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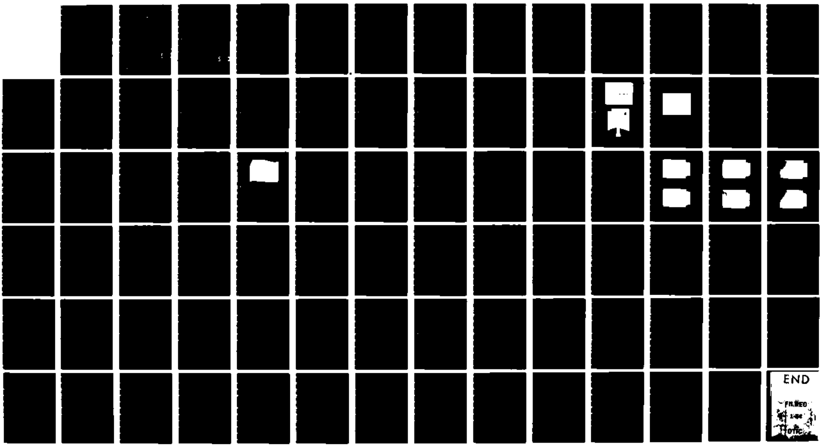

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EXPERIMENTAL INVESTIGATION OF
DYNAMIC STALL

THESIS

AFIT/GAE/AA/82D-6 Daniel C. Daley
Major USAF

DEPARTMENT OF THE AIR FORCE
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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

Daniel C. Daley
Major USAF

Graduate Aeronautical Engineering

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Daniel C. Daley

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List of Symbols

c	airfoil chord
C_l	lift coefficient
$C_{l\ max}$	maximum lift coefficient
$C_{l\ max\ dyn}$	maximum dynamic lift coefficient
$C_{l\ max\ st}$	maximum static lift coefficient
psig	pounds per square inch gauge
u_∞	freestream velocity
α_{stall}	stall angle of attack
$\alpha_{stall\ dyn}$	dynamic stall angle of attack
$\alpha_{stall\ st}$	static stall angle of attack
$\dot{\alpha}$	angle-of-attack angular rate

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Abstract

This thesis discusses an experimental investigation of dynamic stall for an NACA 0015 airfoil rotated at different constant angular rates. It describes a microcomputer-based automatic data acquisition system capable of acquiring 1000 items of data per second. When this information was used to predict stall and compared with film-data stall indications of the same test runs, there was excellent correlation between them. Results of the investigation showed a consistent correlation between the stall angle at dynamic conditions and the nondimensionalized angular rate. Experimental data was obtained for non-dimensional angular rates (defined as one half the chord times the angular rate divided by free stream velocity) in the range of .005 to .06.

EXPERIMENTAL INVESTIGATION OF DYNAMIC STALL

I Introduction

Discussion

Aerodynamicists have always been interested in ways of increasing the maximum lift of an airfoil. The momentary increase in lift due to the higher stall angle of attack encountered when an airfoil is rotating as it passes through the static-stall angle of attack has been an area of recent interest. The static-stall angle of attack is commonly defined as the angle of attack at which maximum lift occurs, (i.e., further increases in angle of attack result in reduced lift). The static-stall angle of attack is obtained by placing an airfoil at fixed angles of attack and measuring the lift. Experiments have shown that when an airfoil is rotated, the static-stall angle of attack can be exceeded and still produce increased lift. The angle at which lift begins to decrease will be delayed and will occur at a new angle referred to as the dynamic-stall angle of attack. It has been suggested that the increase in the dynamic-stall angle of attack is due to the finite time it takes for the boundary layer separation point to move to a new separation point on the airfoil (Ref 2:213). More recent explanations suggest that the delay in separation is caused by a delicate balance between the pressure gradient and the transient terms in the potential flow which impose conditions on the boundary layer which delay separation until higher angles of attack (Ref 4:1). Although investigators are beginning to explore these mechanisms, the exact cause is not really known. It is also probable that the non-Newtonian nature of the boundary of the airfoil plays a role where such is the case (Ref 4:1).

In 1932, Max Kramer was the first person to report on experiments in increases in lift obtained when an airfoil encounters a constant-angular-rate gust. The impetus for his experiment originated from pilot reports of unexplained high lift values in turbulent air (Ref 1:1). In his experiment, Kramer mounted an airfoil on a balance in the test section of a wind tunnel and then used adjustable guide vanes to create a rotating free stream (see Fig 1). It is important to note that the airfoil was fixed in Newtonian space and the free stream was rotating. Air entered the wind tunnel, was rotated by the guide vanes, and collected in the diffuser. The angle of attack varied from 0 to 30 degrees (Ref 1:2-3 and 4:1).

Kramer used three airfoils: a Gottingen 459 (a symmetrical airfoil) of two different chords and a Gottingen 398 (a cambered airfoil). The experiment demonstrated that there was an increase in $C_{l\ max}$ with a constant rate of change in angle-of-attack. Kramer introduced a non-dimensional angular rate parameter of $c\ \dot{\alpha}/u_\infty$, where c is the chord, $\dot{\alpha}$ is the angle-of-attack angular rate, and u_∞ is the freestream velocity (Ref 1:4-6).

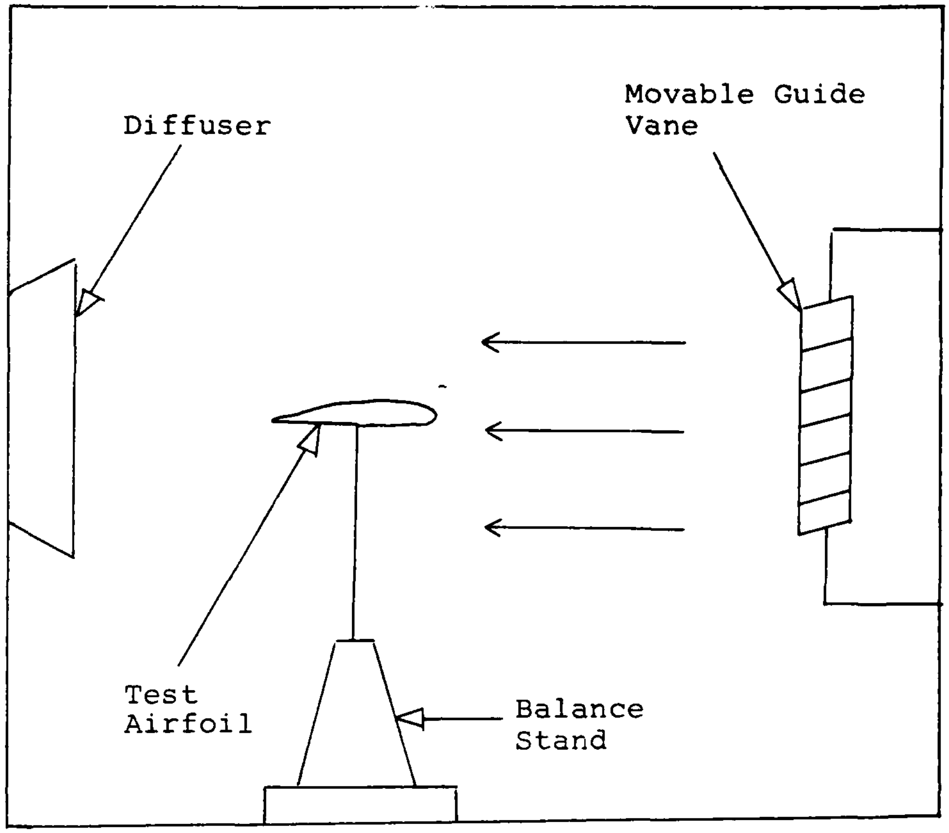

Figure 1. Schematic of Kramer Experiment
(From Ref 8)

Kramer was able to collapse his data on the following equation:

$$C_{l\ max\ dyn} = C_{l\ max\ st} + 0.36c\ \dot{\alpha}/u_\infty \qquad (1)$$

He believed that the most probable reason for increase in lift was that the flow separation did not occur immediately, but was delayed (Ref 1:6-8). Reference 4 presents a theoretical study of gust response of a symmetrical Joukowski airfoil while under the influence of a constant - $\dot{\alpha}$ gust. There was good agreement between Reference 4 and Kramer's results (Ref 4:3).

The majority of research in recent times into dynamic stall has been to investigate dynamic stall effects in helicopter rotor blades (Ref 8:2). Because of the rotor operating environment, this research has concentrated on oscillatory changes in angular rates (Ref 9). The rate of change of angular rate has been reported as the primary factor in peak lift loads during the stall process (Ref 3:49). It has been postulated as a result of angle-of-attack calculations that a rotor blade encounters angles of attack as much as 4 degrees above the static-stall angle over as much as half of every revolution without stall (Ref 3:49).

In 1979, Deekens and Kuebler reported on an investigation of dynamic stall in which the effects of constant angular rate on dynamic-stall angle of attack were considered. Unlike Kramer's experiment, in this case the airfoil rotated about the midchord in a constant velocity freestream, similar to the oscillatory experiments of reference 9 (i.e., a reference frame attached to the airfoil would be a non-Newtonian reference frame). They reported one case of the dynamic-stall angle of attack exceeding the static-stall angle of attack by 36 degrees. A conclusion of their work was that there was a direct relationship between angular rate and an inverse relationship with airspeed to the dynamic-stall angle of attack not unlike that Kramer had reported, but the extent of the effect was approximately ten times greater than that of Kramer. They stated that by using a plot of non-dimensional angular rate versus dynamic-stall angle of attack (see Fig 2) they could accurately predict the dynamic-stall angle of attack in their experimental range (Re = 1.45×10^4 to 3.25×10^4) (Ref 5:11-16).

The Deekens and Kuebler data may be adapted to $C_{l\ max\ dynamic}$ predictions in the manner similar to that in reference 4. Starting with the slope for α_{stall} from reference 4, $\alpha_{stall\ dyn}$ is given by:

$$\alpha_{stall\ dyn} = \alpha_{stall\ st} + (2.5)(1/2c\ \dot{\alpha}/u_\infty) \qquad (2)$$

If further adjusted to the conditions of the Kramer experiment taking into account finite span and the real C_l slope, equation (2) becomes:

$$C_{l\ max\ dyn} = C_{l\ max\ st} + 4.8\ \dot{\alpha}/u_\infty \qquad (3)$$

It should be noted that the slope implied by the work of reference 5 (i.e., equation (3)) is greatly different than that of the Kramer experiment and thus the theoretical work of reference 4 (i.e., equation (1)). Here the difference in experiments should be underscored. The experiments differ in the Newtonian versus non-Newtonian nature of the wing boundary. It is of course possible that the work of reference 5 is in error, although unpublished work by Francis (Ref 6) seems to be in agreement with reference 5. Reference

