AAE334L Project

Cookie-cutter transonic test section inserted in the end of the shock tube. Schlieren measurements and associated tricky timing issues (must time image to microseconds to catch transonic flow). Scanned by SPS 4/30/2004 from original on file.

Timing Issues in Schlieren Imaging of Transonic Flow

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I. ABSTRACT

This experiment is a follow-up investigation on the results and observations made by L. Hamlin in Schlieren Imaging of Transonic Flow over an Airfoil, submitted in the Fall of 1995 as an AAE490 research project. The purpose of this investigation is to identify the conditions (timing issues, hardware settings) necessary to obtain a consistent image of known transonic flow characteristics over a supercritical airfoil using the Schlieren imaging system. The test specimen is constrained inside a rectangular cookie cutter test section[1] appended to the end of the shock tube.

Images of the desired flow regime are obtained by sending a calibrated trigger to the camera in the test section using two Kiestler pressure transducers, a Lecroy 9310 digital oscilloscope, a pulse amplifier, and the Schlieren imaging equipment.

Though we were successful in capturing some of the characteristics of transonic flow that were expected, the absence of other standard features of this type of flow were notably absent[2]. This raised questions about the validity of the results obtained in this investigation and lead to a different goal. One way to verify the validity of these results was by obtaining an image of the primary shock as it traveled over the airfoil rather than the flow behind the primary shock wave. This proved to be a very difficult and fruitless attempt. We were unable to obtain an image of the shock but in trying to do so we discovered other interesting facts about the results we had found previously for what we believed was transonic flow due to the passage of the primary shock wave.

This report describes the experimental setup of the Lecroy 9310 digital oscilloscope and the pulse generator required to trigger the camera in order to obtain an image of the flow behind the primary shock. The timing issues involved with these settings are also discussed. The initial conclusions made are listed as well as why we think these conclusions might not be correct and some possible ways to validate the results presented.

NOTE: Throughout this report it is assumed that the reader is familiar with the operation of the shock tube and the Lecroy digital oscilloscope.

II. OSCILLOSCOPE & PULSE GENERATOR

The experimental setup for the oscilloscope and the pulse generator is shown in Figure 1. The Kiestler pressure transducers (K1) and (K2) are connected directly to the oscilloscope. The first transducer, K1, is connected to CH1 of the digital oscilloscope. The second transducer, K2, is connected to CH2. Of the two transducers only K1 is actually used to trigger the camera. K2 is used for experimental calculations of the shock wave Mach number to compare to theoretical calculations which assume inviscid isentropic flow.

The voltage output from the Kiestler Charge Amplifiers is around 2V to 3V for a strong shock. Since the pulse generator uses TTL logic, a voltage of at least 5V in the EXT/GATE input is required to trigger the camera. So, it is necessary to implement an amplifier. The maximum allowable voltage on the EXT/GATE input is 15V. IT MUST NOT EXCEED THIS VOLTAGE OR THE PULSE GENERATOR MIGHT BE DAMAGED.

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[1] *Design and Manufacture of a 'Cookie Cutter' Test Section in a Shock Tube*; D. Massa, AAE490 Research Project Report, Summer 1993.

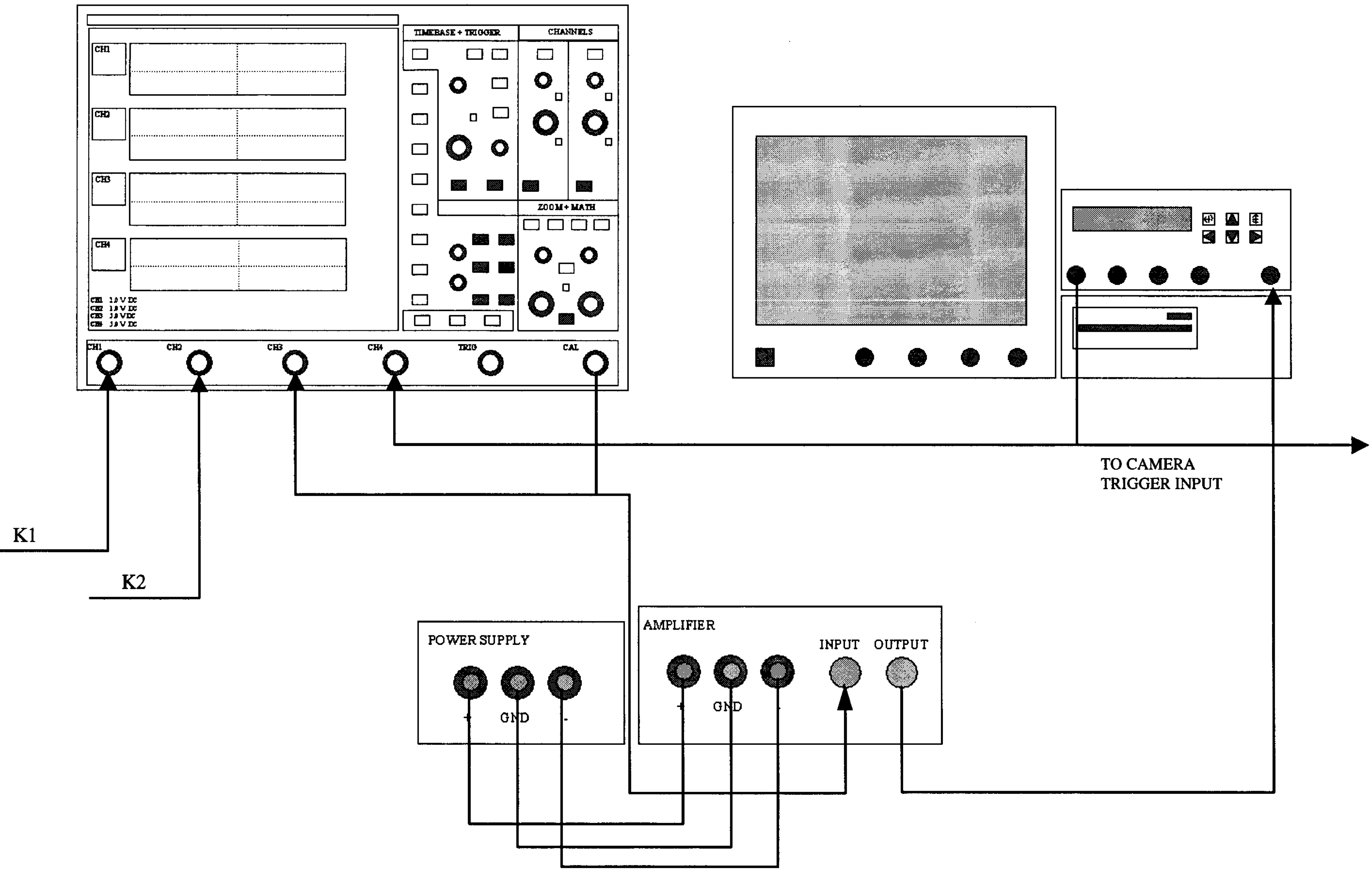

FIGURE 1: EXPERIMENTAL SETUP

To avoid this problem use the CAL output and set it up to send a 1V pulse as the trigger. So regardless of the voltage jump recorded on CH1, the trigger sent to the amplifier is always 1V. There the pulse is amplified to 10V and the amplified signal is sent to the EXT/GATE input of the Pulse Generator. Make sure the amplifier is working before you run the shock tube. The amplifier cannot share the output signal to both the EXT/GATE input and a channel in the oscilloscope. Only a single connection is allowed between the amplifier output and the EXT/GATE input. BEFORE MAKING ANY RUNS YOU MUST HIT THE RUN KEY ON THE PULSE GENERATOR TO ENABLE ALL PULSE OUTPUTS.

