics of rotorcraft and in important aeroelastic effects such as flutter at transonic speeds. In other cases flow instabilities themselves lead to periodic disturbances while the solid surfaces in the flow remain fixed. This class includes many important aeroacoustic flows such as noise generation from vortex shedding and from the interaction of jets, wakes, and vortices with rigid surfaces.

Often insight about flow behavior may be gained when a pattern produced by or related to the flow can be observed by visual inspection. This is especially true for unsteady flows for which knowledge of the flow development and evolution is important. In order to visualize an unsteady flow, however, special schemes must be adopted to enable the experimentalist to resolve the temporal behavior of the flow. This study has concentrated on the development and assessment of two special flow visualization techniques that may be used to investigate quasi-periodic flows.

Conventionally, the visualization of unsteady flows is accomplished by using single-shot and multi-shot spark flash photography and high-speed cinematography.[1] When the unsteady flow is also periodic, the visualization apparatus may include a pulsed light source in which the pulses can be made to coincide with the instants at which successive occurrances of the phenomenon being studied reach a fixed geometrical position. The over-all result produces a stroboscopic effect, creating the illusion that the unsteady motion has stopped at one instant in the period of motion. In common practice the strobe light source, driven by an independent frequency source, is set at a frequency approximately equal to that of the periodic phenomenon under investigation; it is, in other words, fixed-frequency stroboscopy.[2] However, in unsteady aerodynamic experiments small but uncontrollable changes in experimental conditions invariably cause the flow field frequency to drift. As a result, all of the unsteady techniques mentioned are limited in their capacity to capture a flow image at a precise phase in the motion. As a matter of fact, phase uncertainty can be so large that no visual continuity may be obtained. This difficulty can be overcome by synchronizing the light source flashes with the quasi-periodic flow itself. Although synchronization can be used with spark-flash photography and high-speed cinematography, in the present research program we have adapted it to both schlieren and laser interferometer techniques that synchronize a stroboscopic light source with the quasi-periodic flow. In this way the technique enables the experimentalist to visualize the detailed space-time behavior of a quasi-periodic flow while the experiment is in progress.

A description of these two measurement systems together with specific flow field applications follows. The self-synchronizing stroboscopic schlieren system has been extensively developed and successfully used during the grant period while the self-synchronizing stroboscopic laser interferometer has only received a preliminary treatment.

2. SELF-SYNCHRONIZING STROBOSCOPIC SCHLIEREN SYSTEM

An early version of a stroboscopic schlieren system which used synchronization to cope with fluctuating frequency phenomena was developed by Lawrence[3] at the NASA Ames Research Center and was used in a limited application to visualize the vortex discharge behind blunt trailing edge airfoils. The present system is based on the Lawrence design but also incorporates several design changes and some modern improvements. The important components of this system are diagrammed schematically in Figure 1.

Perhaps the best way to understand the operation of this system is to follow a synchronizing signal from its inception at the transducer to its conclusion at the pulsed light source. The synchronizing signal is derived by positioning a convenient transducer (pressure transducer, hot-wire anemometer, microphone, etc.) in the flow field to measure a point variable with a periodic content. If, on the other hand, a flow in which solid surfaces are in motion is being studied, the synchronizing signal may be appropriately derived by measuring the motion of the solid surface. Both approaches were used in the applications presented. In addition to the periodic component, the total transducer signal contains a nonperiodic component, which should be viewed as noise and is caused by a variety of inputs such as intermittent turbulent bursts, turbulence, electronic pickup, etc. For the flows examined, this noise component is minimized by passing the transducer signal through a variable frequency band pass filter. The clean synchronizing signal leaving the filter is fed into a phase-shift circuit which delays the signal by a known and controllable phase. This conditioned signal then drives a pulse generator and an amplifier which in turn drives a mercury flash lamp that serves as the pulsed light source of a Toepler schlieren system with concave spherical mirrors and a conventional schlieren arrangement. The mercury flash lamp has a pulse duration of 25 μsec which sets an upper frequency limit of approximately 4,000 Hz on the periodic flows which can accurately be resolved without using a frequency division scheme. The large-diameter mirrors (0.45 m) allow observation of the global periodic flow field. The image of the flow field formed by the schlieren system is recorded on a camera or viewing screen. A photodiode is mounted at the edge of the schlieren field, and the output from this diode is compared with the transducer output on a dual-trace oscilloscope. This comparison measurement provides the experimentalist with an accurate display of the phase relationship between the stop-action view on the screen and the periodic transducer signal. In this way he is able to correlate the view of the flow with an important point flow variable. By viewing and photographically recording the motion at different phases, the experimentalist is able to reconstruct a high-speed periodic motion.

2.1 APPLICATION-VISUALIZATION OF THE NEAR-WAKE BEHIND AN OSCILLATING AIRFOIL

We first applied this sytem to the visualization of the near-wake behind a pitching airfoil at low speeds. A knowledge about this flow is important for research work on flutter and also provides a check on theoretical assumptions made when estimating the unsteady aerodynamic loads on an oscillating airfoil. Our objective was to examine the structure of the wake at various frequencies and amplitudes.

The experiment (Fig. 2) was performed in a 25 X 35 cm indraft wind tunnel fitted with optical ports. A 15-cm chord model of the NACA 64A006 laminar airfoil, mounted in the test section on pivots at its quarter chord, was positioned so that the trailing edge could be viewed at the side of the optical ports. The model was driven at frequencies of 40 and 60 Hz and pitch amplitude ratios a/c of 0.02 and 0.04. The tunnel speed was varied between approximately 3 and 10 m/s, resulting in a reduced frequency range k between 1 and 10. A phase-shifted signal derived from the signal generator was used to drive the shaker and the schlieren system. The density gradients in the flow were artificially enhanced by heating a Ni-Cr wire embedded in the airfoil near the trailing edge.

RESULTS: The stroboscopic schlieren pictures, shown in Figures 3 to 6 as a sequence of nine frames taken at 45-degree phase increments, are represenative of the results obtained in the experiment. The trailing edge velocity normalized by the free-stream velocity is indicated under each frame. The ability of linearized unsteady airfoil theory to predict the unsteady loading can be correlated with the magnitude of this parameter. Figure 3 shows the unsteady wake for a reduced frequency k near 1.0. The calculated wave length is 42 cm so only a small portion of the wake disturbance is shown. Since wake distortion is small, it bears out the fundamental assumption of small disturbance theory that the wake is just a continuation of the airfoil chord line. This is further confirmed by the small values of the trailing edge velocity ratios. However, the photographic evidence can be misleading. The results of recent pressure measurements on an oscillating airfoil by Satyanarayana and Davis[4] have shown that classical linear thin airfoil theory fails at $k \approx 0.6$ due to the failure of the KuttaJoukouski condition.

Figure 4 depicts the unsteady wake behavior at a higher reduced frequency. The wake distortion is greater, and the larger trailing edge velocity ratios indicate that the limits of small disturbance theory have already been exceeded. The wave length based on the wake disturbance being convected is 13.7 cm so about one half of the wave is visible in the pictures. The curious short-wave disturbance, most evident in frame 6, is a laminar wake instability wave. It will be described in more detail in a subsequent section. Figure 5 shows a similar case, in which the pitch amplitude ratio has been increased to 0.04. The effects are similar but magnified due to the greater excitation. Note that frames 1 and 9, which were taken at different times, indicate exactly the same flow pattern.

Figure 6 shows an extreme example at very high reduced frequency. The wake excursion is so great that it becomes unstable and rolls up into itself, and the velocity ratios are so high that the flow field is almost reminiscent of the flow broadside to a flat plate, as shown in the spark shadowgraphs of Pierce.[5] The calculated wave length based on a convected disturbance is 5.9 cm.

All the visualization photographs were used to classify the near-wake according to the degree of wake distortion. Since the distortion is magnified by increasing either k or a/c, the classification is appropriately displayed on a k vs a/c graph (Figure 7). The results show that the wake is characterized by three different classes that are separated by two boundary curves, where the boundary curves are described by an inverse relation between k and a/c. Class 1 includes wakes of small distortion where linearized unsteady airfoil theory applies, while Class 2 describes those wakes that begin to break up into short-wave-length, vortex-like disturbances. Class 3 includes the extreme cases where the wake appears similar to that of vortex shedding. This classification confirms a previous visualization investigation by Ohashi and Ishikawa.[6]

ANALYSIS OF INSTABILITY WAVES: According to the usual criteria, the boundary layer on this airfoil should remain laminar at the trailing edge. Once the boundary layer leaves the airfoil, the laminar wake is unstable and soon becomes turbulent. Figure 4, frame 6, shows the laminar boundary layer breaking up into a regular pattern. Traces of this regular pattern can also be seen in other figures. These patterns are reminiscent of Tollmien-Schlichting waves on a wall boundary layer, photographic evidence of which was published by Burgh.[7]

In order to investigate the nature of these regular disturbance patterns, the wave lengths were measured from photographs and compared with classical linear stability theory. The stability theory adopted here assumes that the disturbance wave interacts with the mean flow in an unaccelerated flow field. The disturbance stream function is found to satisfy the Orr-Sommerfeld equation with homogeneous boundary conditions. The behavior of the eigenvalues of this equation may be expressed by a neutral stability curve which separates exponentially-growing disturbances from decaying disturbances.

The neutral curve is conventionally displayed as a graph of $\alpha\delta$ vs. Re δ, where $a = 2\pi/\lambda$ is the wave number of the disturbance of wave-length λ; δ boundary layer displacement thickness; and Re $= U_\infty\delta/\nu$. Usually neutral stability curves for boundary layers are displayed for two choices of the mean velocity profile. For this experiment the Blasius profile was chosen as a model of the laminar boundary layer, and the resulting neutral stability curve attributed to Tollmien[8] was used. On the other hand, the velocity defect in the initially laminar wave was represented by an error function profile. The neutral stability curve calculated for this profile and given by Taneda[9] was used to describe the wake. Figure 8 shows both of these curves along with the experimental data. The graph is divided into three regions by the neutral stability curves: Region I, where disturbances are unstable in both the boundary layer region and the wake; Region II, where disturbances are unstable in the wake only; and Region III, where disturbances are unconditionally stable.