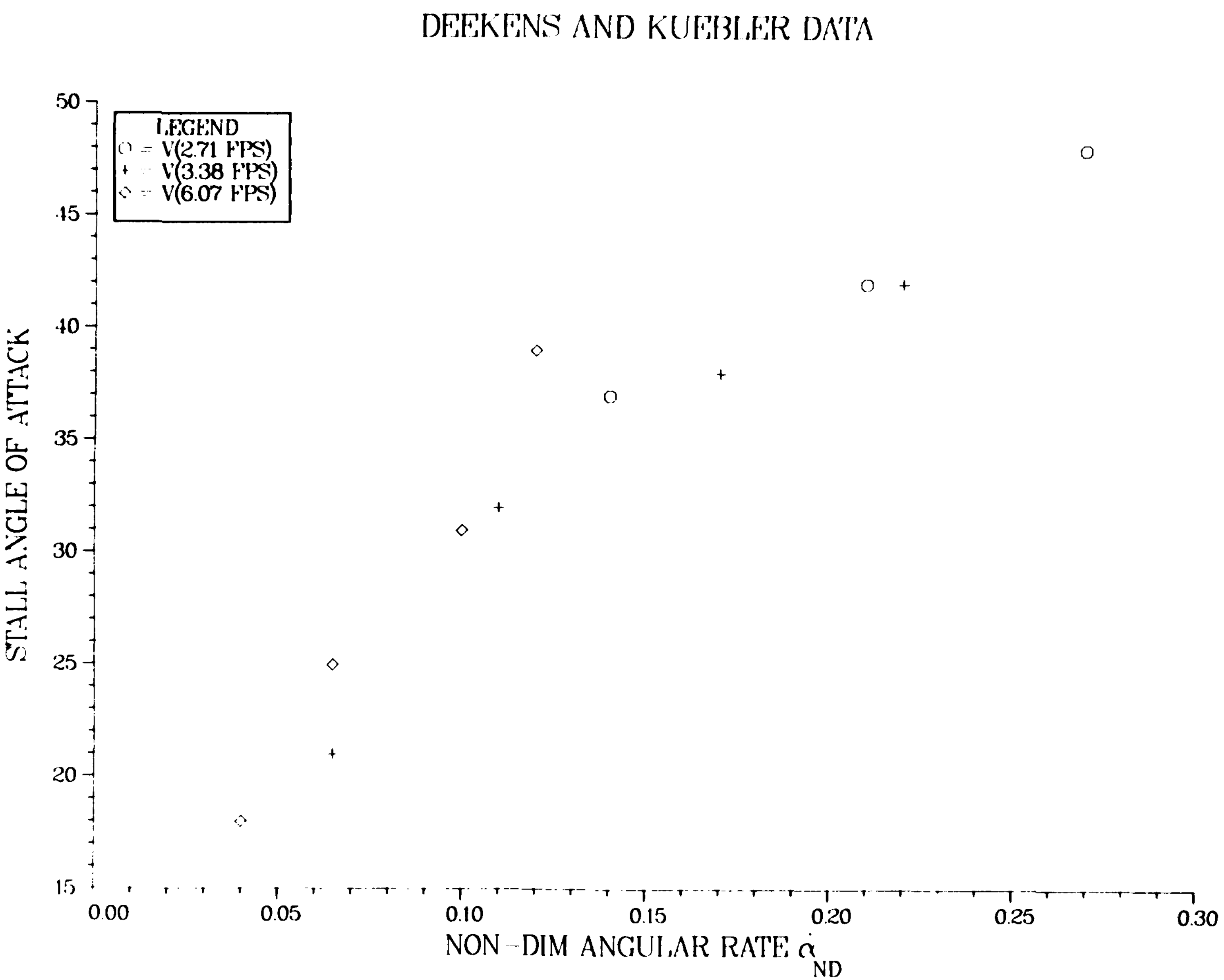

Figure 2. Deekens and Kuebler Experiment Results

5 is further supported by experiments reported by Schelbel in which the airfoil was rotated in a constant velocity free stream (Ref 7:1-4). It is also possible that Kramer's work is in error, but reference 7 mentions an experiment that supported Kramer's results fairly well, at least at the limits of the experiments (Ref 7:1). These thoughts lead to this experiment to further investigate the influence of angular rates and airspeed on dynamic stall.

Problem of Data Acquisition

The measurement of dynamic stall characteristics has been approached from three different perspectives. Kramer used a balance system to measure forces on the wing. Deekens and Kuebler used a high speed film of smoke traces to obtain dynamic-stall angle of attack and angular pitching rates. Francis took pressure measurements by installing pressure transducers in the test airfoil. The information that Francis collected was time, position, and pressure distribution for a rotating airfoil (Ref 6). To get reliable pressure distributions sufficiently detailed to obtain lift information requires on the order of 16 pressure transducers distributed around the airfoil. In addition to these, position and time must be collected. The entire event takes place in approximately half a second. Thus to obtain lift vs angle-of-attack curves of reasonably high resolution requires a capability of reliably collecting a minimum of 300 data samples per second.

Problem Statement

The purpose of my research was to verify the conclusions of Deekens and Kuebler data and expand the airspeed, non-dimensional angular rate range, and Reynolds number range of their work. To accomplish this objective, a major effort of the research was to develop a microcomputer-based automatic data acquisition system to gather time, position, and pressure information. The pressure indications of dynamic stall were to be compared with film indications of stall to see if there was a good correlation.

II Description of Apparatus

Smoke Tunnel

This experiment was conducted in the AFIT smoke tunnel located in Building 640, Area B, Wright Patterson AFB, Ohio. The test section is 4.92 feet by 3.25 feet by 2.69 inches and is enclosed in glass on each side of the smallest dimension. This smoke tunnel is further described in reference 12, which also contains a description of its capabilities.

To provide better illumination, the test section was equipped with two 40 watt fluorescent lights, one on the upper and one on the lower horizontal frame pieces. A piece of Masonite painted flat black was installed against the back glass pane to provide contrast (see Fig 3). This arrangement improved the visibility of the smoke traces and the airfoil outline. It also improved the illumination of calibration marks and information printed in white grease pencil on the front glass pane.

This lighting system gave excellent film exposure results only up to a film speed of 24 frames per second; this resulted in an exposure time of 0.04 second per frame which gave blurred smoke traces such that accurate determination of dynamic stall could not be made. To further improve smoke trace clarity, it was necessary to go to a higher film speed, at these higher speeds the fluorescent lights provided insufficient illumination. Two 3000 watt movie lights were placed

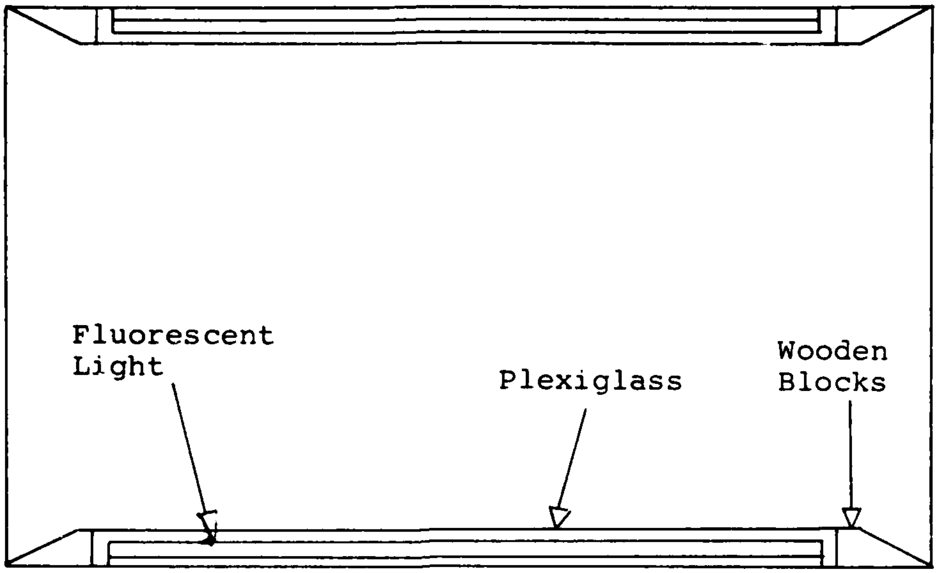

Figure 3. Lighting Modifications to Smoke Tunnel Test Section

close to the front glass pane and adjusted to eliminate most reflections. The fluorescent lights were retained and provided good illumination of the airfoil outline and printed information on the front glass pane.

In order to make the smoke more dense, the 12 uppermost and 18 lowest smoke ejectors were blocked off with duct tape. All test runs were conducted with both smoke generators operating to provide the greatest quantity of smoke. The smoke tunnel provided good filming results up to a velocity of 35 feet per second.

Airfoil

The airfoil used in this experiment was a NACA 0015 with a 1.02 foot chord and width of 2.68 inches. The airfoil was constructed of mahogany and had aluminum side plates. The inside was hollow to allow mounting of up to 16 pressure transducers (see Fig 4). The airfoil was attached at the midchord to a hollow aluminum shaft. After the transducers were installed, the endplates were sealed with modeling clay. Ambient pressure was admitted to the inside of the airfoil during testing through a notch in the shaft used to rotate the airfoil. Thus, the pressure transducers measured the pressure difference between the static pressure in the tunnel at the location of the transducer and the atmospheric pressure in the room. Since the tunnel was a drawdown type, this means that if there were absolutely no losses, the maximum pressure (stagnation pressure) would yield a zero pressure differential. All other pressures would be less than zero. The actual pressure measured would be due to the airflow over the airfoil and any losses. The output signals were preconditioned and collected by a data acquisition system (c.f. below).

The airfoil was mounted at approximately the center point of the test section because the airfoil was to be rotated. A stand was constructed to mount the rotation motor, the position measuring device, and terminal strips (see Fig 5). The angular position of the airfoil was measured by using a ten-turn Helipot #7216 1K ohm precision potentiometer through a gear that allowed approximately 100 degrees of airfoil rotation for ten turns of the potentiometer (see Fig 6). The