The camera trigger comes from T1 of the pulse generator. So, connect a cable from T1 to the camera trigger. Use a BNC Tee and split the signal from T1 such that one connection goes to the camera trigger and the other to CH4 of the oscilloscope. This serves to monitor the amplitude of the pulse sent to the camera. The following table lists the required oscilloscope settings.

Trigger Setup	Timebase Setup	Utilities-Cal. BNC Setup	Display
- Edge	- Sampling = Single Shot	- Trigger Out	- Quad
- DC Coupling	- Sample Clock = Internal	- Amplitude 1V into 1MΩ	
- Pos. Slope	- Seq. = Off		
- Off Holdoff	- Record up to 50K		

Since the camera is triggered off CH1 (i.e. K1) it is necessary to know before hand the time it will take the shock to travel from K1 to mid-chord of the test specimen, for the pressure ratio being considered. For this calculation the program **shock.exe**, provided by Dr. Schneider, can be used to obtain a theoretical value of the shock speed. The shock speed can also be calculated experimentally using the voltage jumps recorded on CH1 and CH2. Using the *cursors* option of the Lecroy digital oscilloscope one can accurately measure the amount of time it takes the shock to travel from K1 to K2. Since the separation between the two transducers is known then the speed is simply the displacement divided by the elapsed time.

The theoretical value of the shock speed is used as an initial guess to set up the pulse delay. The pulse delay is simply the amount of time that the pulse generator will wait before sending the trigger to the camera to grab the current image. The theoretical value of the shock speed can be used to obtain a good initial guess of what the required time delay can be. There is a range of time delays that can be used to obtain a good image of the flow. The pulse generator is sufficiently sophisticated that one can actually set the delay to be sufficiently small such that the picture of the flow is taken before the shock passes over the airfoil.

TIMING IS CRITICAL when obtaining an image. Though the theoretical calculation might provide a good initial guess, that is not always true. Some iteration might be required, especially if one is looking for certain features of the flow which are only observed while the shock is immediately over the airfoil.

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[2] *Shock Tube as a Device for Testing Transonic Airfoils at High Reynolds Numbers*; W. Cook, J. Presley, and G.

III. RESULTS

For a supercritical airfoil a supersonic bubble forms in the upper and lower surfaces of the airfoil. This is a feature of this type of airfoil that is a desired consequence of its design. For a sufficiently strong shock, high transonic flows can be recreated for a short amount of time. Because the Schlieren records changes in density through changes in color depth, it is expected that the expansion fan near the leading edge will be recorded by the Schlieren as a distorted dark bulge similar to that shown in Figure 1a for a symmetric airfoil in transonic flow[3]. Also, the constant density contours at the leading edge should be visible to some extent as well.

The supersonic flow region in the upper and lower surfaces is defined by Mach lines, weak shocks. Since shocks can be thought of as a series of thin viscous layers they should also appear in the Schlieren image[4]. In all the images obtained in this experiment the high density region at the leading edge was easily found, after some iterations on the time delay. However, the Mach lines defining the supersonic region were never captured on image.

The driver pressures considered in this experiment ranged from 96 psig to 150 psig which was the highest driver pressure we were able to achieve using multiple 7 mil Mylar diaphragms. Other diaphragm thickness values were considered but we found that two or four 7 mil diaphragms worked best for high driver pressures. This combination also minimized the difficulties involved in breaking thicker diaphragms with the arrowhead in the shock tube.

The target transonic Mach number behind the primary shock wave is 0.73. This is theoretically achieved with a driver pressure of 146 psig, according to **shock.exe**, for an atmospheric temperature of 292.15 K and pressure of 737.5 mmHg. The driven section is open to the atmosphere so conditions in the driven section are the same as the atmospheric conditions. For these conditions the speed of sound (a) is 342.6759m/sec, the shock Mach number (M_s) is 1.644 and the Mach number behind the primary shock wave (M_2) is 0.7243.

The measured distance between K1 and mid-chord of the airfoil, $\Delta x_{K1-Midchord}$, is 39.25 inches or 0.99695 m. Since the speed of the shock is known theoretically ($V_s = aM_s$) an initial guess for the trigger delay can be calculated as:

$$\delta t = \frac{\Delta x_{K1-Midchord}}{aM_s} = \frac{0.99695m}{(342.6759m/\sec)\cdot(1.644)} = 1.770\text{msec}$$

Note, this is only an initial guess and doesn't guarantee that an image will be captured exactly at this delay value. However, it provides a good starting place. The value of the delay can be adjusted, if necessary, according to

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Chapman; AIAA Journal Vol 17 No 7 Article No. 78-769 p.717.

[3] *An Album of Fluid Motion*; M. Van Dyke, The Parabolic Press, 1982

[4] *A Preliminary Study on the Fixed Transition Technique for a Shock Tube Transonic Airfoil Flow*; Y. Yamaguchi and T. Amemiya; Transactions of the Japan Society of Aeronautical and Space Sciences, V.37 No. 118, Feb 1995.