The conditions of the present experiment are not precisely those which are assumed by the traditional curves presented in Figure 8. Aside from the fact that the boundary layer on the wing is accelerated and decelerated by the pressure gradients, the wing is being oscillated so the basic flow itself is unsteady. An examination of the photographs shows that the disturbance scales in the wake due to the airfoil's oscillations are much larger than the instability scales. The disparity in scales indicates that the unsteady flow problem can probably be "uncoupled" from the stability problem. In this manner the measured wave lengths of the short-wave disturbances were considered to be the disturbance scales for the instability calculations. The value of was chosen as the calculated displacement thickness at the trailing edge and varied from 0.6 to 1.2 mm. All of the experiemental data falls within Region II which indicates only a wake instability. These results indicate that the short wave disturbances on the wake are probably laminar instability waves, similar to those in the shadowgraph photographs of Pierce.[5]

2.2 APPLICATION EDGE TONE SOUND GENERATION

To demonstrate the usefulness of the technique when oscillations in the flow are not the result of moving solids, we chose to visualize the edge tone flow field. This old and thoroughly studied problem[10] is one example of an important larger class that is characterized by the production of sound through the interaction of shear layers with rigid surfaces. A diagram of the flow geometry is shown in Figure 9. It is characterized by a thin laminar free jet which issues from a two-dimensional laminar channel flow of width d and impinges upon an edge aligned on the axis of the jet and displaced an edge distance h from the jet exit.

A striking feature of this flow occurs when the edge is withdrawn from the jet exit plane. When the edge distance reaches a minimum breadth, the device produces an audible tone. As the edge is removed further, the tone decreases in frequency as the inverse of distance h. This frequency decreases until a certain edge distance is reached, at which time the edge tone suddenly jumps to a new higher frequency or mode of operation. These features, together with several others, characterize this interesting phenomenon.

In order to visualize the periodic flow field responsible for this sound, a condenser microphone was placed in the near sound field. The output from the microphone amplifier was fed into the filter input of the signal-conditioning electronics. After filtering the high frequencies (hiss) associated with the jet itself, a variable phase shift was introduced, whereupon the signal was fed into the pulse generator activating the schlieren light source. In this way we were able to stroboscopically stop the edge tone flow field at any phase in one period of the microphone signal.

Figures 10 and 11 are stroboscopic schlieren pictures as a sequence of nine frames taken at 45-degree increments. Figure 10 shows the flow field where the edge distance is slightly greater than the minimum breadth, while Figure 11 captures the flow just before the frequency jumps to the next mode of operation.

Close inspection of these photographs reveals the detailed oscillations of the jet and the formation and growth of vortices on either side of the edge and their motion downstream. The patterns recorded in Figure 11 indicate that the detailed features of the vortices leaving the edge may play a role in the transition to a higher mode.

We have recently reported the application of this self-synchronizing stroboscopic schlieren technique to the oscillating airfoil and edge tone flow fields in the AIAA Journal. In addition to these two flows we have also successfully visualized several others and include a brief description two here as additional examples.

2.3 APPLICATION-2-D PLANAR WALL JET

During 1977 we suggested the use of this technique to researchers at the Joint Institute for Aeronautics and Acoustics, Stanford University and instructed them in the design, construction and initial operation of a stroboscopic schlieren apparatus, in this case applied to the visualization of a 2-D planar wall jet.

The 2-D planar wall jet is similar in nature to the edge tone, thus Figure 9 will suffice as a description of the wall jet. Both of these flows are examples of a class where a jet interacts with a rigid surface. The wall jet apparatus is realized by replacing the edge in Figure 9 with a plane rigid wall of finite height that is alligned tangentially with one jet wall. Now h will represent the wall height above the jet exit plane, while d still characterizes the jet width. When a thin laminar jet issues from the channel and passes tangentially along the wall it becomes unstable, rolls up to form a convecting array of discrete vorticies, and emits discrete audible tones.

This flow field is visualized in a manner similar to the edge tone by placing a condenser microphone in the near sound field and synchronizing the stroboscopic schlieren source with the microphone signal. Figure 12 shows a record of the wall jet as a sequence of eight frames taken at 45-degree increments. The flow is characterized by a steady region of approximately 10 jet widths beyond the jet exit which then grows into a discrete vortex pattern that is convected down stream. Experimental observations of this wall jet have recently been reported by Horne and Karamcheti[11].

2.4 APPLICATION-AXISYMMETRIC PULSED SONIC JET

As a last example of the schlieren technique we show some preliminary results for the visualization of an axisymmetric pulsed sonic jet. This flow field is produced by mechanically chopping a high pressure (80 psig) jet which issues through a small orifice (0.125 in. diameter), into a resonant tube (0.75 in. diameter; 5 in. long), and finally into the ambient atmosphere.[12] The jet is sonic at the orifice and consequently density changes in the exit flow field are sizable. We chose this example as a representative of a prototype periodic transonic flow. Figures 13 and 14 are stroboscopic schlieren pictures of the exit flow that depict its outstanding features for mutually perpendicular knife edge orientations. These visualizations were derived by synchronizing the stroboscopic schlieren source with the output from a condenser microphone which measures the near field sound. The flow is characterized by the formation of a coherent ring vortex train which becomes unstable after about 8 jet diameters. The generation of each vortex ring is accompanied by the formation of a spherically shaped finite amplitude sound wave (weak shock wave). Both vortex and shock wave frequencies are coincident with the mechanical chopper frequency. We are presently engaged in a detailed examination of this flow as a function of the resonant tube geometry and flow parameters.

3. SELF-SYNCHRONIZING STROBOSCOPIC LASER INTEFEROMETER

Based on the success of self-synchronizing stroboscopic schlieren flow visualization to the applications mentioned earlier we proposed to extend this notion to include an interferometric technique. This addition would provide the experimentalist with an opportunity to record space-time density field of important periodic compressible flows. We felt it would have special application to the experimental study of unsteady transonic flows over airfoil sections tha were either stationary or oscillating. It would be expecially applicable to the not-yet-fully-understood problem of shock wave/ boundary layer interaction and shock-induced separation. Recent publications by Finke,[13] Kooi,[14] Meier,[15] and McDevitt[16] reported experimental results for a number of different transonic flow problems related to the shock wave/ boundary layer interaction, but none of the visualization technic ntioned permitted the experimentalist to synchronize or lock in a differe specific intermediate phases in one period of this complicated motion. In addition, a recent solution for this problem, which was calculated with a full Navier-Stokes computer code, indicated that the shock-induced separation produces a large-scale vortex-shedding phenomenon[17]. An experimental verification of this unsteady periodic result would seem very illuminating.

3.1 TECHNIQUE

Based on this background, we designed, and constructed a self-synchronizing amplitude-modulated laser interferometer shown schematically in Figure 15. The interferometer is a modified Mach-Zehnder type in which both the reference and test beam optical paths pass through the test section. However, the test beam is expanded with a large magnification telescope to allow for a free aperture viewing field of six inches. The laser source is an internally amplitude-modulatable helium-cadmium laser (441.6 mm) incorporating an acousto-optical modulator cell within the laser cavity. This source allows the experimentalist to stroboscopically stop an interferogram of the unsteady density field at any instant in a periodic transonic flow by using a signal derived from the transducer monitoring the flow to synchronously trigger a pulse generator. In turn, the pulse generator commands the laser modulator to provide an optical output with a frequency identical to that of the unsteady flow. By phase-delaying the command pulse with respect to the transducer signal, interferograms for any instant in the motion can be recorded. The signal conditioning and control electronics for the stroboscopic schlieren system operated in a similar fashion.

3.2 PRELIMINARY APPLICATION

We have employed the self-synchronizing laser interferometer on preliminary experiments to study the axisymmetric pulsed sonic jet. A photograph of this system is shown in Figure 16. These experiments have demonstrated both the feasibility of the interferometer and technique system. However, interferograms of propagating weak shock waves obtained in these experiments were of poor quality and limited spatial extent (1.5 in. diameter).

3.3 RECOMMENDATIONS

Although this field size has allowed us to examine the feasibility of the self-synchronizing stroboscopic laser interferometer technique, it is not large enough for the study of such problems as shock-induced separation and unsteady transonic flow about airfoils. The interferometer optics should be modified by incorporating high quality, large aperture optics, such as off-axis parabolic mirrors, in the test leg of the interferometer. This system could then first be tested by studying the unsteady transonic flow in a two-dimensional diffuser exhibiting periodic shock oscillations[18], and finally adapted to the transonic wind tunnel facility at NASA Ames Research Center and conducting a series of experiments on the shock-induced separation problem in unsteady transonic aerodynamics.

4. CONCLUSIONS

We have found that the self-synchronizing stroboscopic schlieren system visualization technique provides an extraordinarily effective means of studying quasi-periodic flows in real time. Based on the applications described, our experience indicates that this visualization system allows the experimentalist to examine patterns of a quasi-periodic motion at any phase in a cycle while the experiment is in progress. Secondly, the image on the viewing screen is a spatial signal average of the coherent periodic motion rather than a single realization, and this record results in a much higher signal-to-noise ratio since random components of the image cancel in the averaging process. Finally, the high-speed motion of a quasi-periodic flow can be reconstructed by recording photographs of the flow at different fixed time delays in one cycle. In order to record a meaningful stop-action view of the flow, the basic flow requirements should be that (1) the size and shape of each disturbance must be nearly the same, and (2) the time history of each disturbance from a fixed point must be approximately constant for each cycle.

With additional development it also appears that self-synchronizing stroboscopic laser interferometry can provide the experimentalist with an excellent tool for investigating periodic compressible flows.