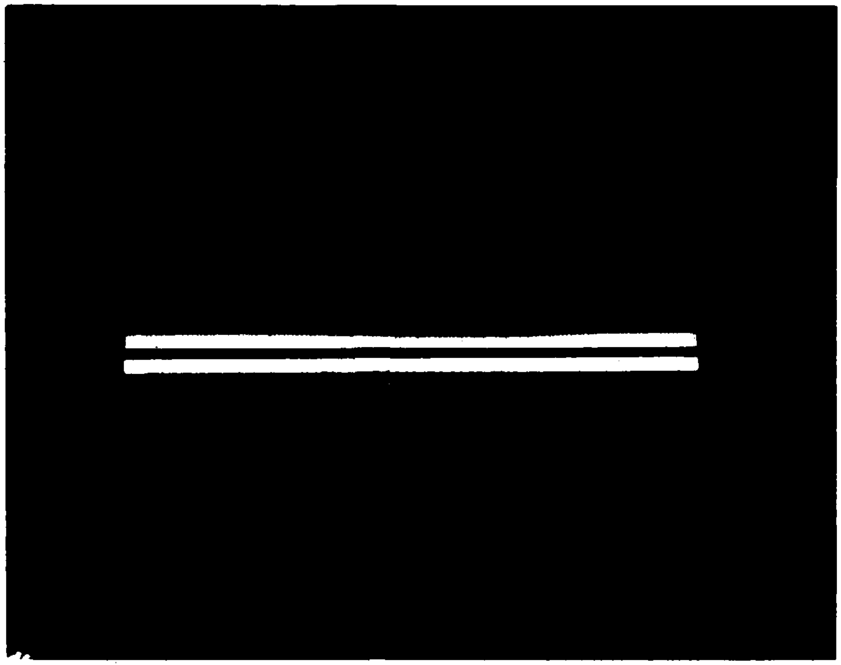

Figure 4. Airfoil With Transducers Installed

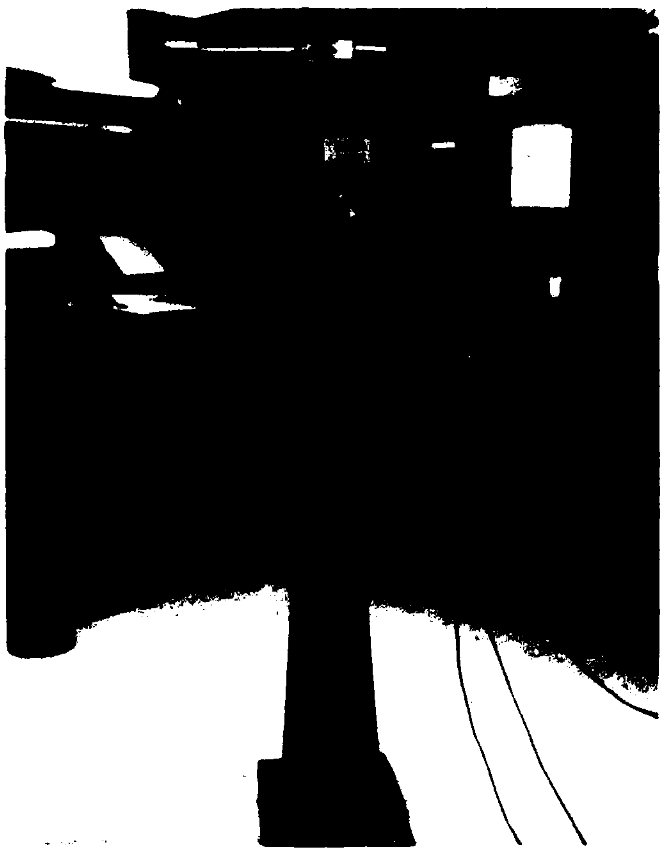

Figure 5. Support Stand With Airfoil Mounted

potentiometer was supplied with five volts DC and the position was obtained from the voltage output from the potentiometer moving arm.

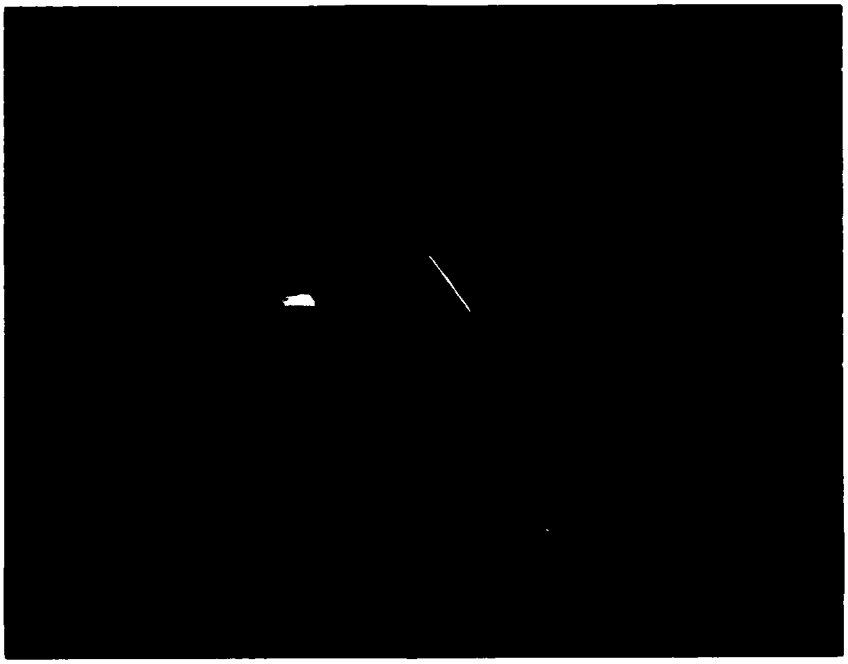

Figure 6. Gear Train and Potentiometer for Angle of Attack Determination

The motor used to rotate the airfoil was a TRW Globe Model 5A2298-4 constant-speed motor. This was a 12 volt DC high torque motor that came up to speed almost immediately. By varying the input voltage, the angular rate could be adjusted over a range of constant rates from 30 degrees per second to 90 degrees per second. The motor was turned on and off by a manual switch that allowed positive and negative rotation.

Timer

In order to compare data obtained from the data acquisition system with filmed information, there were several markings placed on the front glass pane of the wind tunnel in white grease pencil. To obtair angle of attack, a horizontal line was drawn and tick marks used to mark angles up to 90 degrees. Another horizontal line was drawn two feet long with one inch tick marks for airspeed calibration using smoke traces.

The run velocity was obtained by measuring the travel of a patch of smoke over a measured distance and dividing by the time interval obtained from the film. The velocities measured were slightly higher than indicated by the smoke tunnel airspeed vs inches of water curve. These filmed runs were used to construct a calibrated tunnel speed correction curve. This curve was then extrapolated using a curve which matched the theoretical line shape that would be expected for higher velocities. This calibrated airspeed curve was then used to correct tunnel speeds for the higher velocity runs where films were not made (see Fig 7).

A timer mechanism was necessary for the film data to get angular rates and airspeed. Initially, the timer consisted of a Fluke Model 1900A Multi-Counter that was used to count hundredths of a second. The input to the counter was a signal from a Wavetek Model 148 20MHz AM/FM/PM Generator adjusted to give an output signal of a hundredth of a second.

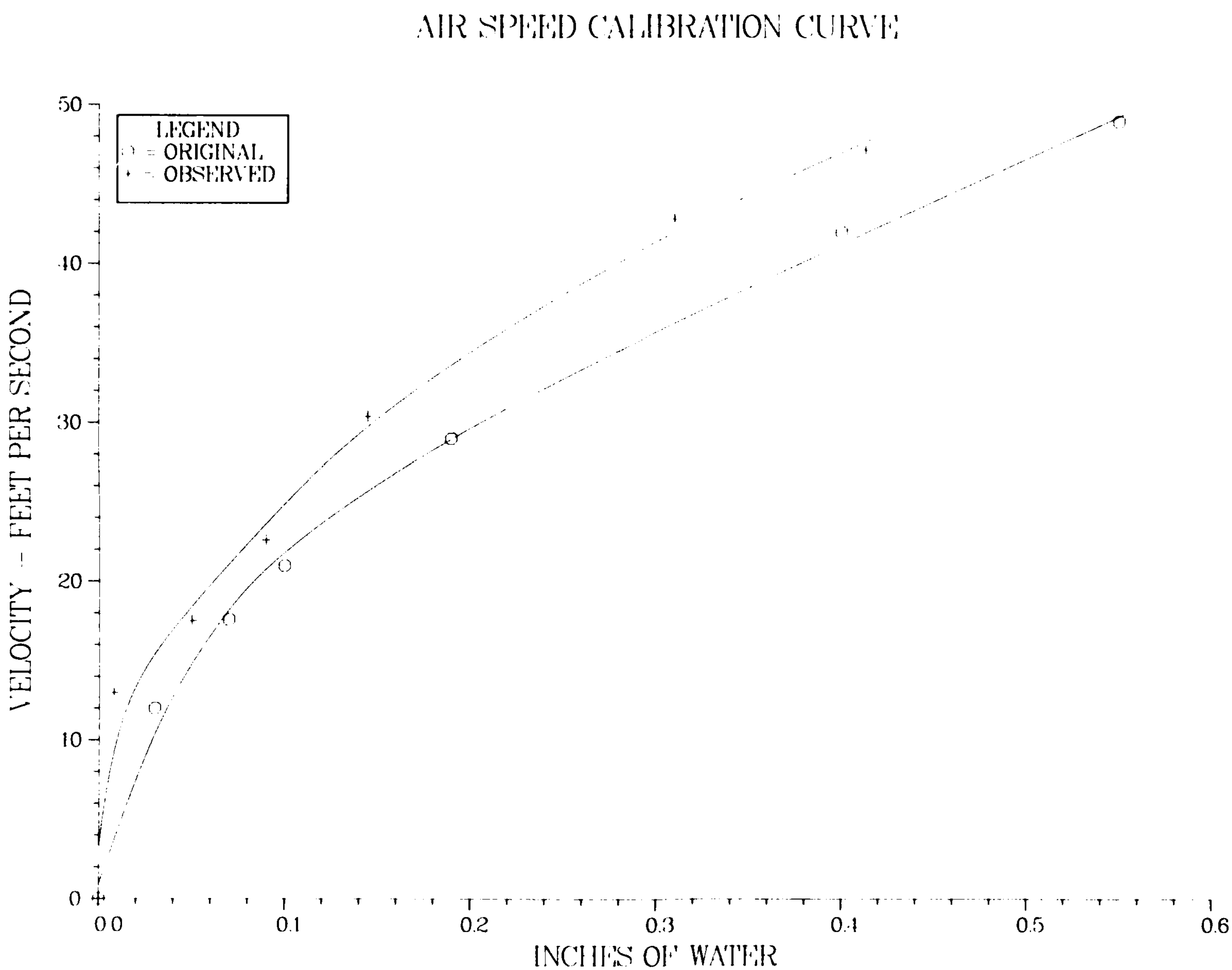

Figure 7. Smoke Tunnel Velocity Calibration

The wave generator was calibrated using a Hewlet-Packard Model 5325B Universal Counter. The Fluke counter was mounted behind the rear glass pane of the smoke tunnel and the numbers were filmed with the test run. Because of the low level of light available, the movie camera lens was adjusted to a low f stop (wide open). This resulted in a very short depth of field and the numbers of the counter were out of focus when the smoke traces and calibration markings on the front glass pane were in focus. Because of this problem, this timing mechanism was discarded in favor of an in-camera timing system that placed timing information on each frame of the film.

Filming

The first movie camera used was a Mitchell 16 high speed movie camera. This camera was used for filming up to 48 frames per second, or 0.02 sec per frame. To get a higher frame rate and take advantage of an in-camera timing system, it was decided to use a Redlake Corporation Locam II Model 51-0003 16mm high speed motion picture camera. The camera was equipped with a 25mm f2.8 lens. This camera was tried at 500 and 200 frames per second. The 200 frame per second (0.005 sec per frame) speed was used because it provided the best resolution/exposure combination. The camera also was equipped with a Visual Instrumentation Corporation Hexadecimal Model HDRS-10-5102 Data Recording System that recorded the time to 0.001 second on the side of each frame.

A Photo Optical Data Analyzer, Model LC 50444, 16mm motion picture projector was used to analyze the film data. This projector allowed frame by frame, multi-frame, and normal movie viewing of the films. The film used for all test runs was Kodak Video News Film with an ASA of 400.

Data Acquisition System

The data acquisition system was microcomputer based. The microcomputer system consisted of a Electronic Control Technology S-100 bus with a SD Systems SBU-100 Single Board Z-80 based Computer, an Expandoram II board from SD Systems, a MD 2022 Tarabell Disk Controller board, and an AIM-12 Analog to Digital board from Dual Systems Control Corporation; a Tarabell Model VDS-IID dual eight inch floppy disc drive; and a Heathkit H-19 terminal. The Digital Research CP/M operating system, version 2.2, was used along with Microsoft Fortran, version 3.4, and Wordmaster editor, version 1.6.