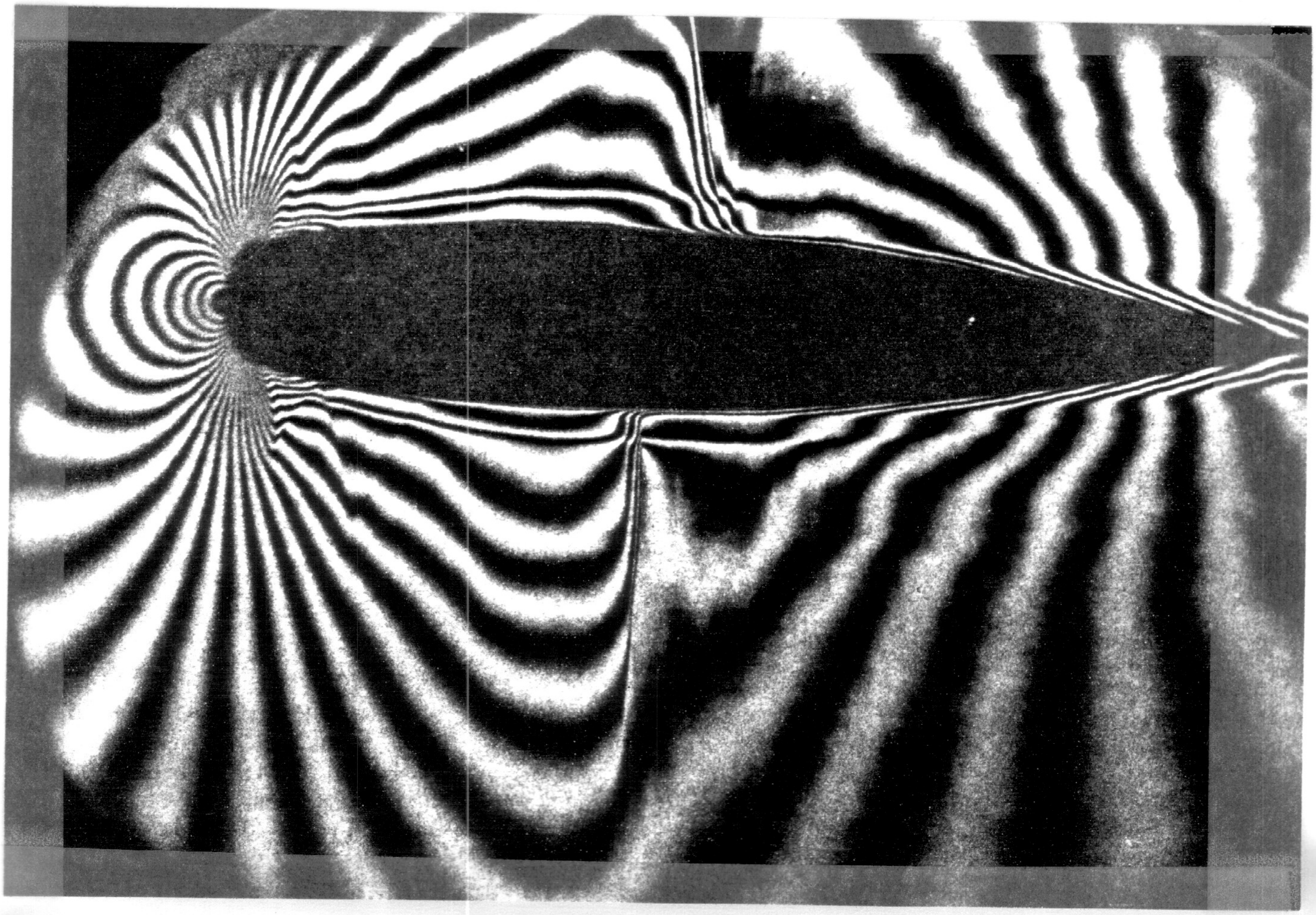

Figure 1a - Symmetric Airfoil at Mach 0.8

the experimentally measured shock speed. That is, knowing that the distance between the two transducers, Δx_{K1-K2}, is 24 inches one can use the shock speed measured using the oscilloscope to calculate the delay (δt).

$$V_{s,\exp} = \frac{\Delta x_{K1-K2}}{\Delta t_{oscilloscope}}$$

$$\delta t = \frac{\Delta x_{K1-Midchord}}{V_{s,\exp}}$$

Through a series of iterations we found that the shock speed was consistently slower than predicted by theoretical calculations. However, once the shock entered the cookie cutter section it seemed to accelerate. The calculated shock speed based on K1 and K2 seems to agree closely with the theoretical calculations. But neither experimental nor theoretical calculations accurately describe what occurs inside the test section. Hence, we performed a study on the range of allowable time delays for a given driver pressure and discovered that something is happening to the shock in going from the shock tube into the test section, but we cannot explain exactly what it is without further analysis.

Figure 2a shows an image of the airfoil as seen through the camera before the shock tube is fired. Figure 2b shows the image afterwards for a time delay of 1.74 msec and a driver pressure of 146 psig. Figures 2c, 2d, and 2e show the images corresponding to a driver pressure of 145 psig for time delays of 1.759 msec, 1.750 msec, and 1.761 msec respectively. Figure 2d shows an image for a driver pressure of 150 psig for a delay of 1.794 msec. These images correspond all to individual runs. As can be seen from these images, if the shock were in fact moving at 563.2 m/sec as theoretically calculated, then for a time delay of 1.759msec the shock should have covered a distance of 39.00 inches from K1. The mid-chord of the airfoil was measured to be at 39.25 inches from K1. According to this theoretical result, the shock should be visible in the image, but clearly it is not.

Variation in Δt = 0.013 × 349 m/s = 3.5mm
0.044ms = 15mm

Granted, there are many sources of error that could cause this, the first being an apparent leak in the driver section which made it very difficult to fire the shock tube at the same driver pressure consistently. Although, to +/- 5 psig there is no significant change in the required time delay or shock speed. There is also the possibility of some hardware delays that we couldn't account for in sending the trigger pulse to the camera. Of course, there is always measurement uncertainty. It is rather difficult to measure the exact distance from K1 to the mid-chord of the airfoil since the airfoil is inside the cookie cutter section. The best measurement we could take was from K1 to the Kulite transducer that was located roughly above mid-chord of the airfoil in the test section. These might seem unimportant at a first glance but when considering events that occur in a matter of micro seconds, they are not insignificant.

Based on these inconsistencies between the expected and the observed behavior other test cases at lower driver pressures were considered. At first by looking at Figure 2 we thought that we had the image we were looking for, but we weren't entirely sure because at least the Mach line we expected to see past the mid-chord is not seen in Figure 2. So, we tried other test cases including driver pressures of 132 psig, 114 psig, and 96 psig. The