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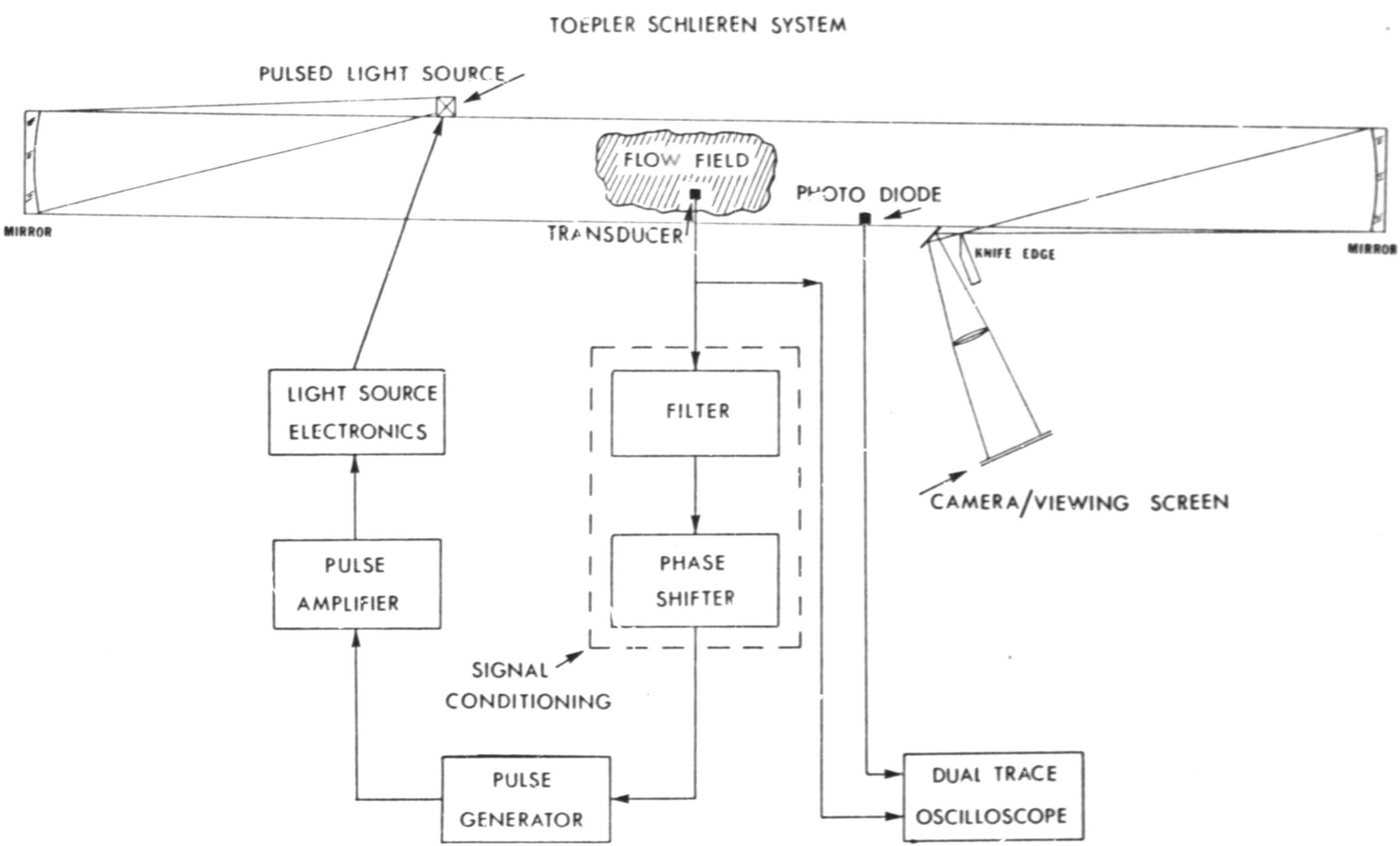

Figure 1. Schematic diagram of self-synchronizing stroboscopic schlieren system.

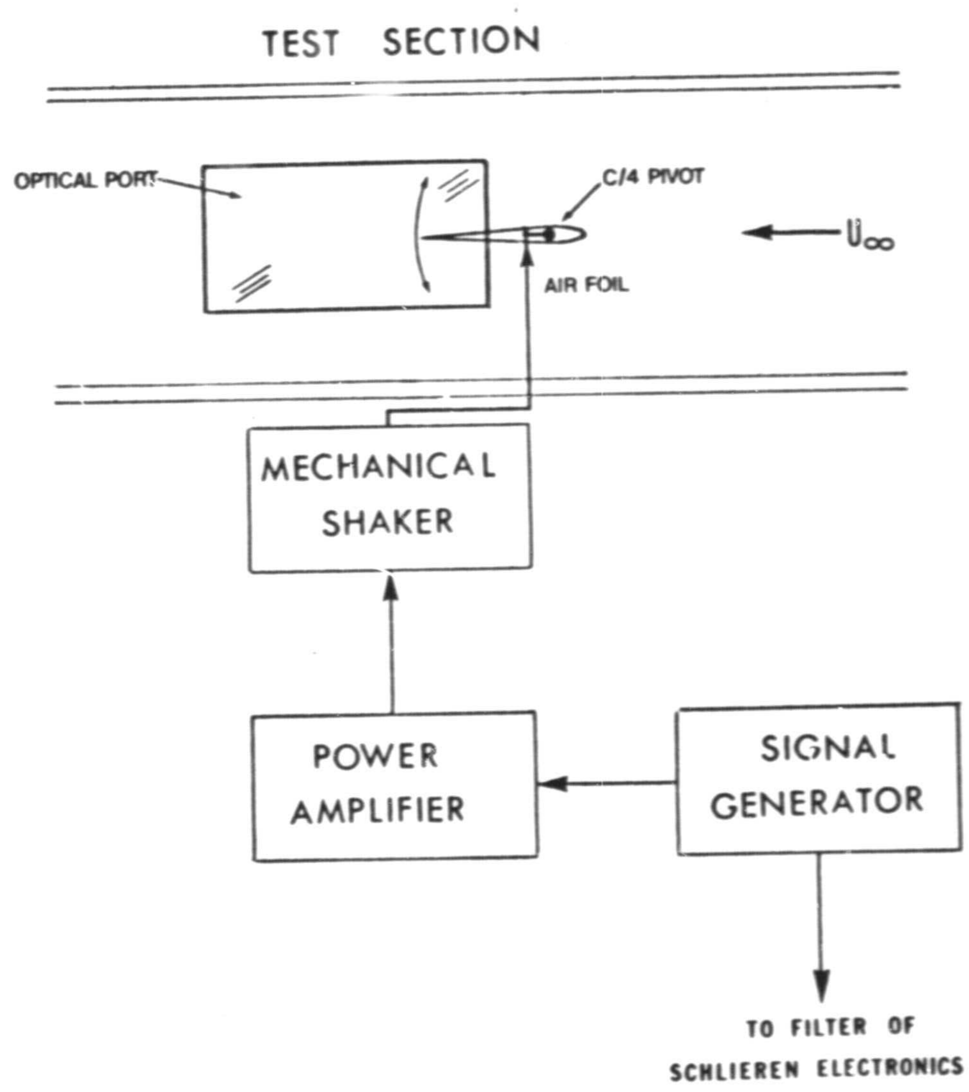

Figure 2. Pitching airfoil experimental apparatus.

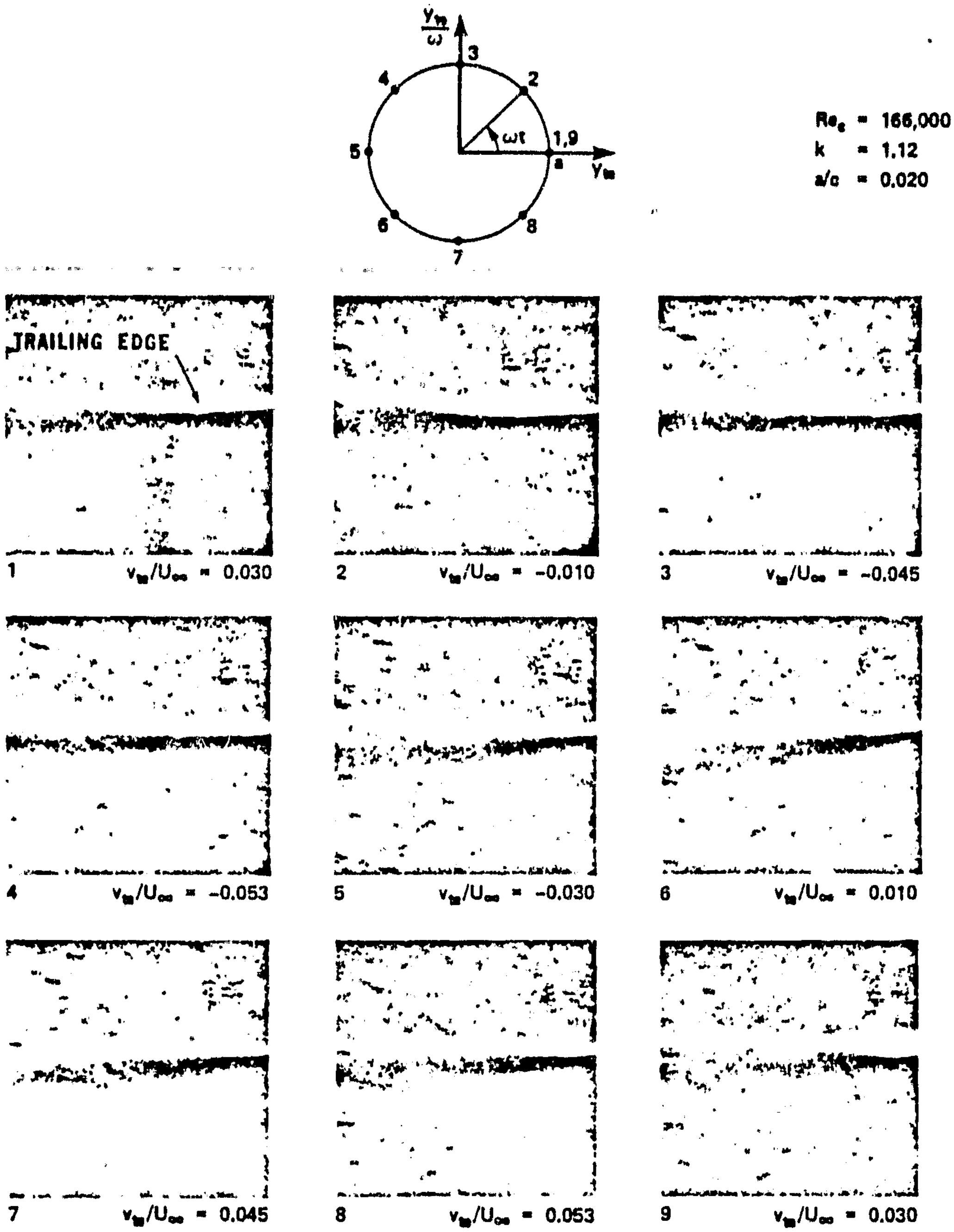

Figure 3. Visualization of the near-wake behind a pitching airfoil: Re_c = 166,000; k = 1.12; a/c = 0.02.