The AIM-12 board was advertised as having an instrumentation amplifier gain of 100 capability, but because of problems which have not yet been determined to have been procedure or hardware based, it was not possible to calibrate the board at this gain setting. Conversations with the board designer at Dual Systems Control Corporation revealed that others had reported similar problems when using the AIM-12 in the gain of 100 mode; although, apparently some users had been successful. Because we were not able to use the AIM-12 board in the gain of 100 mode and because of the small signal strength of the transducers, external amplifiers were used. The amplifiers of an Electronic Associates, Inc TR-48 Analog/ Hybrid Computer were used. These amplifiers provided a gain of 100 but there was a loss of signal strength of 14% in the amplification process.

Initially, sixteen transducers were used with this board, but due to amplifier problems and transducer problems, this number was reduced to four. The final configuration of the board was in a gain of 1, plus or minus five volts DC range, and in the single ended mode. The AIM-12 was used to convert analog signals from the position potentiometer and the four transducers. The analog to digital conversion time was 25 microseconds.

A timer capability was provided by the internal Z-80 counter timer circuit of the SBC-100 Single Board Computer. The microcomputer was programmed to count counter timer clicks that were 0.0010046 seconds apart. The difference in clicks was then converted to seconds.

Transducers

The transducers used in the experiment were Endevco 8507-2 and 8506-2 miniature piezoresistive pressure transducers. Both transducers required a 10 volt DC power supply and had a pressure range of plus or minus 2 psig. The only difference between the two was that the 8506-2 had a threaded case. The transducers were installed on the top portion of the NACA 0015 airfoil in the following positions:

#1 0.688 in. from the leading edge

#2 1.813 in. from the leading edge

#3 2.625 in. from the leading edge

#4 4.188 in. from the leading edge

Several transducers were tested to verify that they were operating properly. To test the operation of the transducers, a test rig shown in Fig 8 was used. The test chamber was pressurized with a small Air Jammer Road Rammer hand operated air pump. Then the test chamber was closed off and the manometer reading was compared with the value obtained from the transducer, after proper conversion to indicate pressure. The four transducers selected for the test runs gave readings accurate to within 0.4%, 1.2%, 1.5%, and 4.0% respectively of the reading indicated by the manometer.

The power supply for the transducers were Burlington Battery Corporation Model BA-230/U multi voltage batteries, used in the 10.5 volt DC setting. Initially, DC power supplies were used to power the transducers. When the power supplies were used, erroneous signals were generated, probably due to the common ground on the power supply and the common ground on the instrumentation amplifiers rendering three legs of the internal bridge in the transducers impotent. Individual batteries were then used to eliminate this problem by

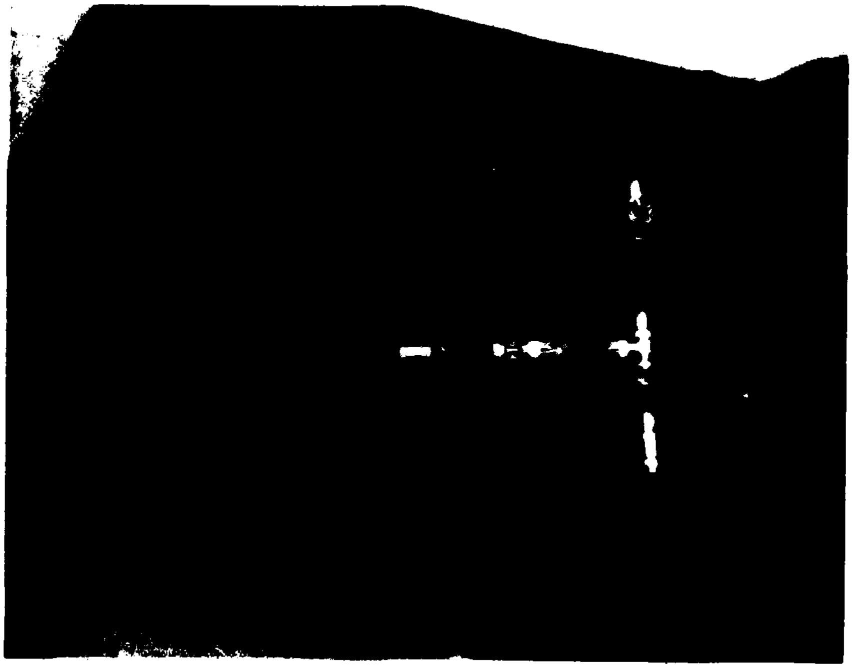

Figure 8. Transducer Pressure Test Rig

providing independent 10 volts DC sources to each transducer. The operation of the batteries was very stable. During a three hour run, the voltage dropped from 10.6 volts to 10.3 volts.

The wiring setup for power distribution and signal distribution consisted of four-wire cables. The wires were wound and shielded to prevent signal interference. The power rack distributed DC power to the rotation motor and the position potentiometer. The output of the position potentiometer was input directly into channel 0 of the AIM-12 board. As mentioned previously, the transducers were powered by independent DC batteries. The outputs of the transducers were fed into the analog computer amplifiers and from there into channels 1 to 4 of the AIM-12 board (See Fig 9). All connections for input and output wires were made at a pinned terminal strip on the drive motor stand. Quick disconnect connectors were used to ease maintenance.

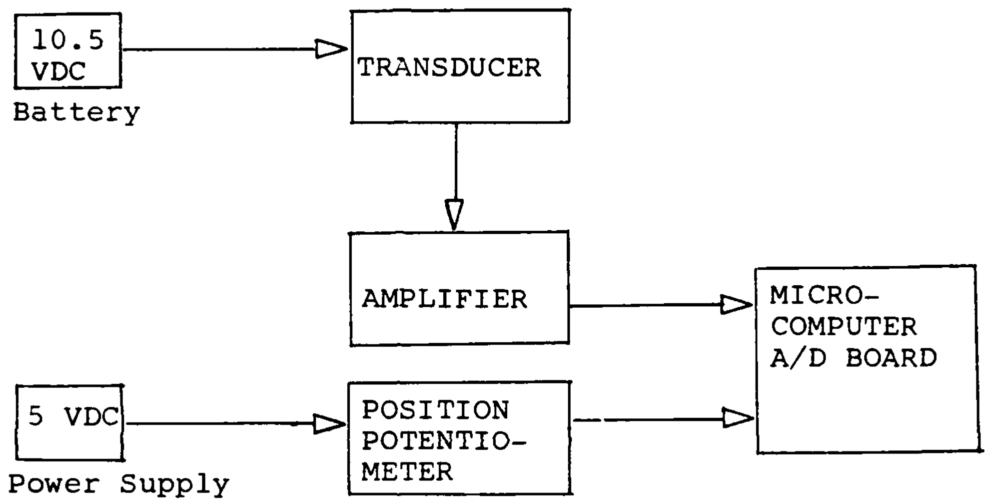

Figure 9. Schematic of Electrical Signal Processing

Several other pieces of laboratory equipment were also used throughout the research effort. These items are listed in Table 1.

TABLE 1

Miscellaneous Test Equipment

Nomenclature	Use
1. Soltec TR-6141 Programmable DC Voltage/Current Generator	Calibration and testing of AIM-12 board
2. Power Mate Corp Regulated Supply Model BPA 10C	Motor power up to 10 VDC
3. Hewlett-Packard 3466A Digital Multimeter	General testing and monitoring of motor voltage
4. Hewlett-Packard 6205B Dual DC Power Supply	Supply 5 VDC to the position potentiometer
5. Hewlett-Packard 6205C Dual Power Supply	Supply 12 VDC to the motor

III Procedure

Calibration

To calibrate the position potentiometer, a level line was drawn on the front glass pane of the smoke tunnel test section. Then a protractor was used to mark angles from 10 to 40 degrees in five degree increments and thereafter in 10 degree increments. The power supplies for the position potentiometer and rotation motor were turned on. The airfoil was rotated to the 0 degree position and the voltage value program was used to obtain the voltage reading of the position potentiometer. The voltage reading of the 90 degree position was obtained in a similar manner. The voltage values of these two positions were recorded on the floppy disc for use by other programs.

The initial values program was used to check various positions of the airfoil and check for agreement between the angle value from the microcomputer and the angle indicated by the marks on the front glass pane of the smoke tunnel. If there was good agreement between the two values, the angle calibration procedure was complete.

Data Gathering

When the smoke traces appeared, the smoke tunnel motors were adjusted for the desired airspeed. Then the airfoil was adjusted to obtain the static stall angle-of-attack. This condition was filmed and the initial values program was used to obtain the static stall angle-of-attack. Again, the angles indicated from the microcomputer and the angle markings on the front glass pane were checked for good agreement.

If the two angles were close together (within 0.5 degrees), the airfoil was initialized to zero angle-of-attack and the initial values program was used to obtain the zero angle-of-attack pressure readings. Five values for each transducer were obtained and the averages were recorded on the disc for use by other programs. The zero angle-of-attack readings were later subtracted from the pressure readings obtained while the airfoil was rotating to obtain a pressure difference.

After determining the static characteristics of the airfoil, test runs were made while the airfoil was rotating. The run number, velocity, and motor voltage were printed on the smoke tunnel front glass pane. The same information was input into the data gathering program. When everything was ready the camera was turned on. After a slight delay to allow the camera to come up to speed, the airfoil was rotated from approximately -5 degrees to +90 degrees. Following the test run the data files for the particular run were given a distinctive name and the airfoil was set up for the next run and the motor voltage was adjusted, if required.

Data for sixty such runs were obtained following this procedure. Five different airflow velocities were used. At each velocity, four different motor voltages were used: 6, 8, 10, and 12 volts. Three runs at each motor voltage were conducted. It was possible to store data information from 15 runs per floppy disc. Sixteen additional runs were obtained at higher velocities where the smoke was not dense enough to be filmed. Data from these runs were collected in a similar manner with the exception of filming.

Velocities and Reynolds Numbers

The velocities for the test runs ranged from 12.3 fps to 47.2 fps. These velocities corresponded to a Reynolds number range of from 7.83×10^4 to 3.01×10^5, based on the chord length. Thus, all test runs were in a Reynolds number regime usually considered to be laminar flow.

IV Data Reduction and Discussion of Results

Preliminary Data

Following the test runs, the data acquisition system information was reduced using the preliminary reduction program to obtain a readout of time, position, angular rates, nondimensional angular rates, and pressure readings. After the films were developed, they were viewed and compared with the preliminary reduction program outputs.

It was postulated that the indication of stall from the data acquisition system preliminary data would be indicated by a buildup of negative pressure followed by a sharp drop off to lesser (negative) pressure. Transducer #4 was assumed to be the best indicator of stall. After reviewing the printouts of preliminary data, an angle and time of dynamic stall were obtained for comparison with data from the film.

For this investigation, the dynamic-stall angle of attack was defined as occurring when the airflow was no longer attached at the quarter chord. Figures 10 through 15 show the smoke trace pattern from a test run film. Figure 13 shows the position of the dynamic-stall angle of attack.