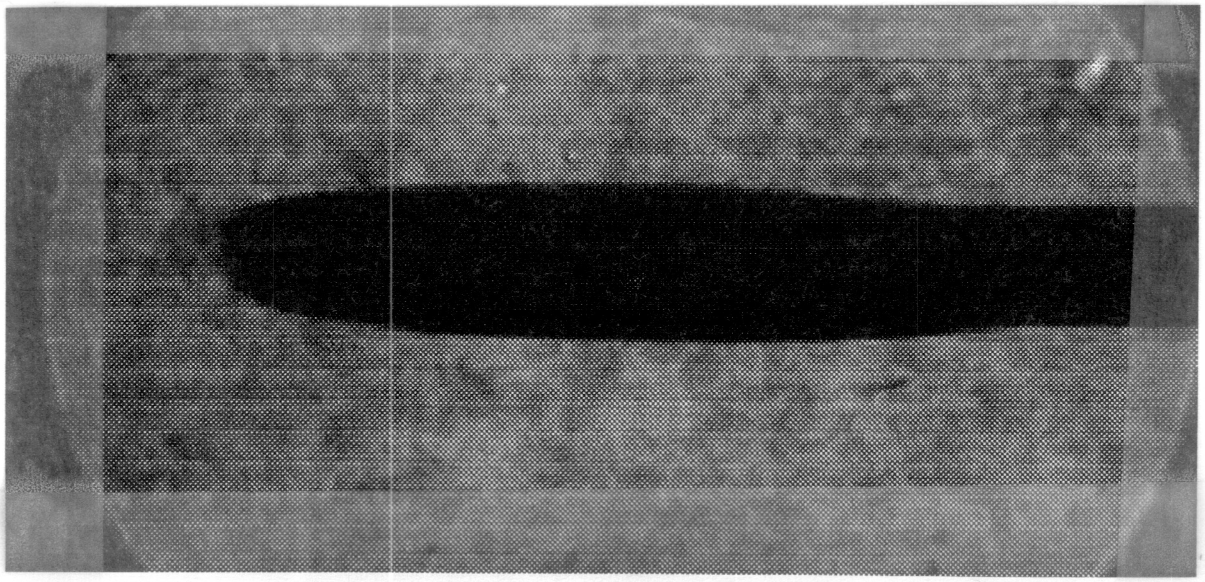

Figure 2a - Schlieren Image of Airfoil Before Shock Tube is Fired

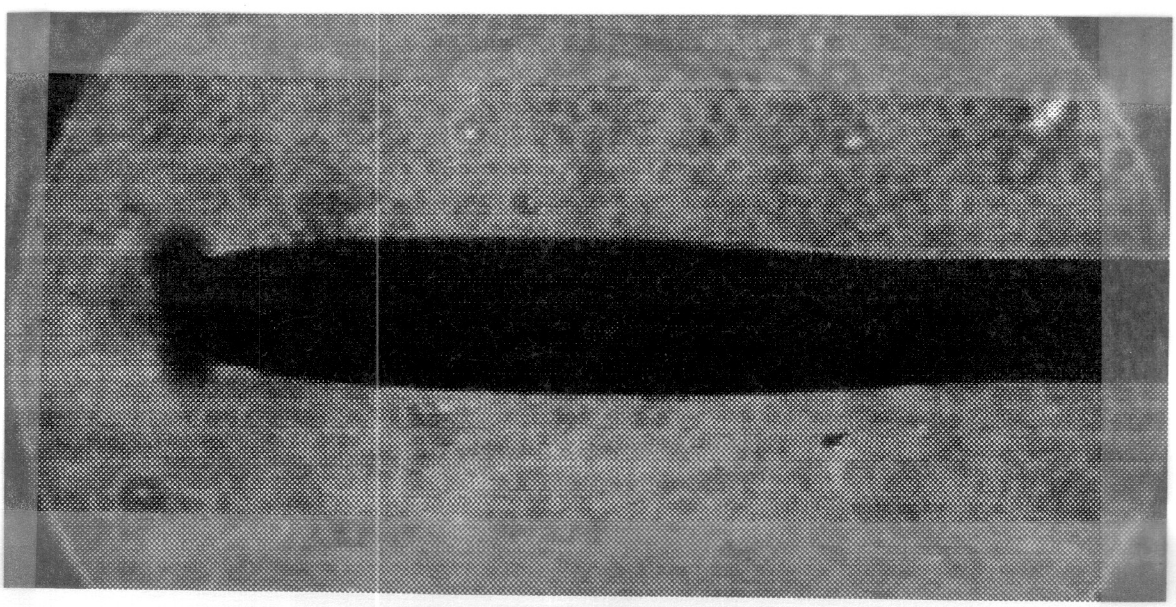

Figure 2b - Image for $P_4 = 146$ psig $\delta t = 1.74$ msec

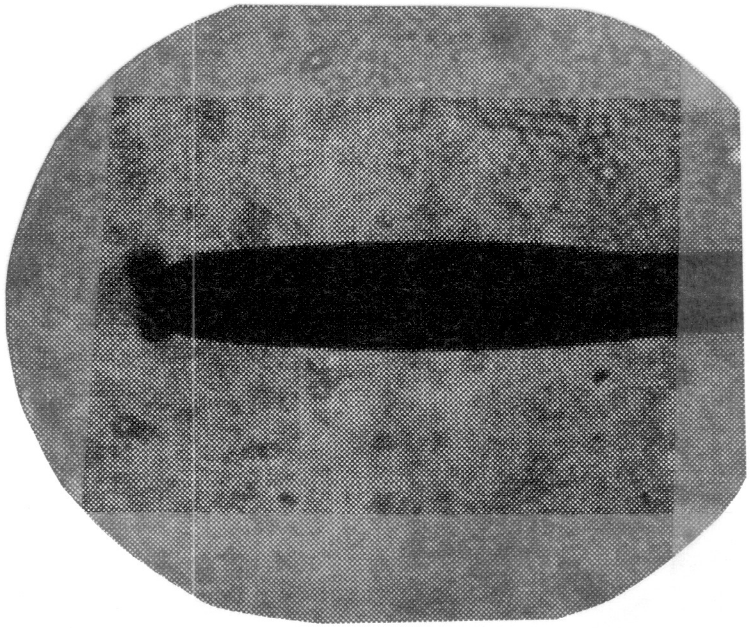

Figure 2c - Image for P_4 = 145 psig δt = 1.759 msec

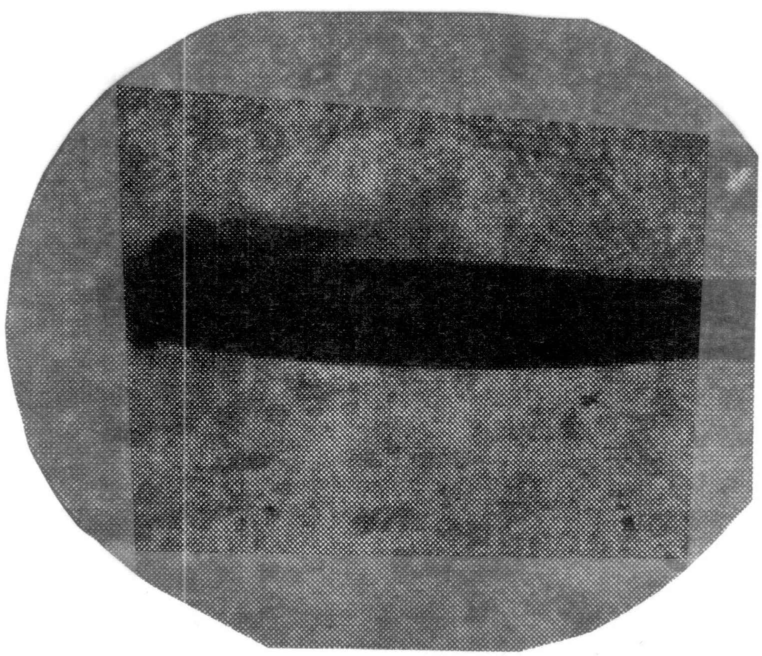

Figure 2d - Image for P_4 = 145 psig δt = 1.760 msec

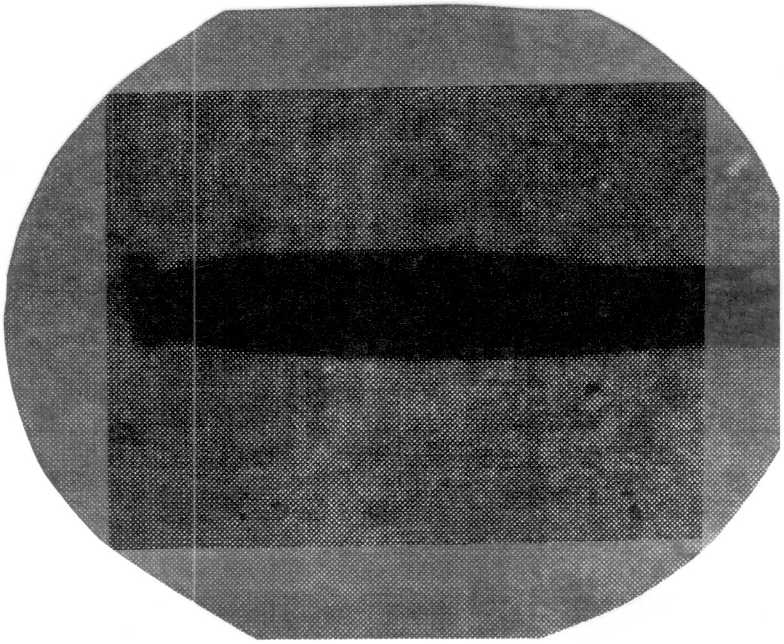

Figure 2e - Image for P_4 = 145 psig δt = 1.761 msec

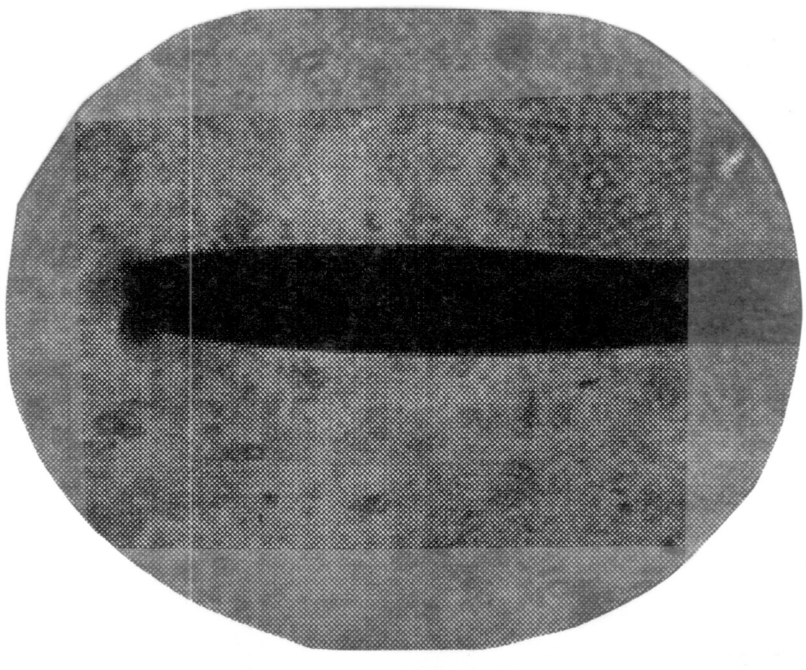

Figure 2f - Image for P_4 = 150 psig δt = 1.794 msec atmospheric conditions for these trials were recorded as 741.68 mmHg for the atmospheric pressure and 292.95 K for the atmospheric temperature.

Figure 3a shows the image corresponding to a driver pressure of 132 psig. Figure 3b shows the oscilloscope record of the changes in K1 and K2. According to theoretical calculations, the shock Mach number for the given conditions is 1.614, the speed of sound is 343.1448 m/sec, and the Mach number of the flow behind the primary shock wave is 0.7007. Based on these numbers, it takes the shock 1.101 msec to travel from K1 to K2. According to the oscilloscope measurement it took the shock 1.105 msec to cover that distance. These are in close agreement but once again we are not sure if the shock is being accelerated once it enters the cookie cutter test section. According to the theoretical calculations a time delay of 1.8004 msec is required to capture an image with the shock at mid-chord. There are lines and shadows in Figure 3a that might be the features we are looking for, but they don't stand out sufficiently to say for sure. Obviously, the shock has already passed over the airfoil but the image is not good enough for our purposes. Also, we are unsure of the dark bubble-like region at the leading edge. So, we continued to lower the driver pressure to observe what happened to this feature as the Mach number of the flow behind the shock was decreased.