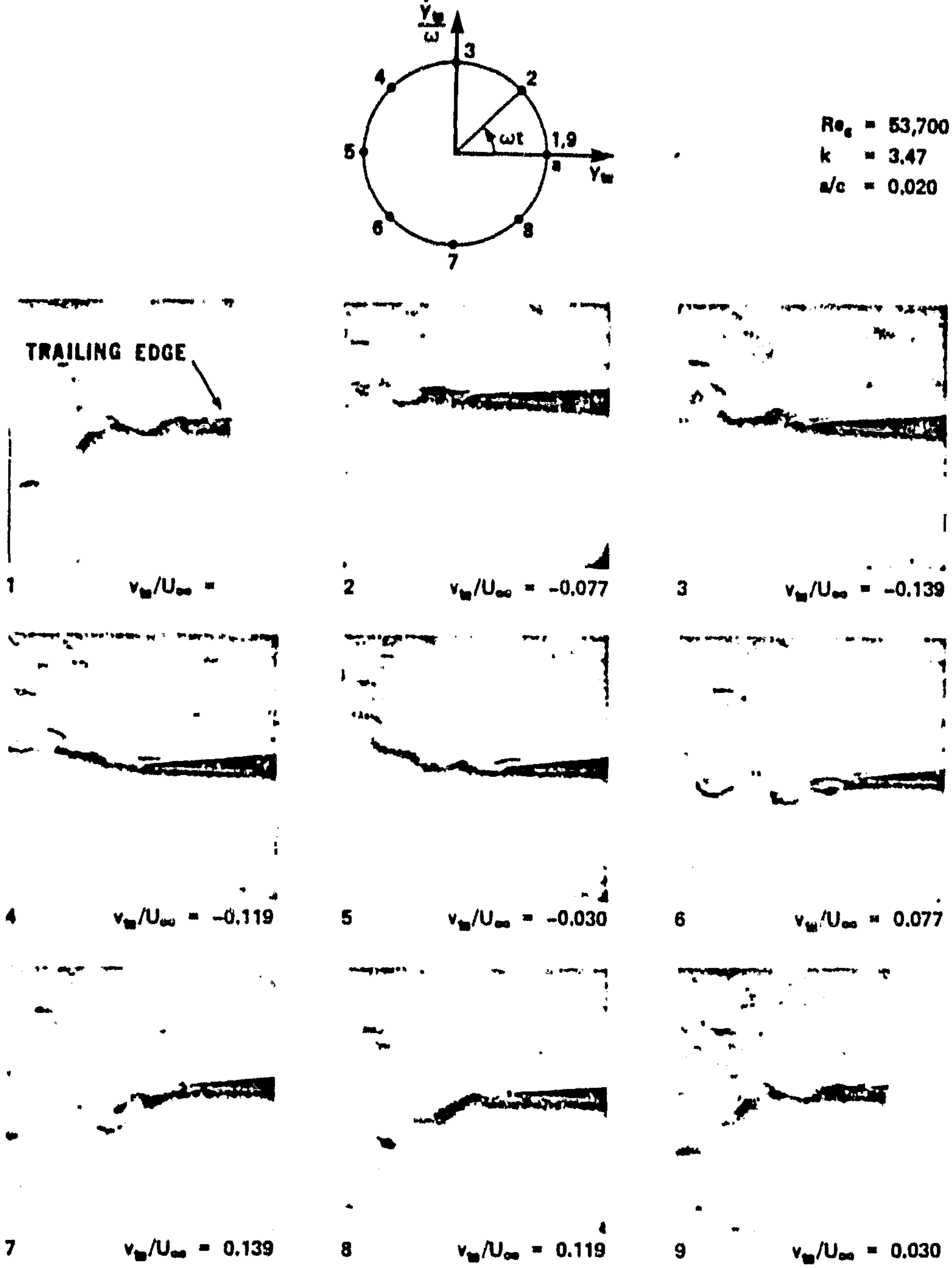

Figure 4. Visualization of the near-wake behind a pitching airfoil: Re_c = 53,700; k = 3.47; a/c = 0.02.

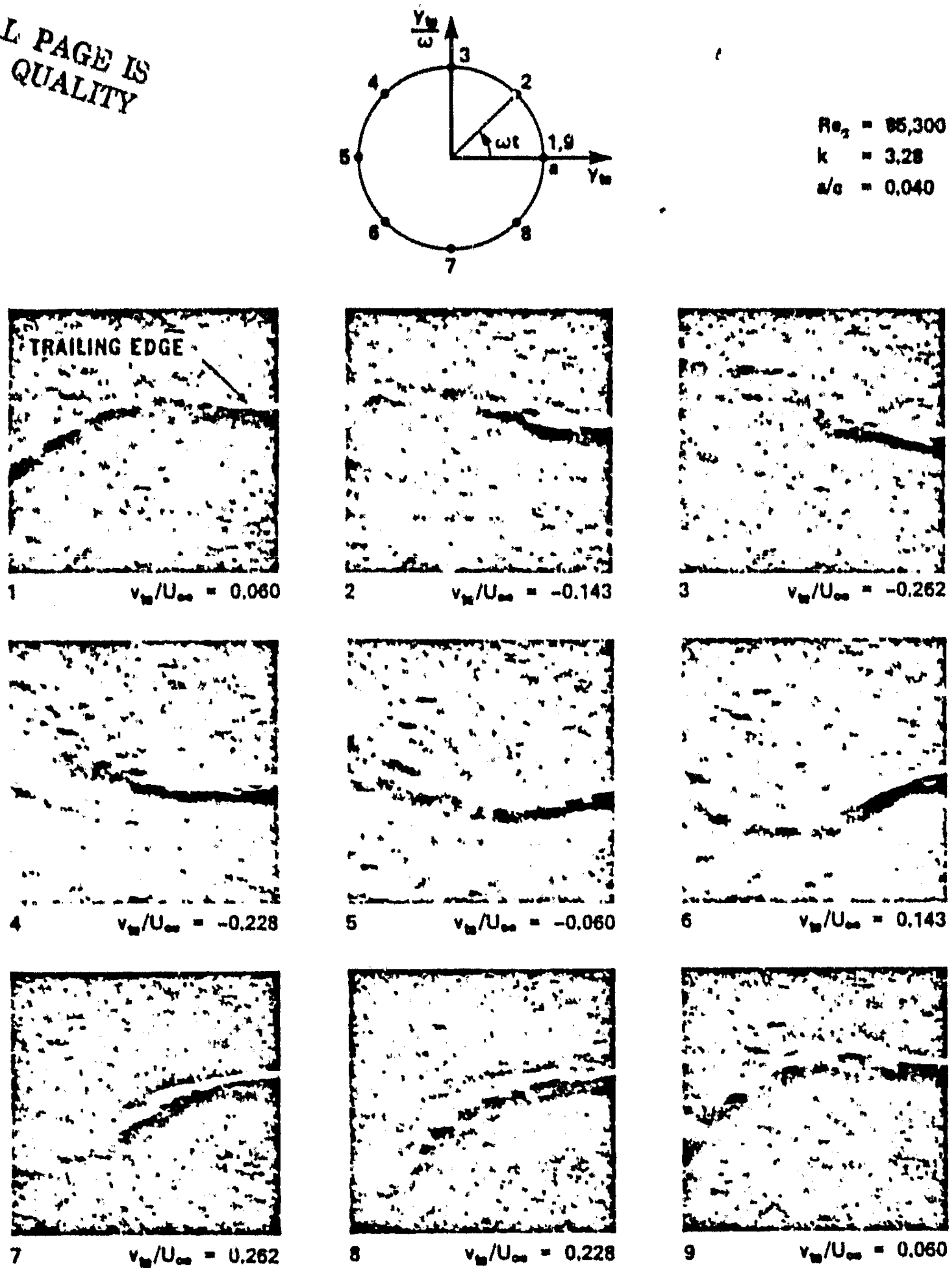

Figure 5. Visualization of the near-wake behind a pitching airfoil: Re_c = 85,300; k = 3.28; a/c = 0.04.