When the information from the film and data acquisition system was compared, it was apparent that the dynamic-stall angle of attack was best indicated by maximum negative pressure at transducer #3. This was confirmed by several test runs, so transducer #3 was used as the dynamic-stall angle-

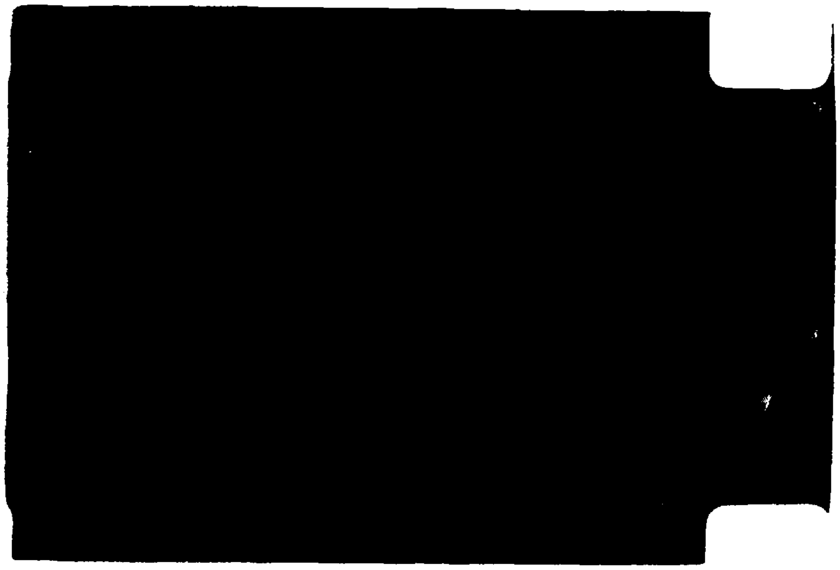

Figure 10. Film Excerpt, $\alpha = 0^{o}$

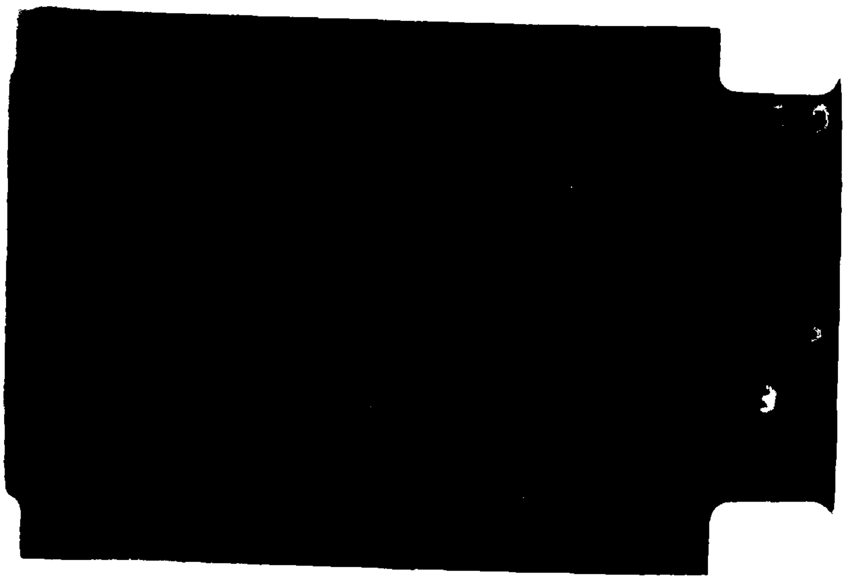

Figure 11. Film Excerpt, $\alpha = 10^{o}$

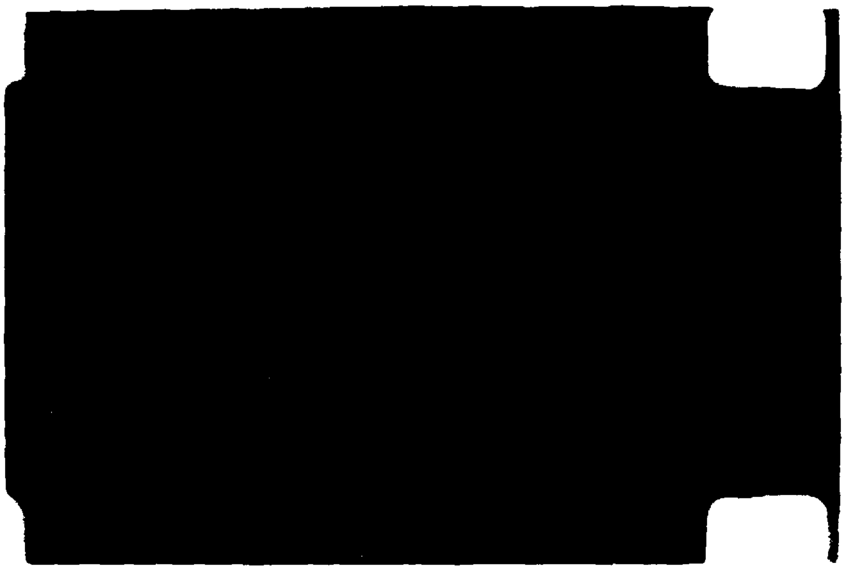

Figure 12. Film Excerpt, $\alpha = 15^{\circ}$

Figure 13. Film Excerpt, $\alpha = 20^{\circ}$, Dynamic Stall

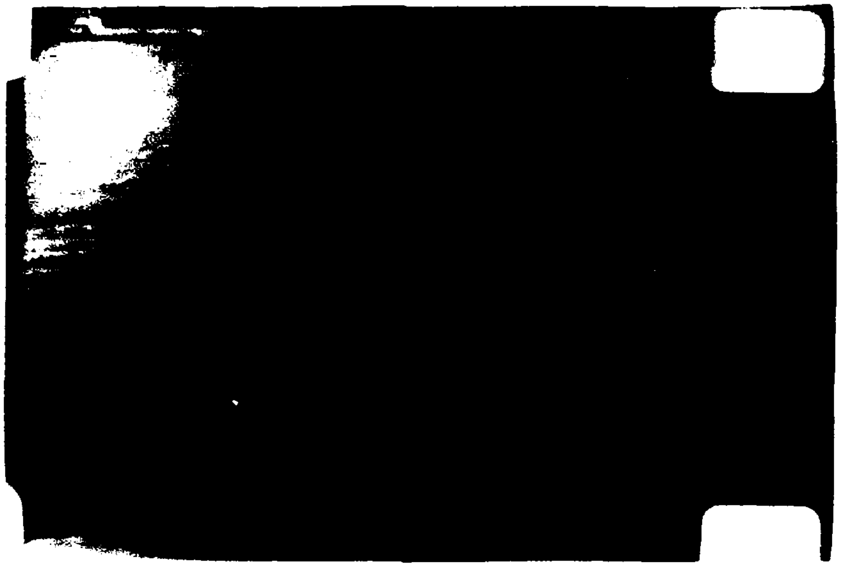

Figure 14. Film Excerpt, $\alpha = 25^{\circ}$

Figure 15. Film Excerpt, $\alpha = 30^{\circ}$

of-attack indicator in this investigation.

This introduced a problem in that the maximum negative pressure occurred at the highest angle of attack at transducer #4 and then at slightly lower angles of attack at transducers #3 and #2. It was assumed that the pressure build-up would be in the reverse order. This was clarified by further viewing of the film. It was observed that the vortex generated during flow separation momentarily formed a stagnation point near the location of transducer #4 and this could have caused the pressure anomolies at this location. To obtain a better indication of the pressure distribution, the normalized pressure program was used to obtain a listing of pressure readings divided by the highest pressure reading observed. Figure 16 shows the general trend of the observed normalized pressure distribution of transducers 2 and 3 and it is apparent that the negative pressure built up to a maximum and then dropped off abruptly.

Film and Data Acquisition System Data Comparison

After the point of dynamic-stall angle of attack was established for the data-acquisition-system data, the next data reduction effort was to compare the information from the film and the data acquisition system to verify the operation of the data acquisition system. Information that was compared was run velocity, angular rates, and dynamic-stall angle of attack. The comparison reduction program was used

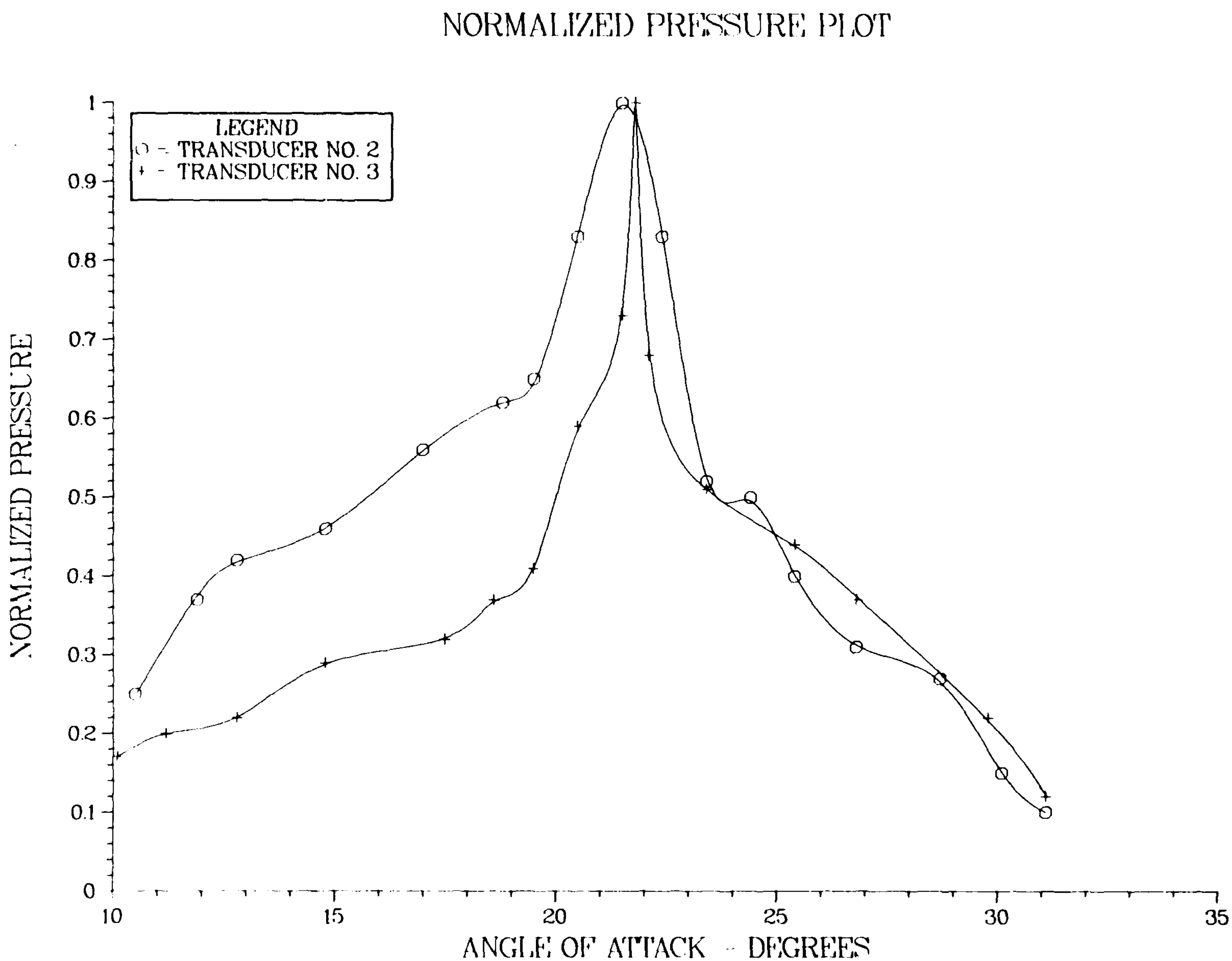

Figure 16. Normalized Pressure Distribution

for this procedure (see Appendix).

The angular velocities were calculated from the film by observing the time between 10° to 40° angle of attack. The angular velocities from the data acquisition system were calculated by taking the time interval between the closest position to 10° and 40°. There was excellent agreement in all comparisons of angular velocities.