Figure 4a shows the airfoil image for a driver pressure of 114 psig with the same atmospheric conditions as for the previous case. It seems the bubble becomes larger for slower moving flows, i.e. lower driver pressures. Based on theoretical calculations from shock.exe, for the given driver pressure the shock moves at Mach 1.573, the speed of sound is 343.1448 m/sec, and the flow behind the shock moves at Mach 0.6678. However, based on the oscilloscope recording shown on Figure 4b, the shock covered the distance between the transducers in 1.195 msec. Hence, experimental data shows the shock Mach number is actually 1.487. These experimental results suggest that the time delay should be 1.954 msec rather than 1.847 msec as the theoretical results suggest. Hence, according to the measured shock speed the shock should be 37.10 inches away from K1 rather than at 39.25 inches, where the mid-chord is. So, if according to experimental measurement the shock has not yet reached the airfoil, how is the image in Figure 4a possible? There are two immediately obvious explanations for this. One is that the shock is somehow accelerated when it enters the cookie cutter section hence neither the theoretical nor the experimental speed measured using the oscilloscope and transducers accurately describe the speed of the shock. The second plausible explanation is that the shock never entered the test section. As shown in Figure 4b there is some degree of reflection going on. Hence, it is possible, because of the configuration of the shock tube and how the cookie cutter test section is appended to it, that somehow the shock reflected and never entered the test section and what is observed in Figure 4a is actually the flow behind the reflected shock, which would not be transonic and hence the features we were looking for would thus never appear on the image.

Finally, figure 5a shows the image corresponding to 96 psig. The theoretical Mach number for this driver pressure is 1.523, the speed of sound is 343.1448 m/sec, and the Mach number behind the primary shock is 0.6290. The calculated theoretical time delay is 1.902 msec. Oscilloscope readings from Figure 5b indicate that the shock is moving at a Mach number of 1.493. Based on this Mach number the time delay should be 1.946 msec. At this speed, the shock should be visible in Figure 5a but there is no obvious indication that this is the case.