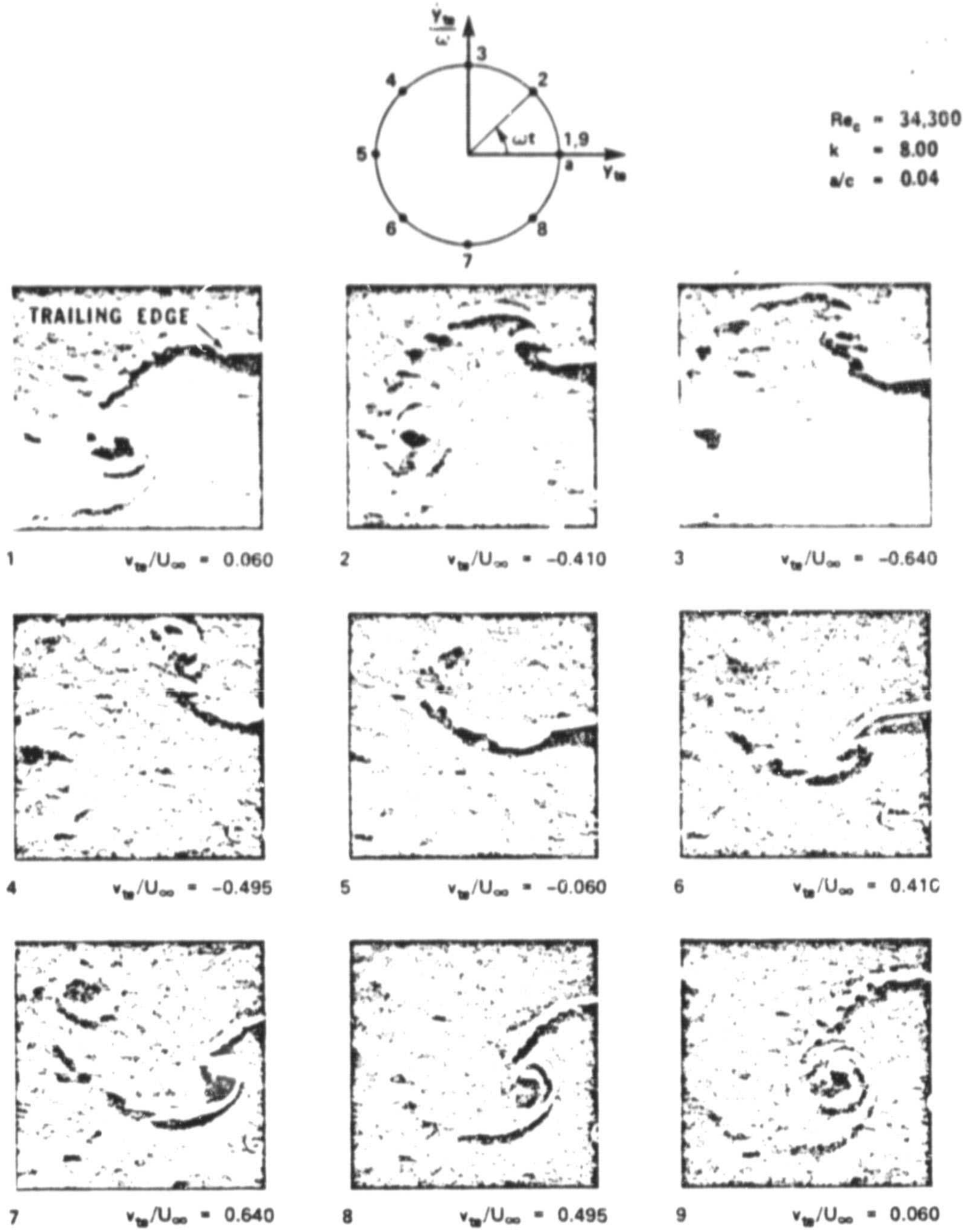

Figure 6. Visualization of the near-wake behind a pitching airfoil: Re_c = 34,300; k = 8.00; a/c = 0.04.

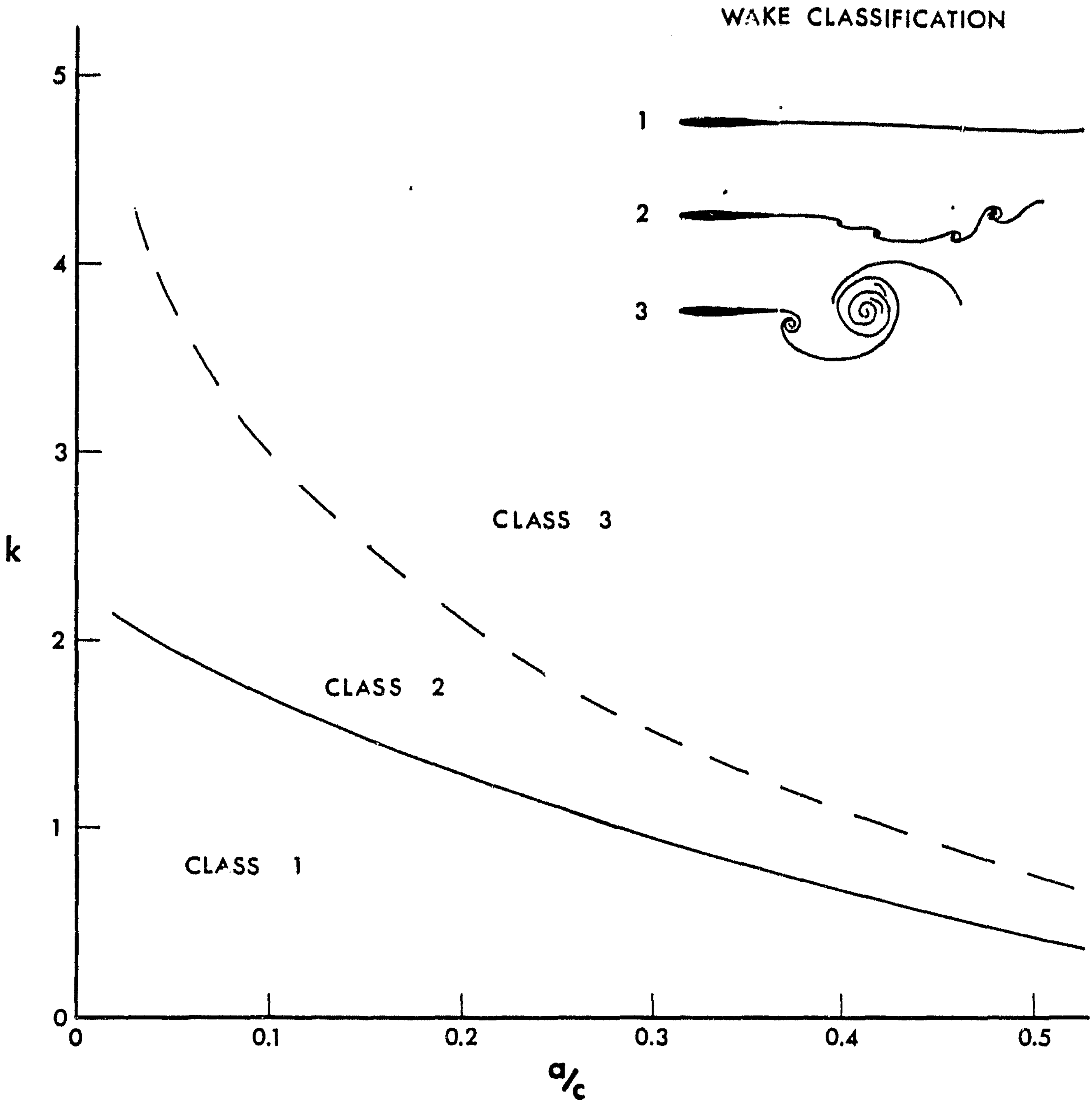

Figure 7. Characterization of near-wake flow patterns.

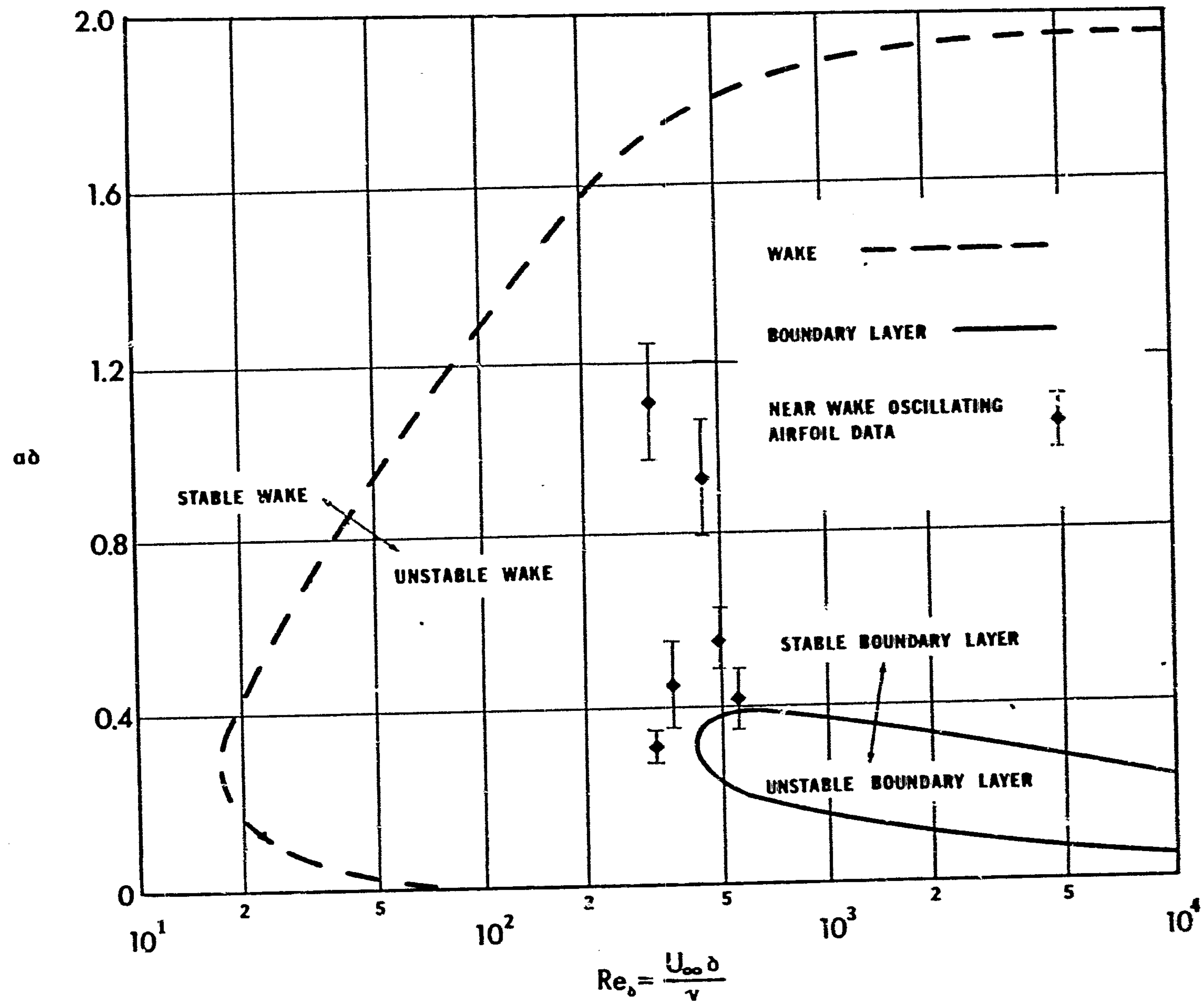

Figure 8. Curves of neutral stability for near-wake flow field.