The final comparison was between the film and data acquisition system dynamic-stall angle of attack. The accuracy of the data for angle of attack obtained from the film was estimated to be plus or minus one degree and all readings were taken in whole degrees. The accuracy of the angle-of-attack data from the data acquisition system was much higher because the position was obtained by voltage readings taken at a rate of 300 readings per second. The comparison between these two systems for angle of attack was excellent. Table 2 is a listing of the results from the data acquisition system and the film analysis. Graphs of dynamic-stall angle of attack vs non-dimensional angular rate for each group of velocities are shown in Figure 17 through Figure 21. These graphs were constructed based on average velocity for the five different airflow velocities sets; the average non-dimensional rate obtained from the film data and data acquisition system for each set of three runs at the same rotation motor voltage; and the average dynamic-stall angle of attack obtained from the film data and data acquisition system for each set of

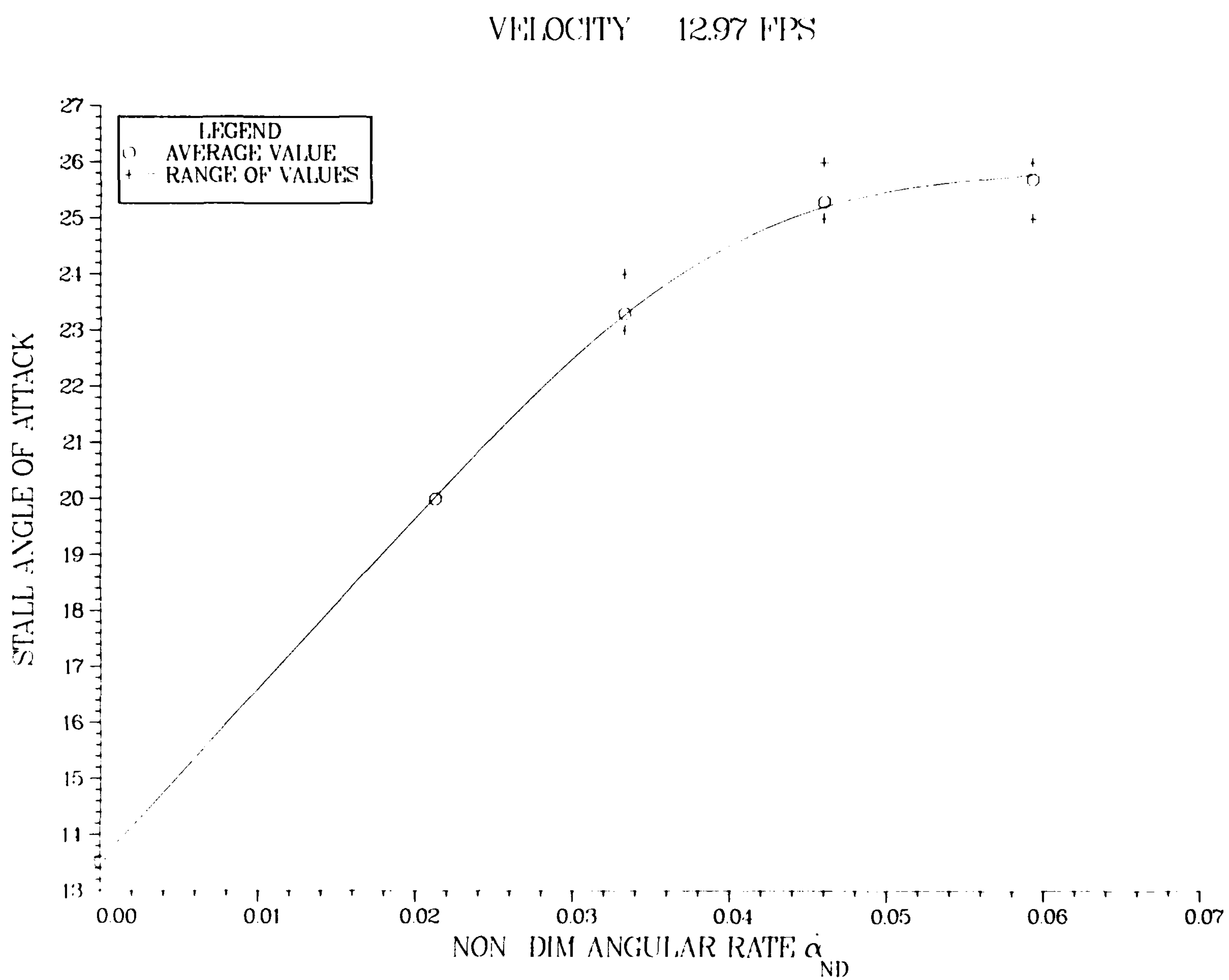

Figure 17. Data Summary, V = 12.97 FPS

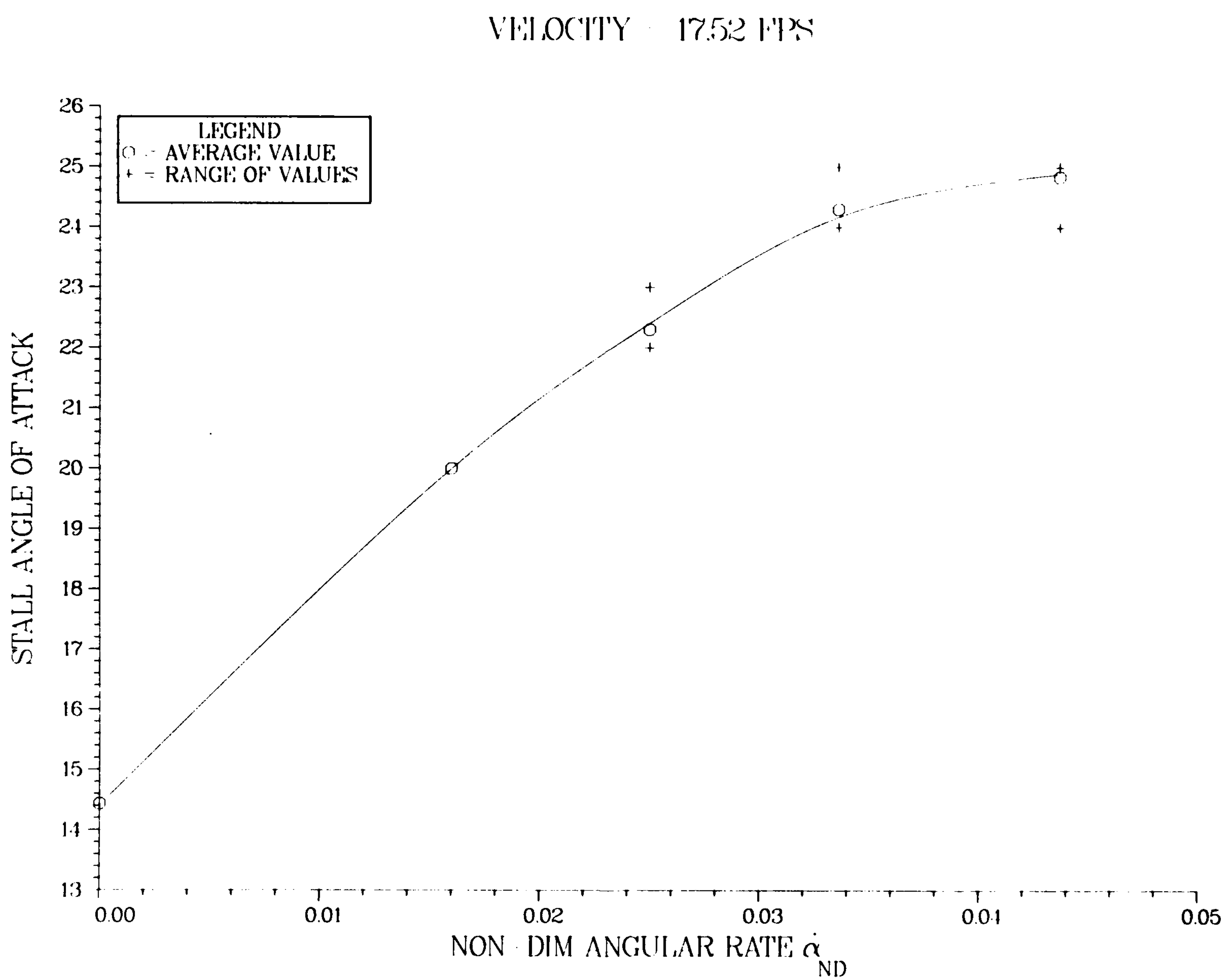

Figure 18. Data Summary, V = 17.52 FPS

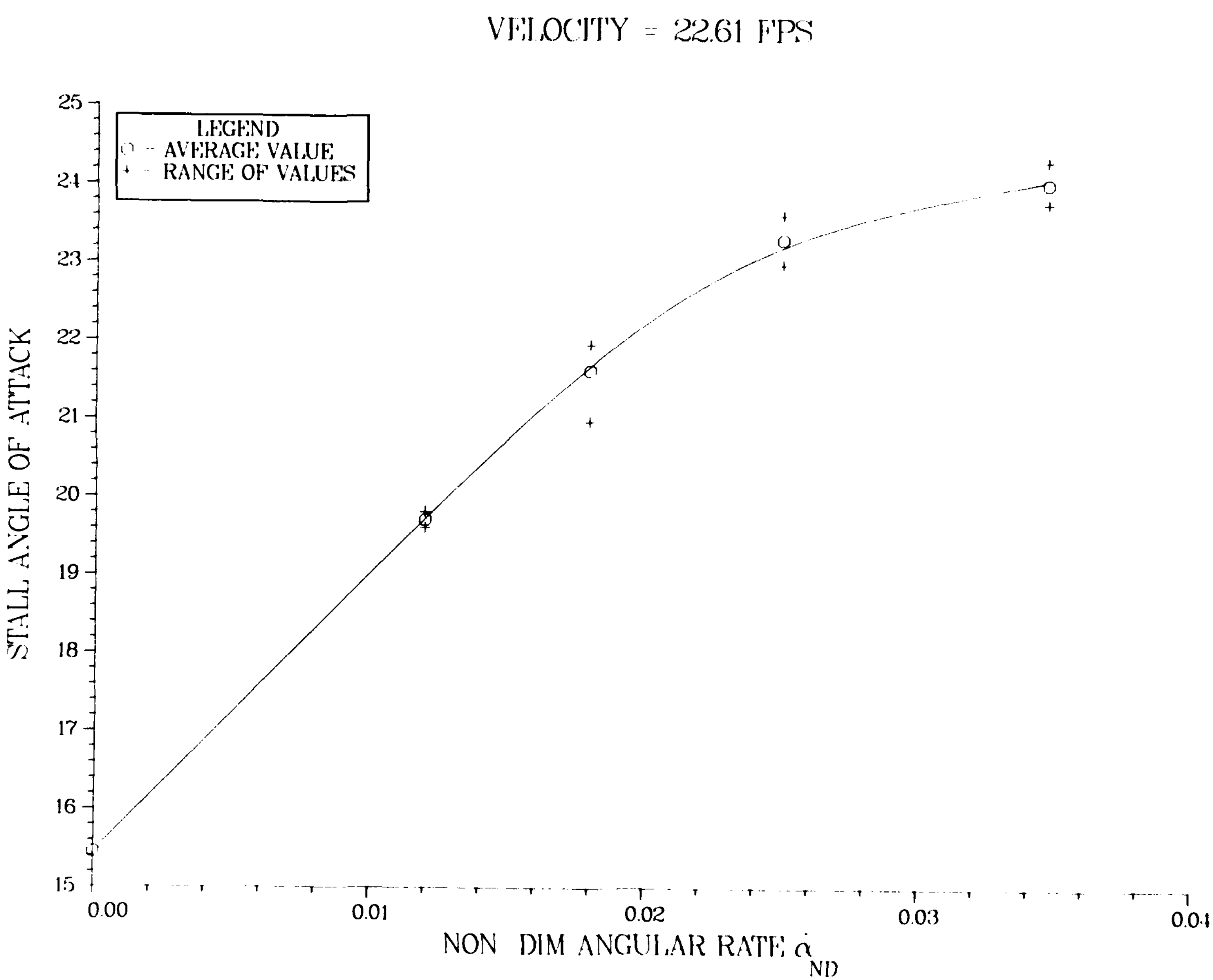

Figure 19. Data Summary, V = 22.61 FPS

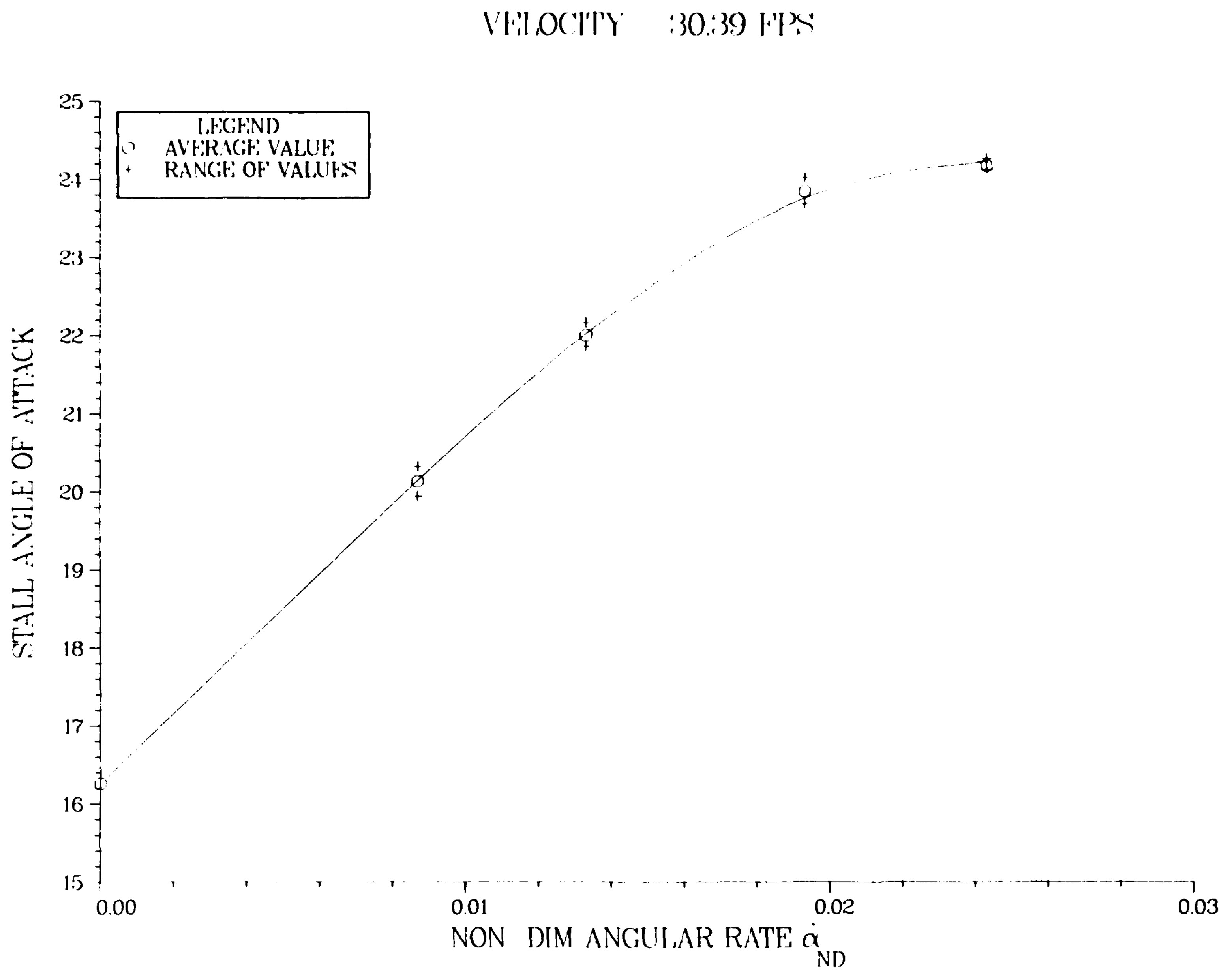

Figure 20. Data Summary, V = 30.39 FPS