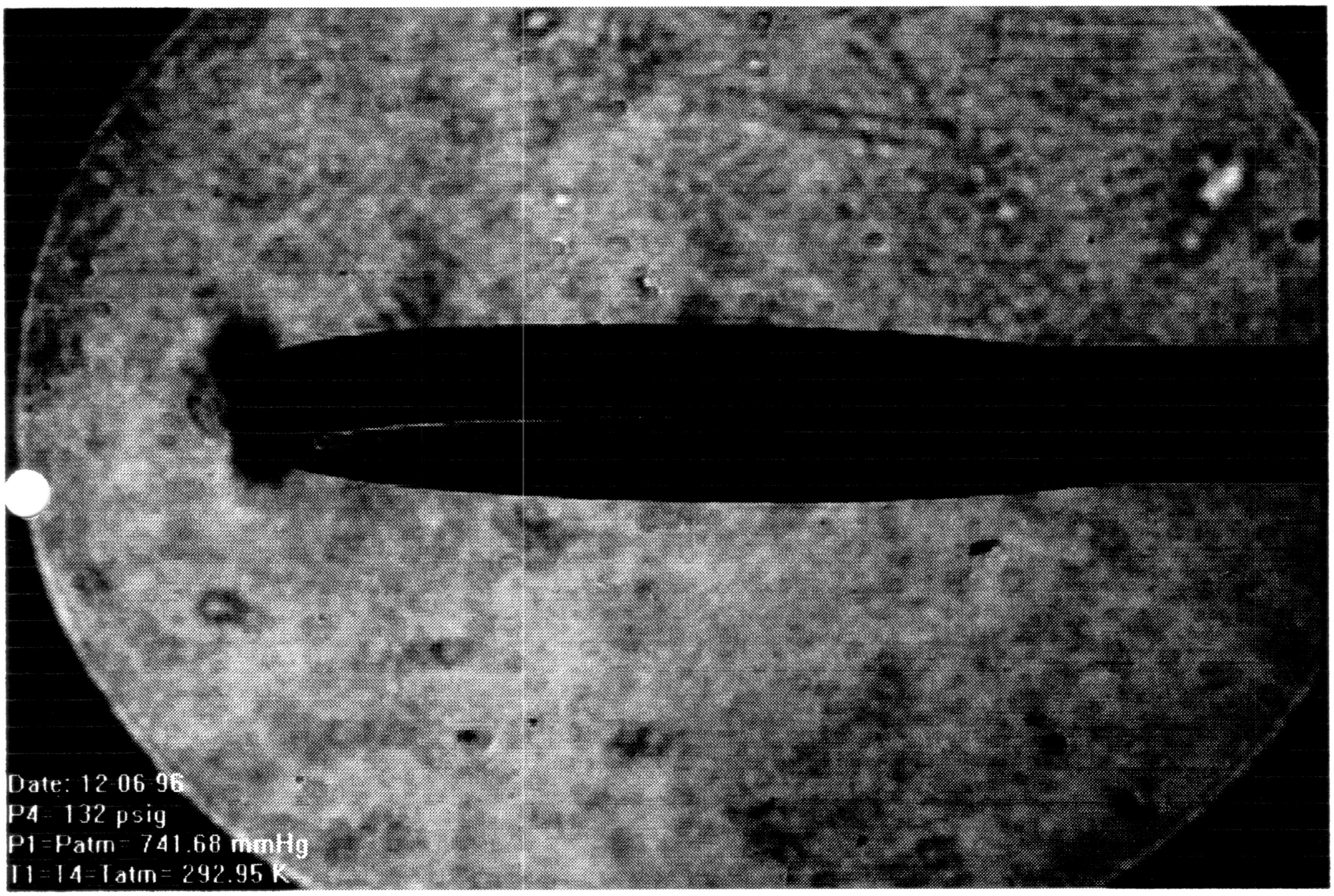

Figure 3a - Image for P_4 = 132 psig δt = 1.800 msec

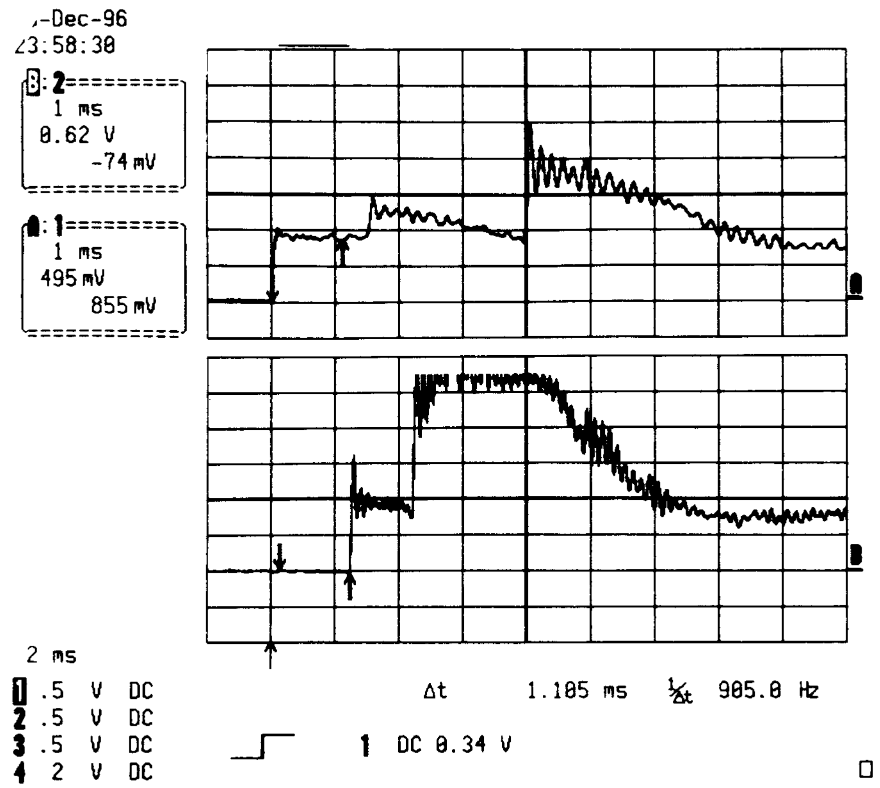

Figure 3b - Oscilloscope Record of K1 and K2 for for P_4 = 132 psig

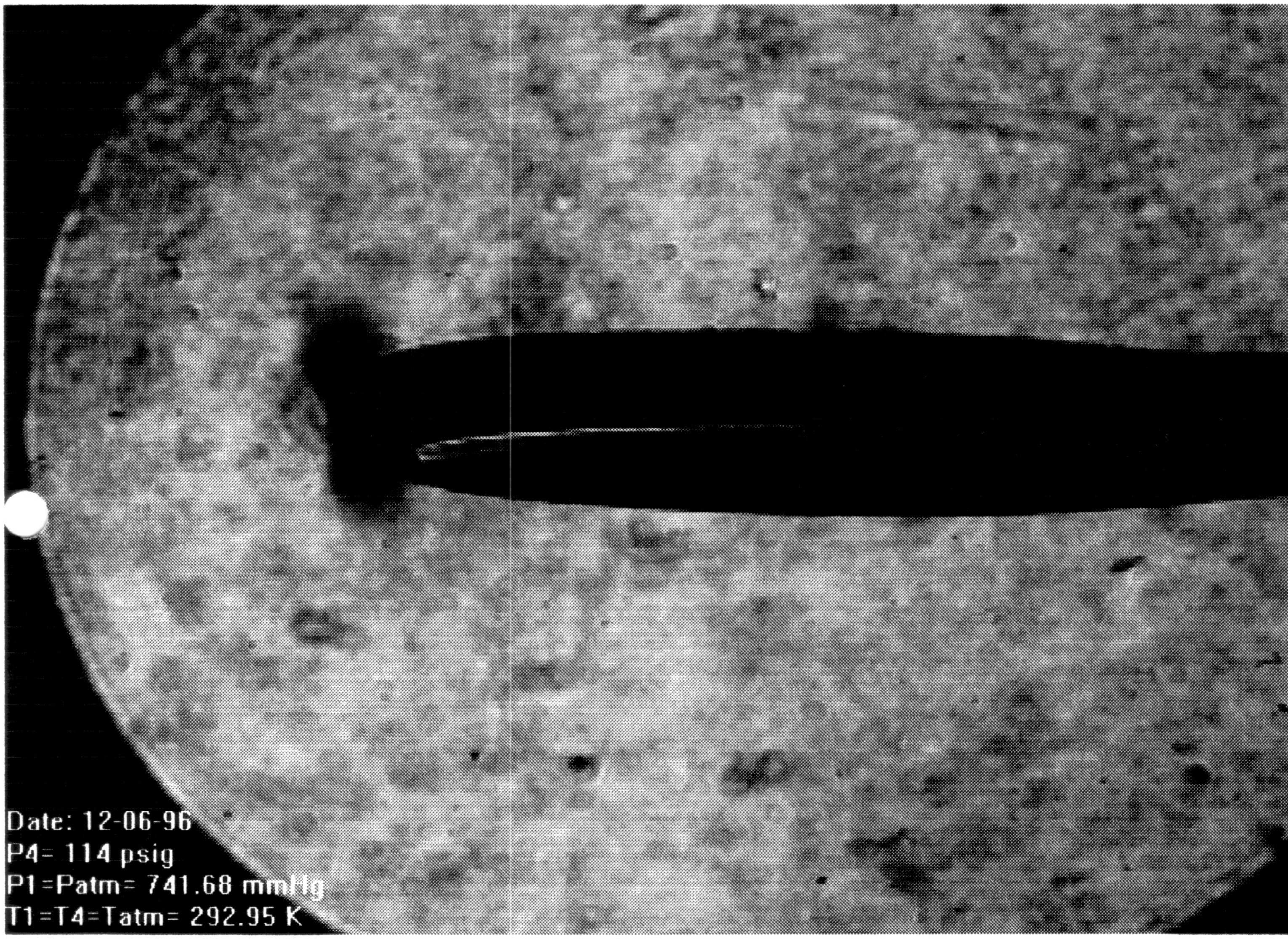

Figure 4a - Image for P_4 = 114 psig δt = 1.847 msec

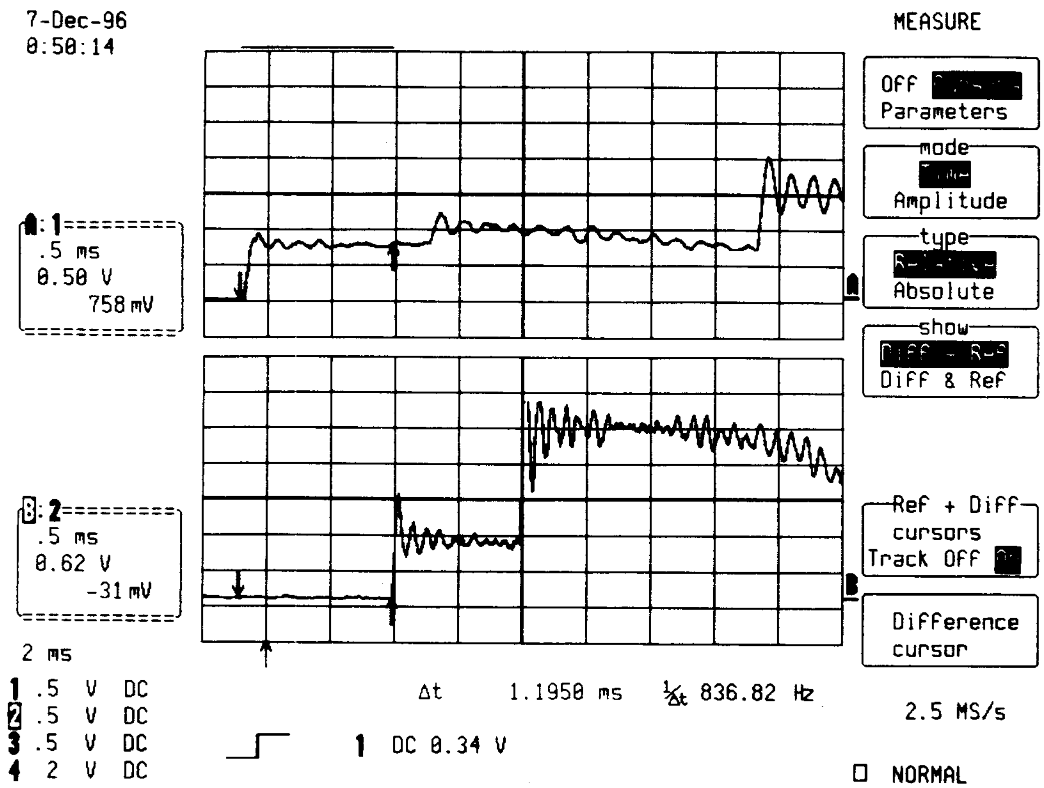

Figure 4b - Oscilloscope Record of K1 and K2 for for P_4 = 114 psig

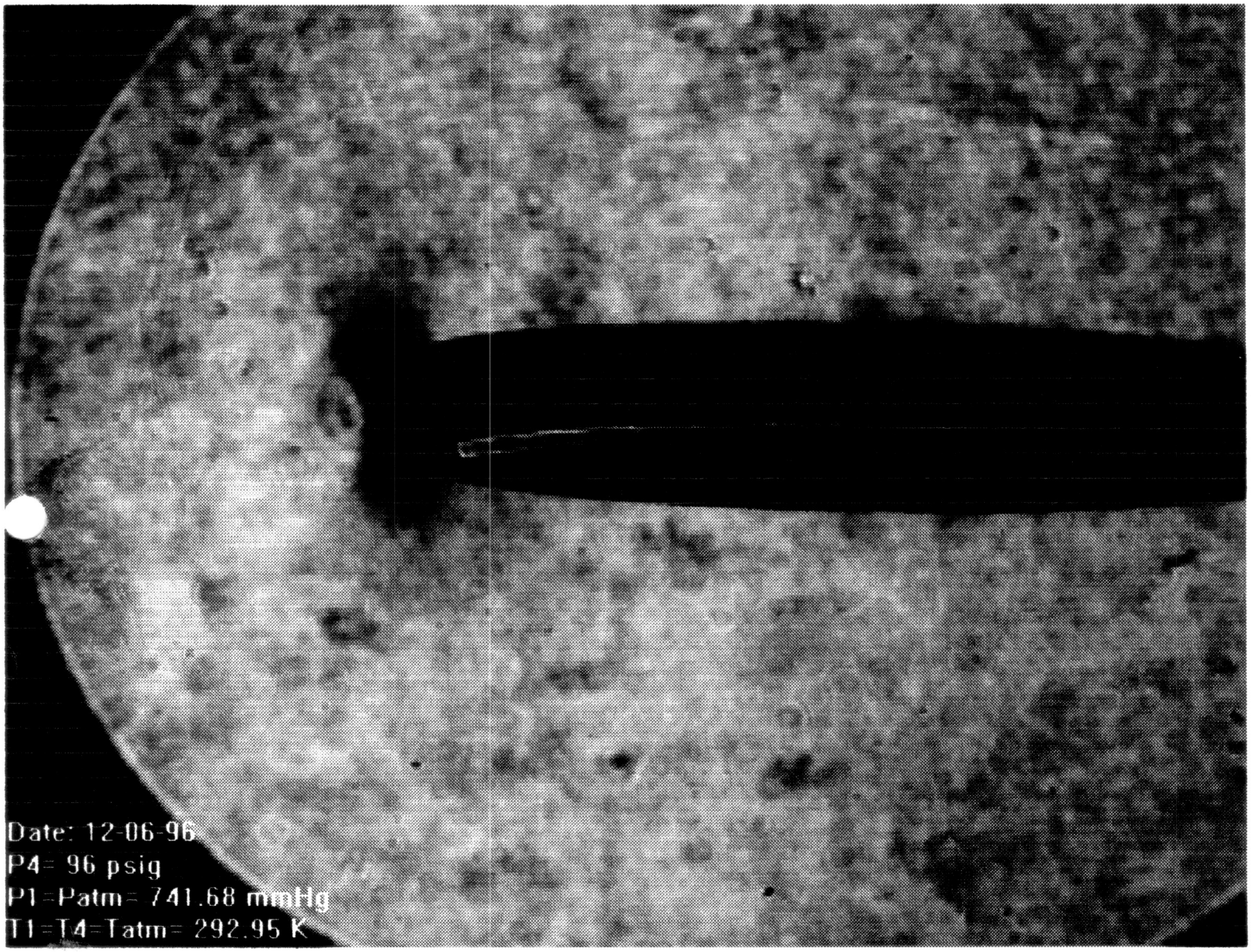

Figure 5a - Image for $P_4 = 96$ psig $\delta t = 1.902$ msec

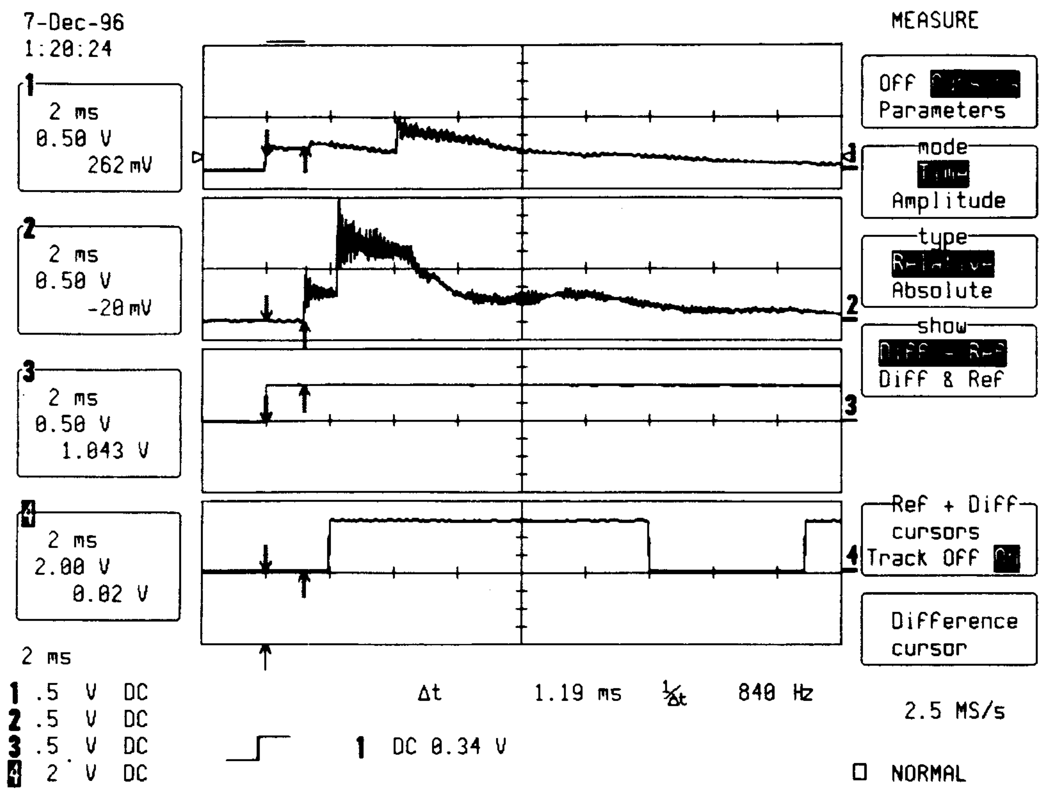

Figure 5b - Oscilloscope Record of K1 and K2 for for P_4 = 96 psig

IV. CONCLUSIONS AND RECOMMENDATIONS

The results obtained thus far are insufficient to make any final conclusions about the images seen in this report. For a driver pressure of 146 psig the images obtained seem to show some of the desired features of transonic flow. However, when lower driver pressures were attempted such that the flow behind the shock was high subsonic rather than transonic, those features were still present. Higher driver pressures than 150 psig were desired but unachievable for the equipment available. Using a series of 7 mil Mylar diaphragms at higher pressures resulted in premature bursts which is unacceptable when attempting controlled bursts. Using fewer diaphragms of larger thickness also proved