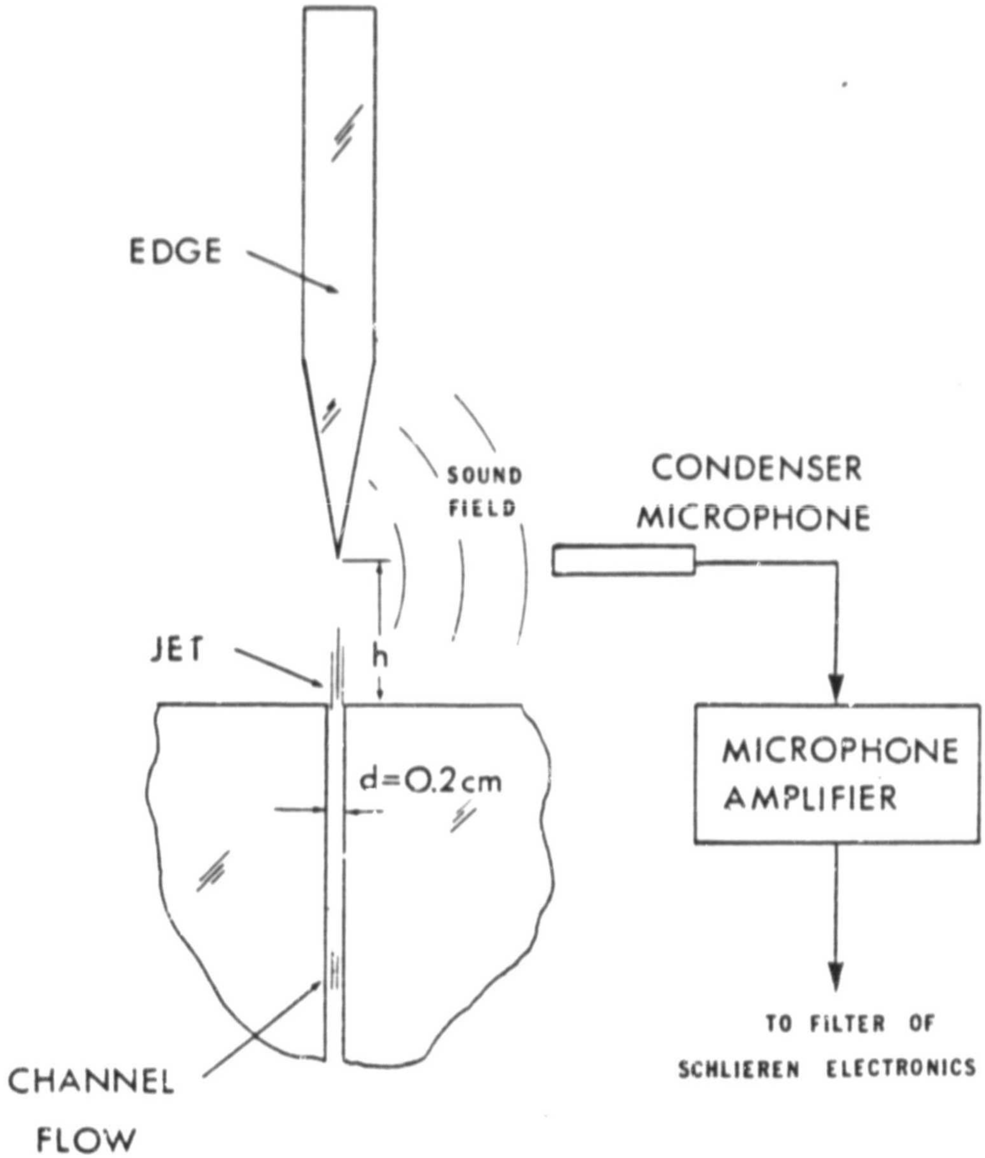

Figure 9. Edge tone sound generation experimental apparatus.

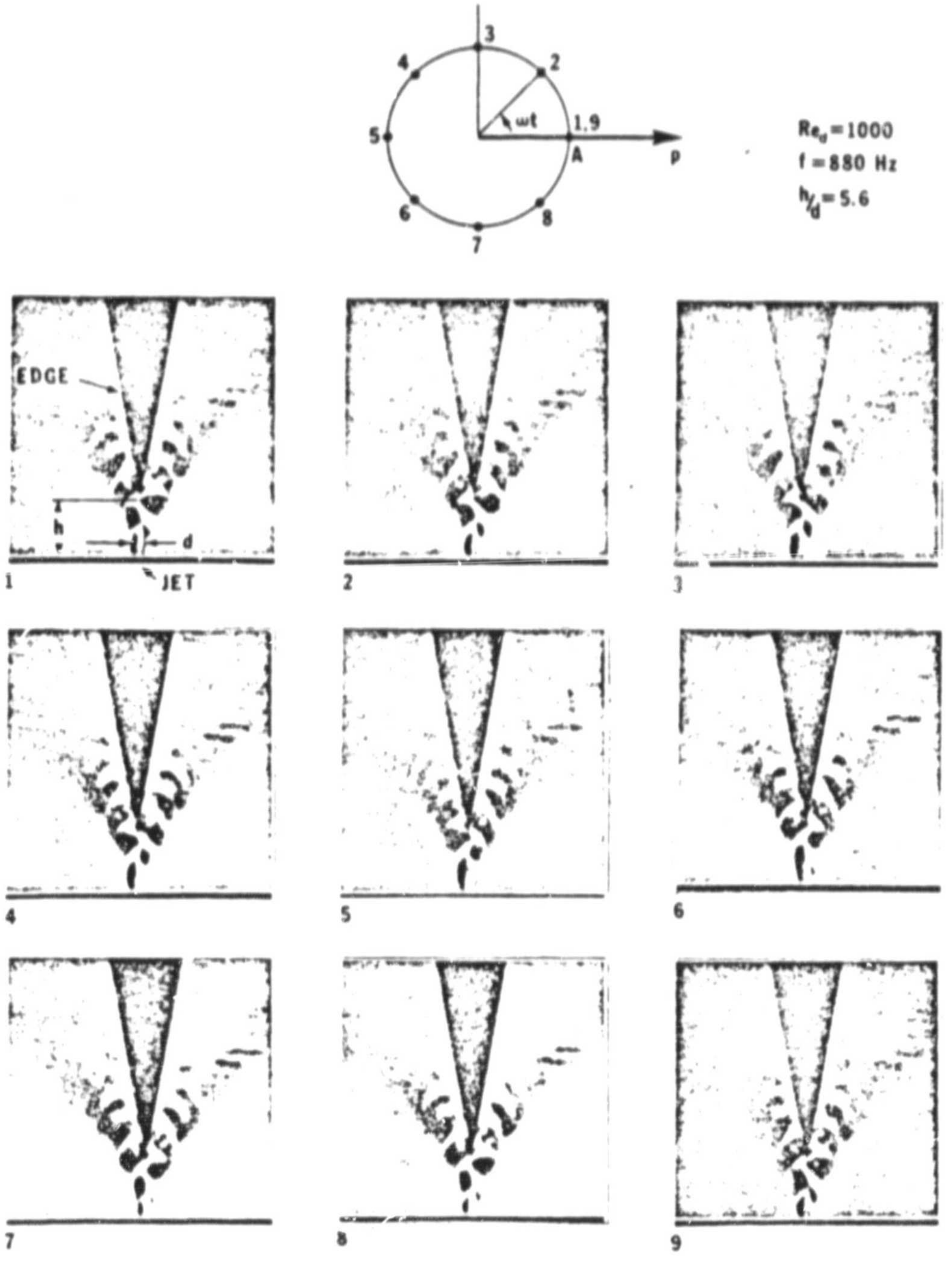

Figure 10. Visualization of edge tone flow field: Re_d = 1000; f = 880 Hz; h/d = 5.6.