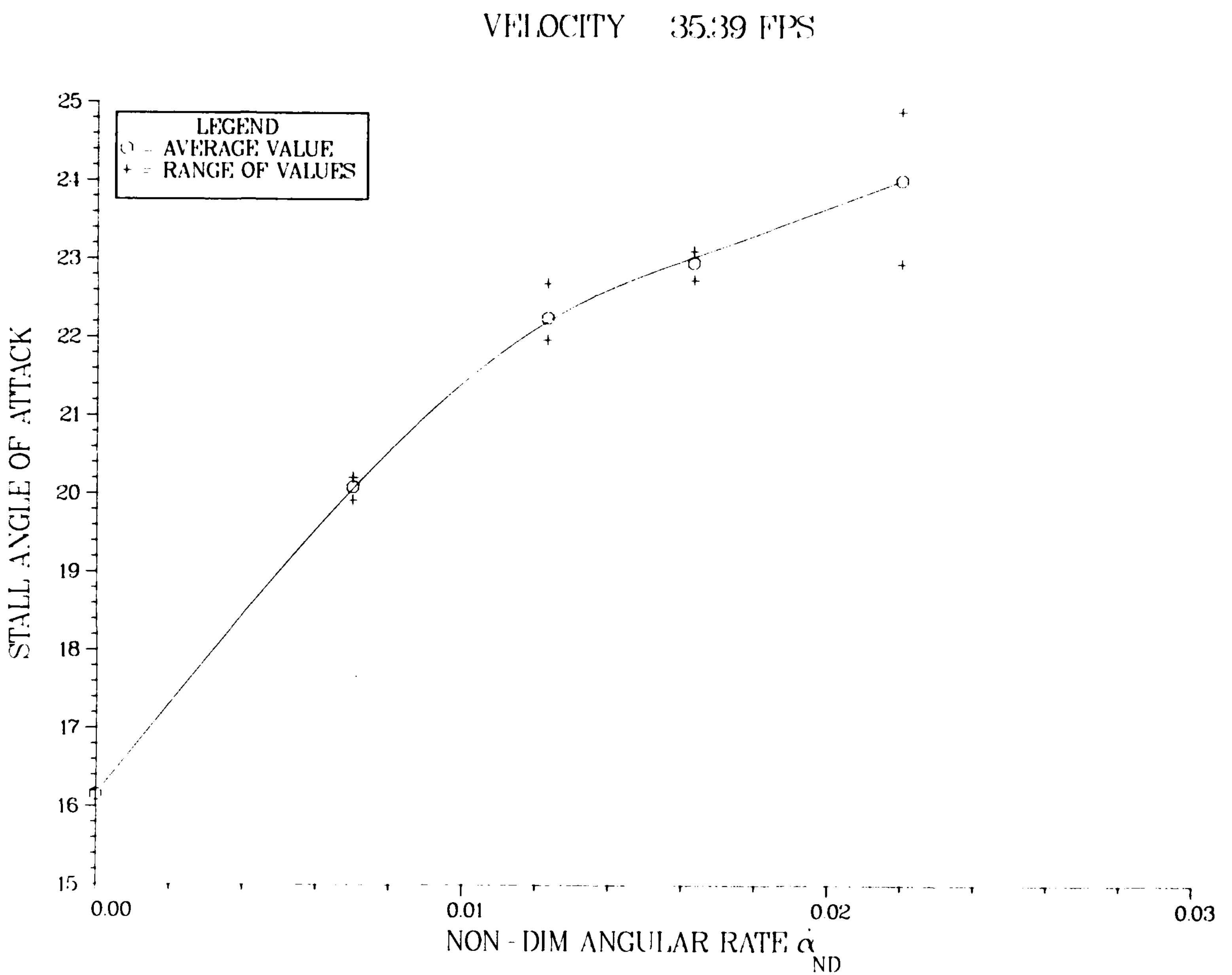

Figure 21. Data Summary, V = 35.39 FPS

TABLE II

Film and Data Acquisition System Data Summary

RUN	VEL	ND RATE (FILM)	ND RATE (DAS)	ALPHA STALL (STATIC)	ALPHA STALL (DYNAMIC-FILM)	ALPHA STALL (DYNAMIC-DAS)
1	12.3	0.022	0.022	13.51	20	N/A
2	12.4	0.022	0.022	13.51	20	N/A
3	13.0	0.021	0.020	13.51	20	N/A
4	12.8	N/A	N/A	13.51	23	N/A
5	12.8	0.034	0.034	13.51	24	N/A
6	12.9	0.033	0.033	13.51	23	N/A
7	13.2	0.047	0.045	13.51	25	N/A
8	12.8	0.046	0.046	13.51	26	N/A
9	13.3	0.047	0.047	13.51	25	N/A
10	13.3	0.060	0.060	13.51	25	N/A
11	13.6	0.057	0.057	13.51	26	N/A
12	13.2	0.061	0.060	13.51	26	N/A
13	17.6	0.016	0.016	14.43	20	N/A
14	17.6	0.016	0.016	14.43	20	N/A
15	17.2	0.016	0.016	14.43	20	N/A
16	17.4	0.025	0.025	14.43	22	N/A
17	17.2	0.025	0.025	14.43	23	N/A
18	17.6	0.025	0.024	14.43	22	N/A
19	N/A	N/A	0.034	14.43	25	N/A
20	17.6	0.033	0.033	14.43	24	N/A
21	17.6	0.034	0.033	14.43	24	N/A
22	18.0	0.044	0.043	14.43	24	23.99
23	17.6	0.043	0.043	14.43	25	25.39
24	17.2	0.044	0.044	14.43	25	25.66
25	23.1	0.012	0.012	15.45	20	19.61
26	23.1	0.013	0.012	15.45	20	19.23
27	22.6	N/A	0.012	15.45	20	18.90
28	22.6	N/A	0.019	15.45	22	21.90
29	22.6	N/A	0.019	15.45	22	21.90
30	22.7	0.019	0.018	15.45	22	19.94
31	23.1	0.025	0.025	15.45	23	22.96
32	23.1	N/A	0.025	15.45	22	21.77
33	23.1	0.025	0.025	15.45	24	23.23
34	23.1	0.033	0.033	15.45	24	24.64
35	20.8	0.036	0.036	15.45	24	23.99
36	21.9	0.035	0.035	15.45	24	23.56

TABLE II (Continued)