inefficient because it became increasingly difficult to puncture all the diaphragms at the same time with the arrow. This often resulted in the first diaphragm being punctured all the way through but the second or third only being fractured which does not allow a controlled burst because the lasts diaphragms burst due to fatigue.

The experimentally measured shock speed was consistently less than the theoretically predicted speed. The time delays used to trigger the camera were initially based on theoretical calculations. However, the results obtained thus far seem to indicate that either:

(a) The shock is accelerated when it enters the cookie cutter section which implies smaller time delays than the theoretically calculated value must be used if attempting to photograph the shock moving over the airfoil. very likely

(b) The shock never entered the test section. Instead, at some time it reflected before reaching the test section in which case the images obtained show the low subsonic flow behind the reflected shock wave rather than the high transonic flow behind the primary shock wave. This would explain the notable absence of some of the features of transonic flow over a supercritical airfoil.

So, two unanswered questions remain; What are these images really showing? What is the source of the problem? To identify the source of the problem we attempted to use the Kulite transducer placed directly above the test specimen. However, at the time of this investigation the Kulite transducer was malfunctioning and we were unable to proceed any further.

If a properly working transducer is available, it could be used to verify whether or not the shock ever entered the test section. Another alternative would be to place two additional pressure transducers inside the cookie cutter test section to replace the use of the Kiestler transducers. The pulse generator would then be triggered using the transducers inside the test section and the shock speed inside the test section could be measured. Using all three transducer inside the cookie cutter test section one could also determine whether the shock is accelerating or not. K1 and K2 could still be used along with the three additional transducers inside the cookie cutter test section to determine this.

Also, to obtain a better defined image of transonic flow a higher target Mach number should be used, probably around 0.8. However, this Mach number would require driver pressures of over 180 psig and we were unable to get past 150 psig for controlled bursts. This is another issue that needs to be addressed. Higher driver pressures are definitely necessary, but right now they cannot be achieved through uncontrolled bursts.