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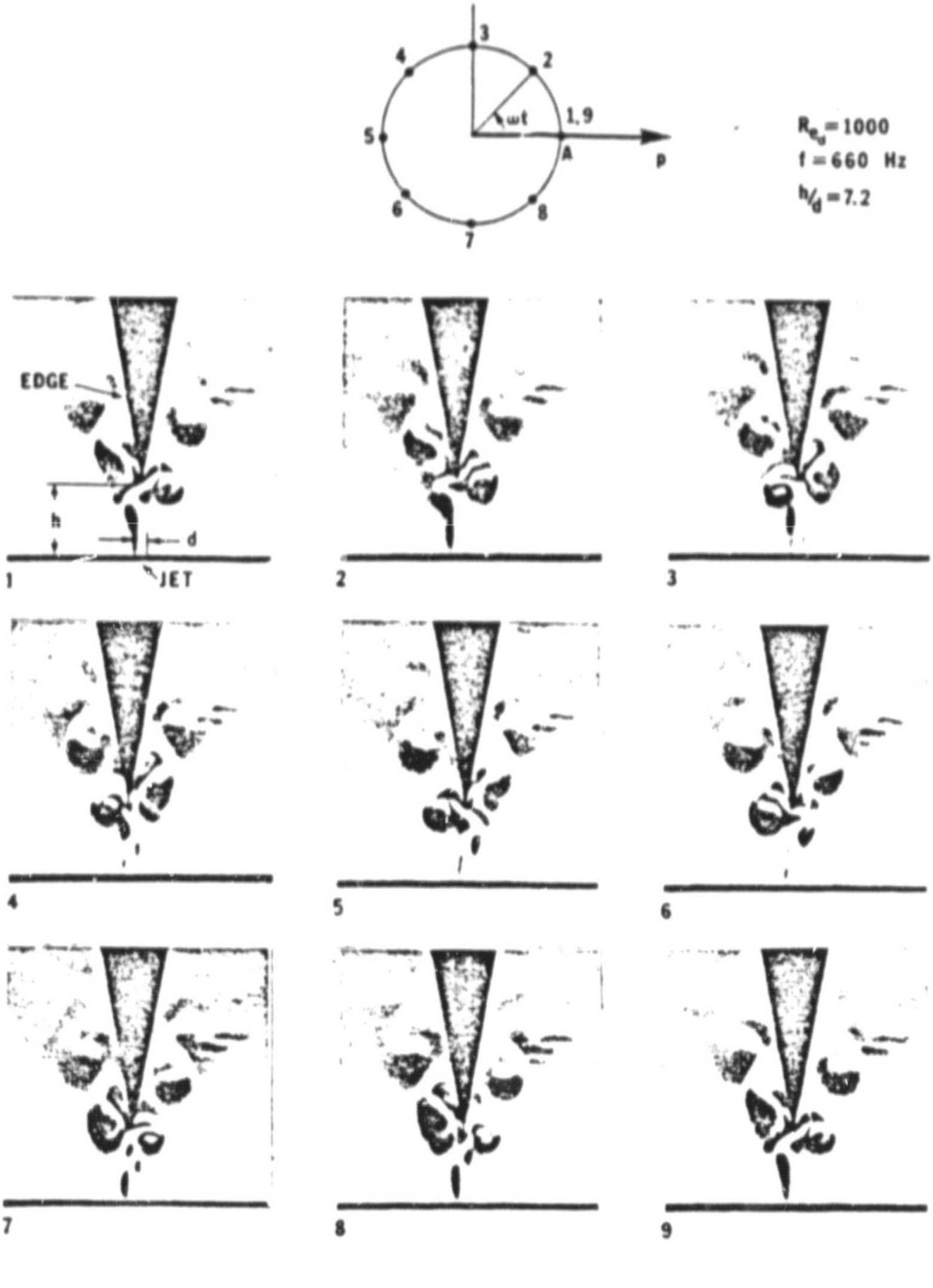

Figure 11. Visualization of edge tone flow field: Re_d = 1000; f = 660 Hz; h/d = 7.2.

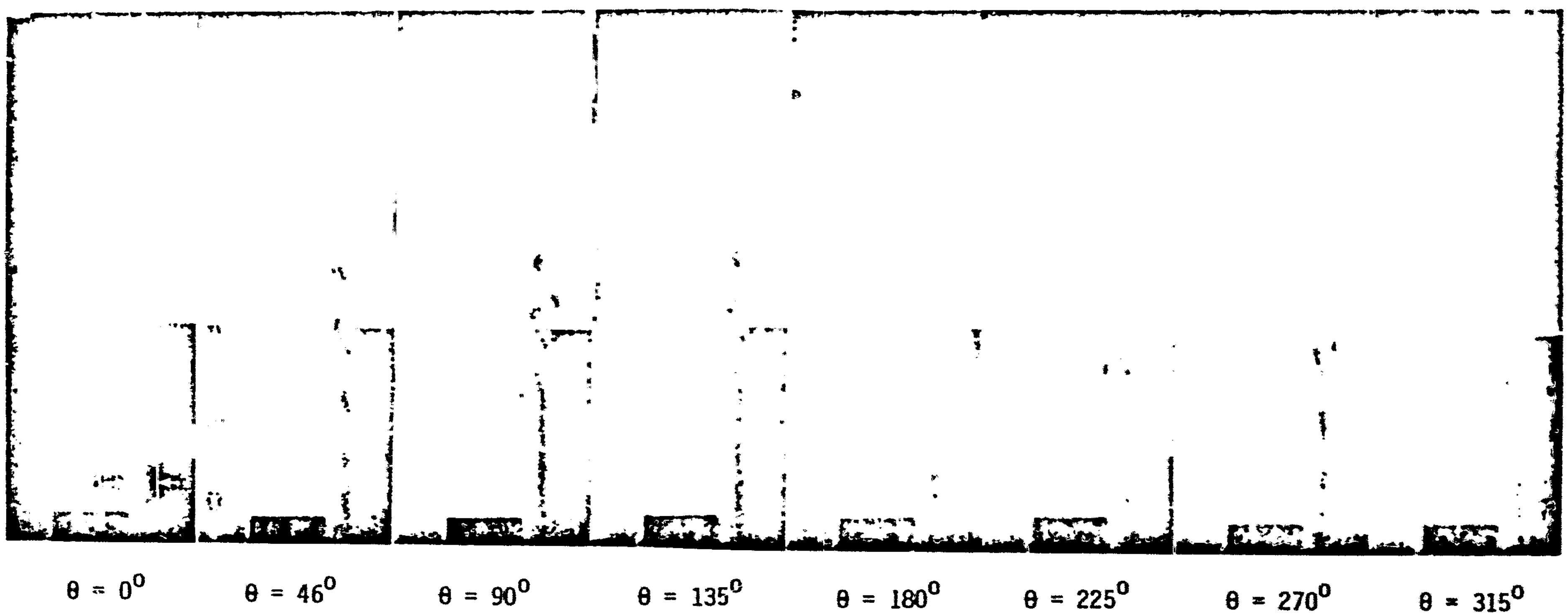

Figure 12. Visualization of 2-D planar wall jet: $Re_d = 4740$; $f = 5294$ Hz; $h/d = 7.54$

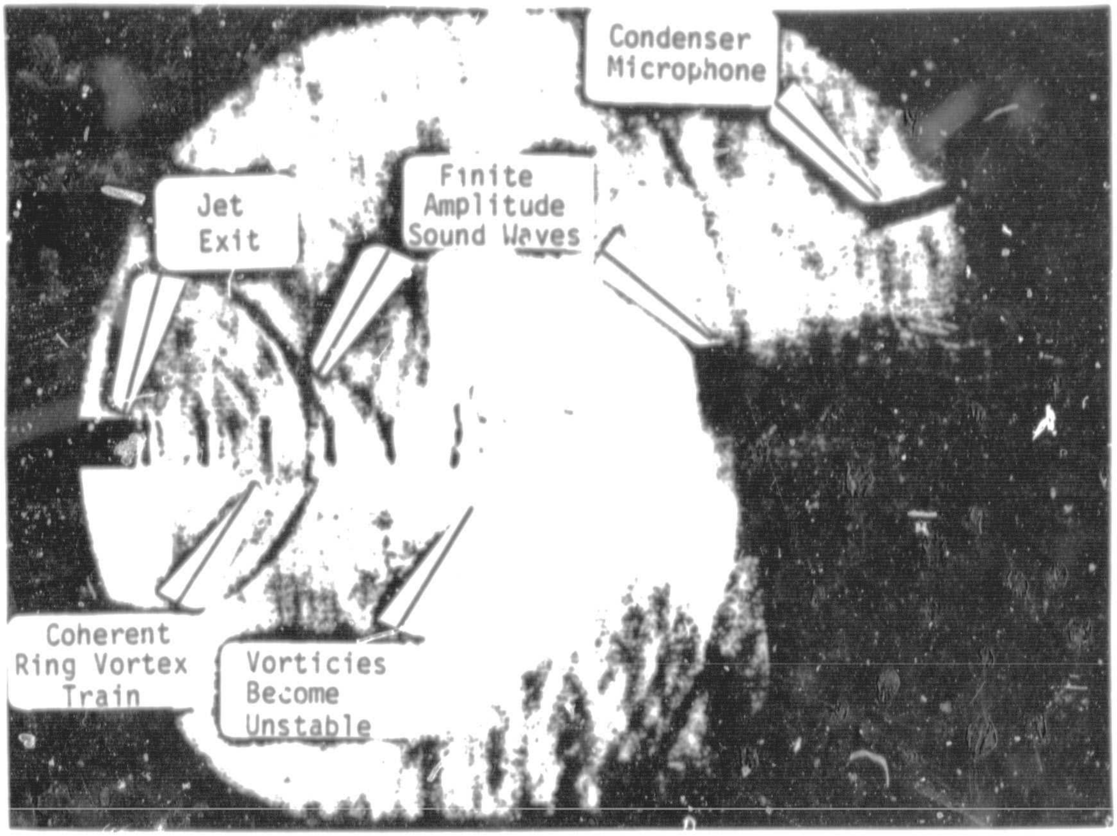

Figure 13. Visualization of axisymmetric pulsed sonic jet: schlieren knife edge perpendicular to jet axis.

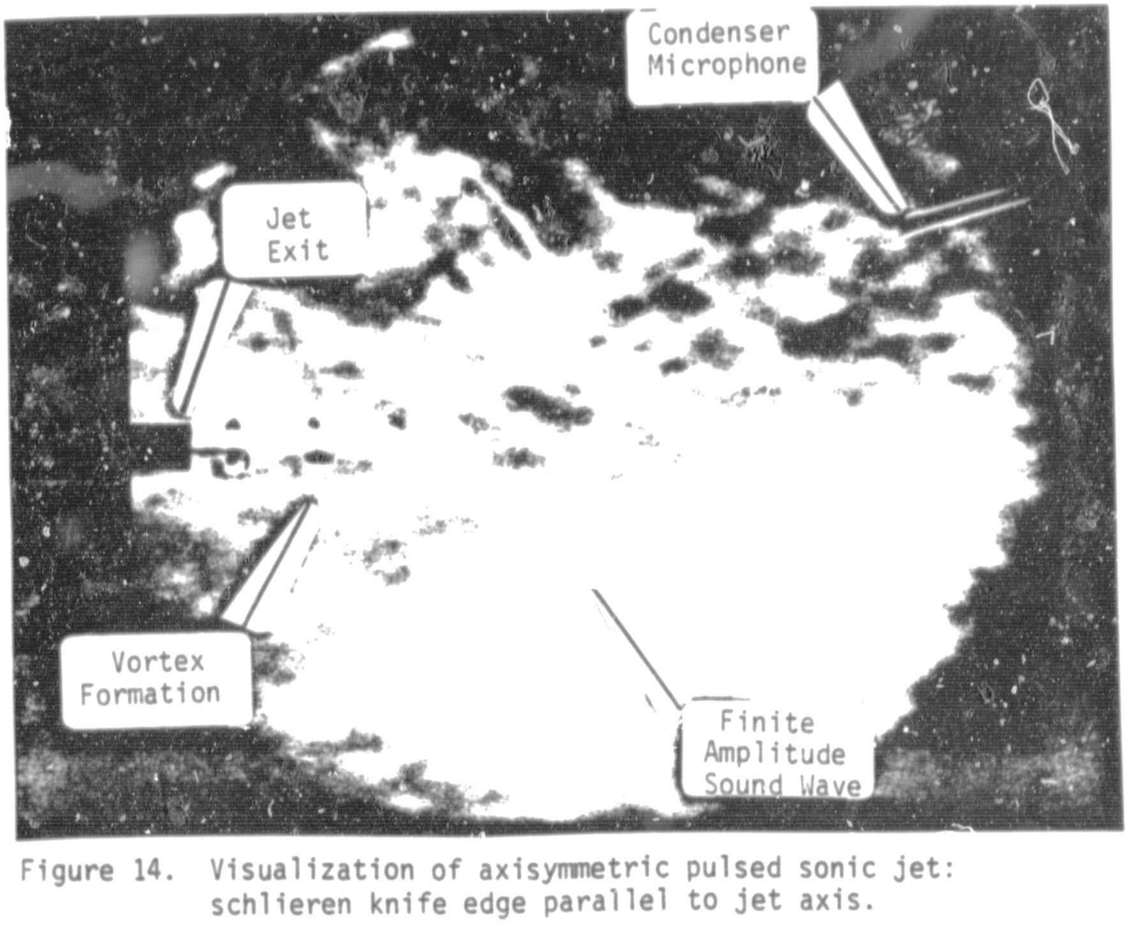

Figure 14. Visualization of axisymmetric pulsed sonic jet: schlieren knife edge parallel to jet axis.

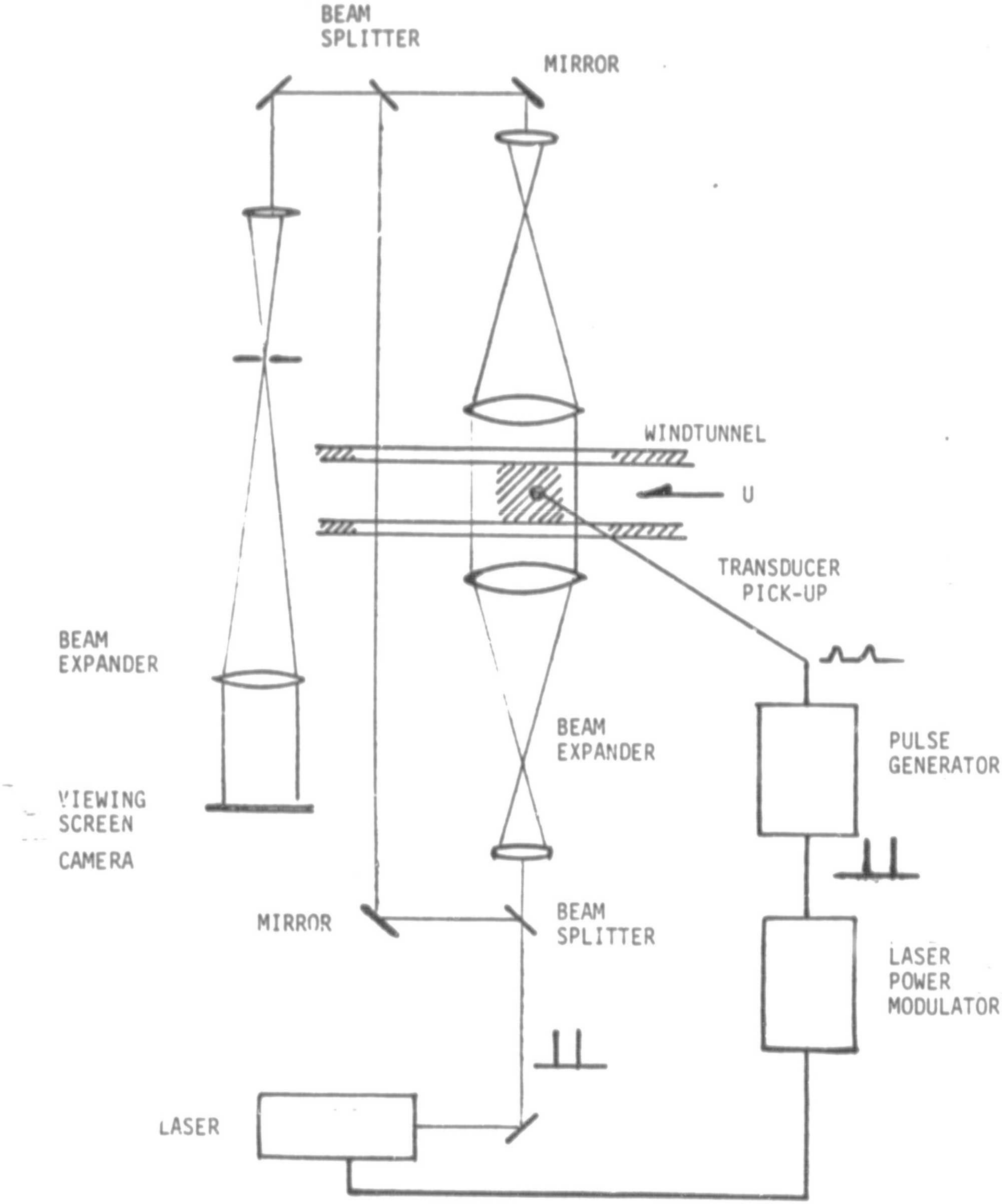

Figure 15. Self-Synchronizing Amplitude-Modulated Laser Interferometer

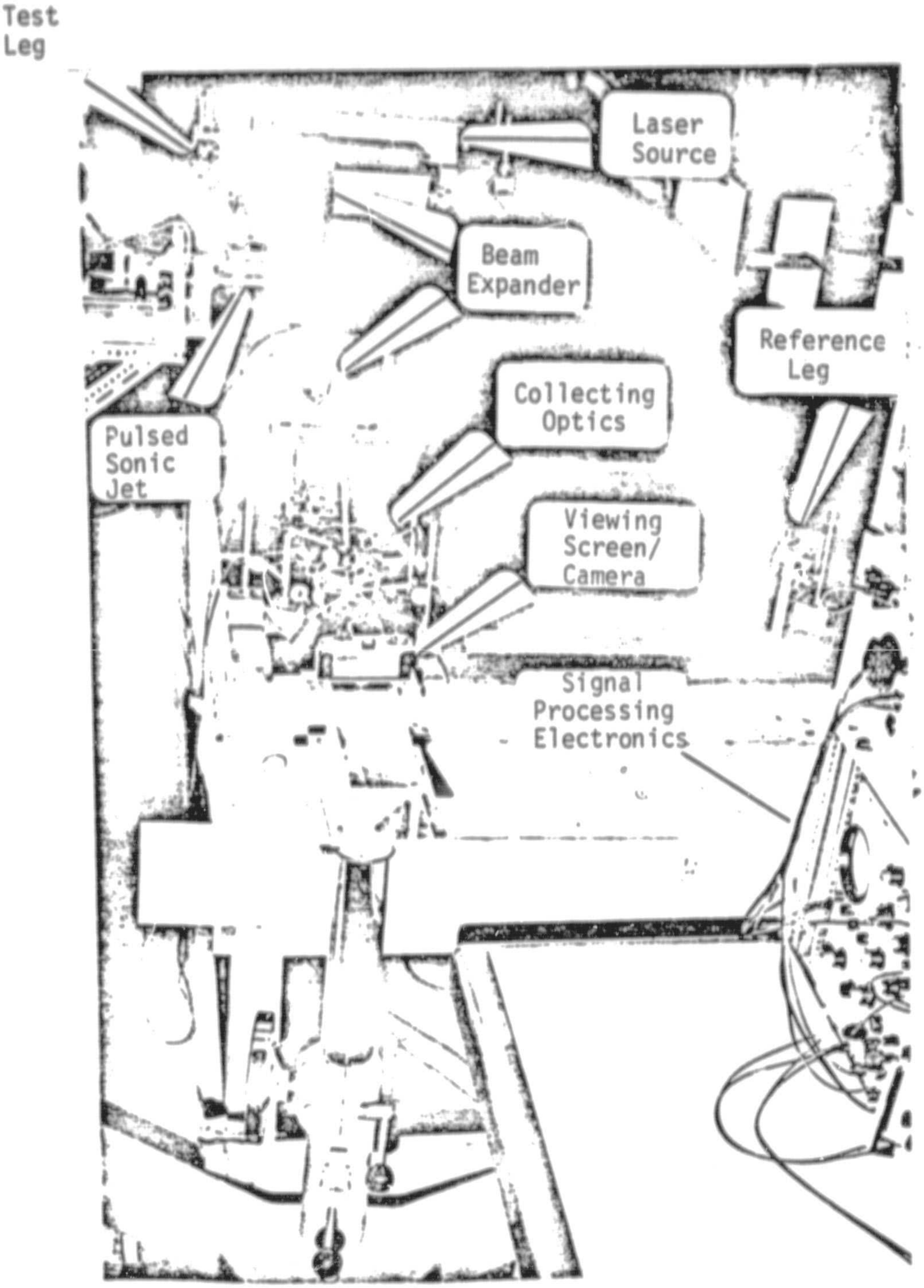

Figure 16. Photograph of preliminary stroboscopic laser interferometer system.