RUN	VEL	ND RATE (FILM)	ND RATE (DAS)	ALPHA STALL (STATIC)	ALPHA STALL (DYNAMIC-FILM)	ALPHA STALL (DYNAMIC-DAS)
37	29.8	0.009	0.009	16.26	20	19.88
38	29.8	0.008	0.009	16.26	20	20.26
39	30.5	0.008	0.008	16.26	20	20.64
40	30.5	0.014	0.014	16.26	22	22.31
41	30.5	0.013	0.013	16.26	22	21.94
42	30.5	0.013	0.013	16.26	22	21.72
43	30.5	0.019	0.019	16.26	24	23.39
44	30.5	0.019	0.019	16.26	24	23.66
45	29.1	0.020	0.020	16.26	24	24.04
46	30.5	0.025	0.025	16.26	24	24.26
47	31.2	0.024	0.024	16.26	24	24.26
48	31.3	0.025	0.024	16.26	24	24.53
49	36.8	0.007	0.007	16.15	20	20.42
50	36.8	0.007	0.007	16.15	20	20.26
51	35.7	0.007	0.007	16.15	20	19.83
52	36.8	0.012	0.012	16.15	22	22.15
53	34.7	0.012	0.012	16.15	23	22.37
54	33.8	0.013	0.012	16.15	22	21.94
55	35.7	0.016	0.016	16.15	23	22.48
56	35.7	0.016	0.017	16.15	23	23.23
57	35.7	0.017	0.017	16.15	23	23.07
58	34.7	0.022	0.022	16.15	24	24.42
59	34.7	0.022	0.022	16.15	25	24.80
60	34.7	0.022	0.022	16.15	23	22.91

DAS = Data Acquisition System

N/A = Not Available (timer malfunction or pressure too small to measure)

TABLE III

Data Acquisition System Data Summary

RUN	VEL	ND RATE (DAS)	ALPHA STALL (STATIC)	ALPHA STALL (DYNAMIC-DAS)
61	42.8	0.006	17.8	20.78
62	42.8	0.006	17.8	21.01
63	42.8	0.009	17.8	21.92
64	42.8	0.009	17.8	21.92
65	42.8	0.013	17.8	22.84
66	42.8	0.013	17.8	23.70
67	42.8	0.017	17.8	24.02
68	42.8	0.017	17.8	23.97
69	47.2	.005	17.8	21.87
70	47.2	.005	17.8	22.14
71	47.2	.008	17.8	22.35
72	47.2	.008	17.8	22.67
73	47.2	.011	17.8	23.05
74	47.2	.011	17.8	24.40
75	47.2	.015	17.8	25.80
76	47.2	.015	17.8	25.90

DAS = Data Acquisition System

three runs at the same rotation motor voltage. The range of the dynamic-stall angle of attack has also been indicated.

Data for the two highest velocities, 42.8 fps and 47.2 fps, were obtained only from the data acquisition system. The data obtained from these runs are listed in Table 3. Graphs of dynamic-stall angle of attack vs non-dimensional angular rate for these velocities are shown in Figure 22 and Figure 23. The irregular shape of Figure 23 might have been caused by the airfoil being pinched between the smoke tunnel glass panes at higher airspeeds. It should also be remembered that the Reynolds number for this test run was approximately 300,000. Thus, the irregular shape may be due to transition from laminar to turbulent flow. Reference 13 reported Reynolds number effects below Reynolds numbers of 200,000, while 500,000 is the usually considered the low Reynolds number regime (Ref 13:1). All of the data from both the film and the data acquisition system are shown in Figure 24 as a plot of the difference between dynamic-stall angle of attack and the static-stall angle of attack vs the non-dimensional angular rate.

Tables 2 and 3 show that there is excellent agreement between the film data and the data acquisition system in the determination of non-dimensional angular rates. The agreement in dynamic-stall angle of attack between the two data ranges from almost exact to within one degree. Figure 24 also includes data from the Deekens and Kuebler experiment.

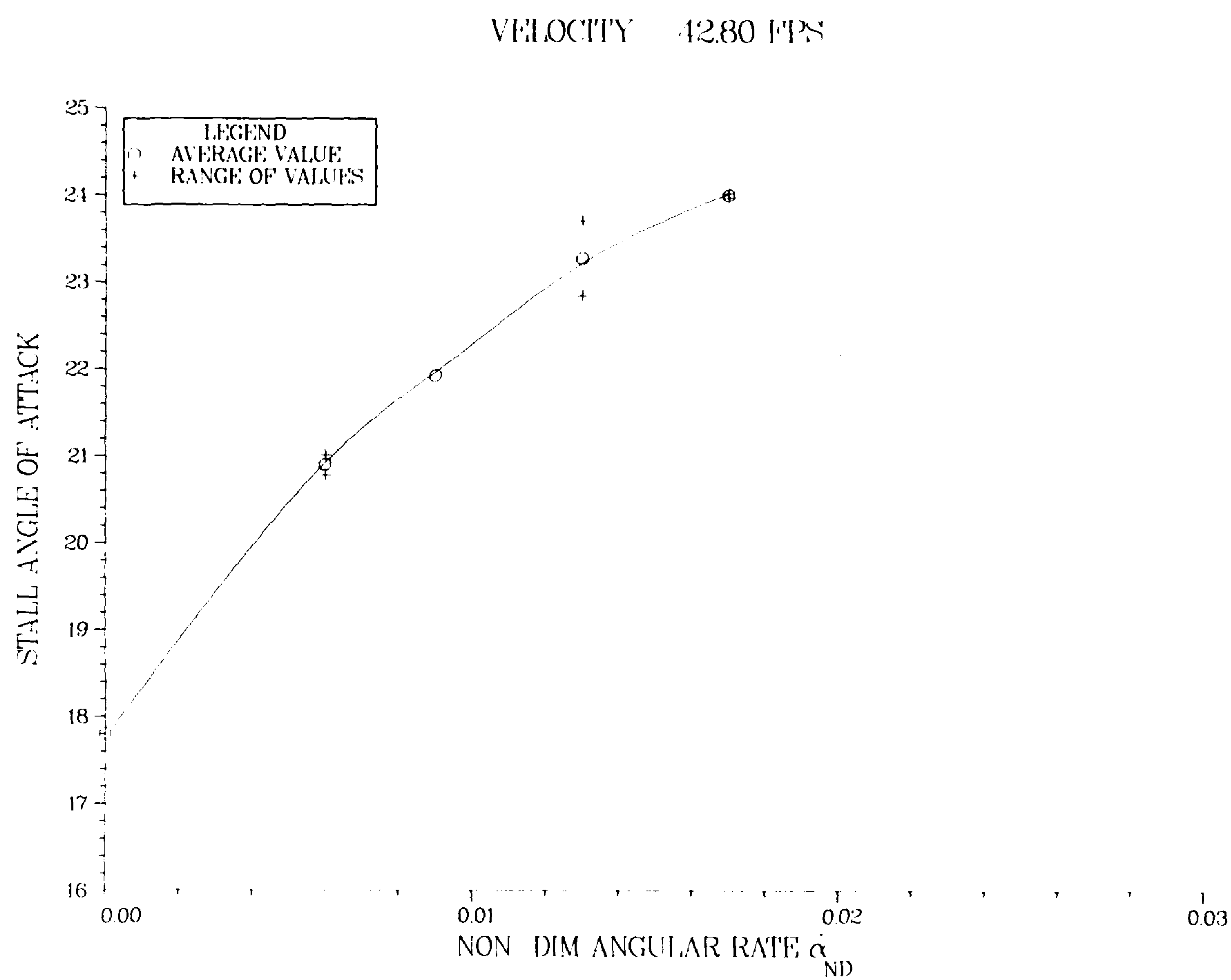

Figure 22. Data Summary, V = 42.8 FPS

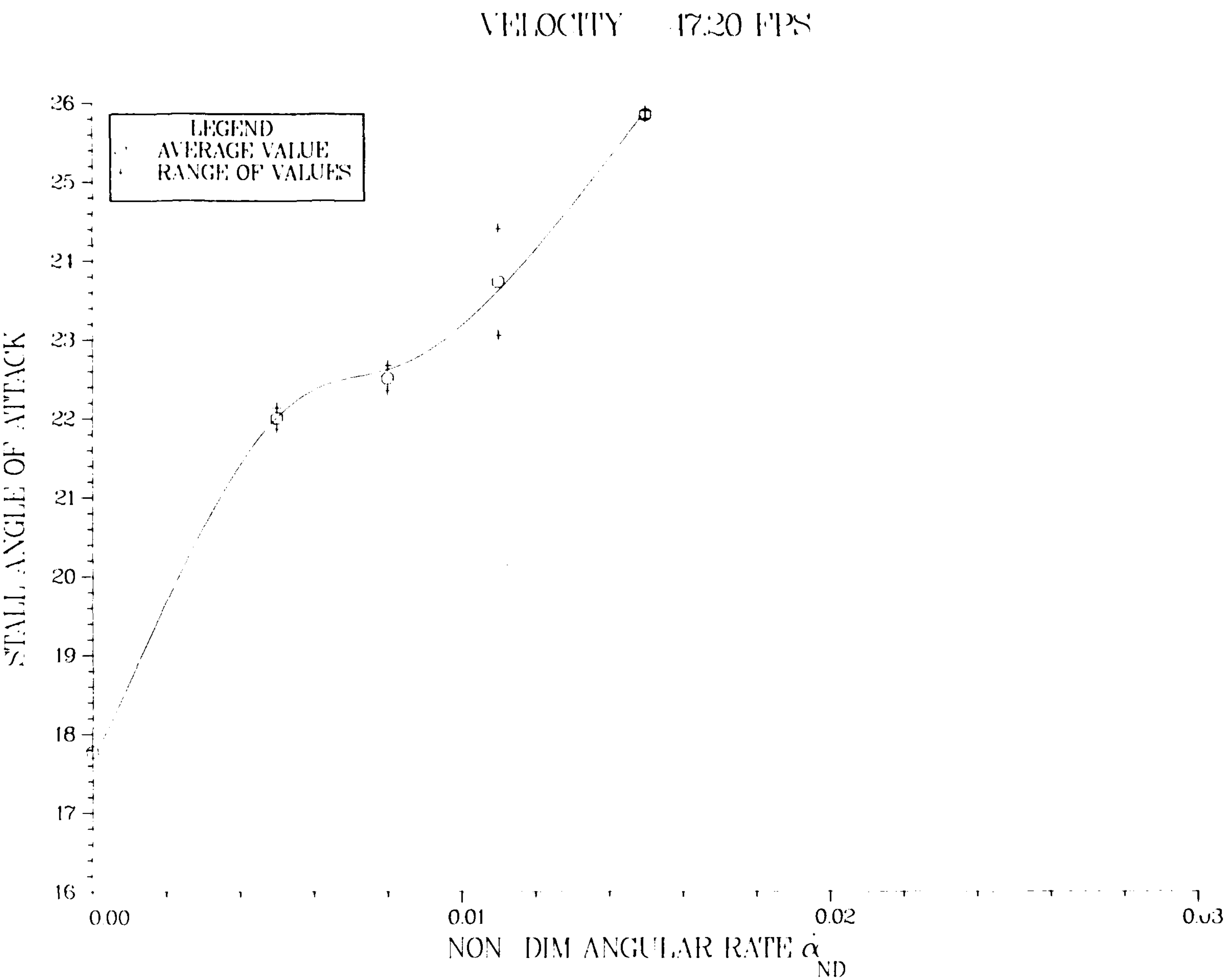

Figure 23. Data Summary, V = 47.20 FPS

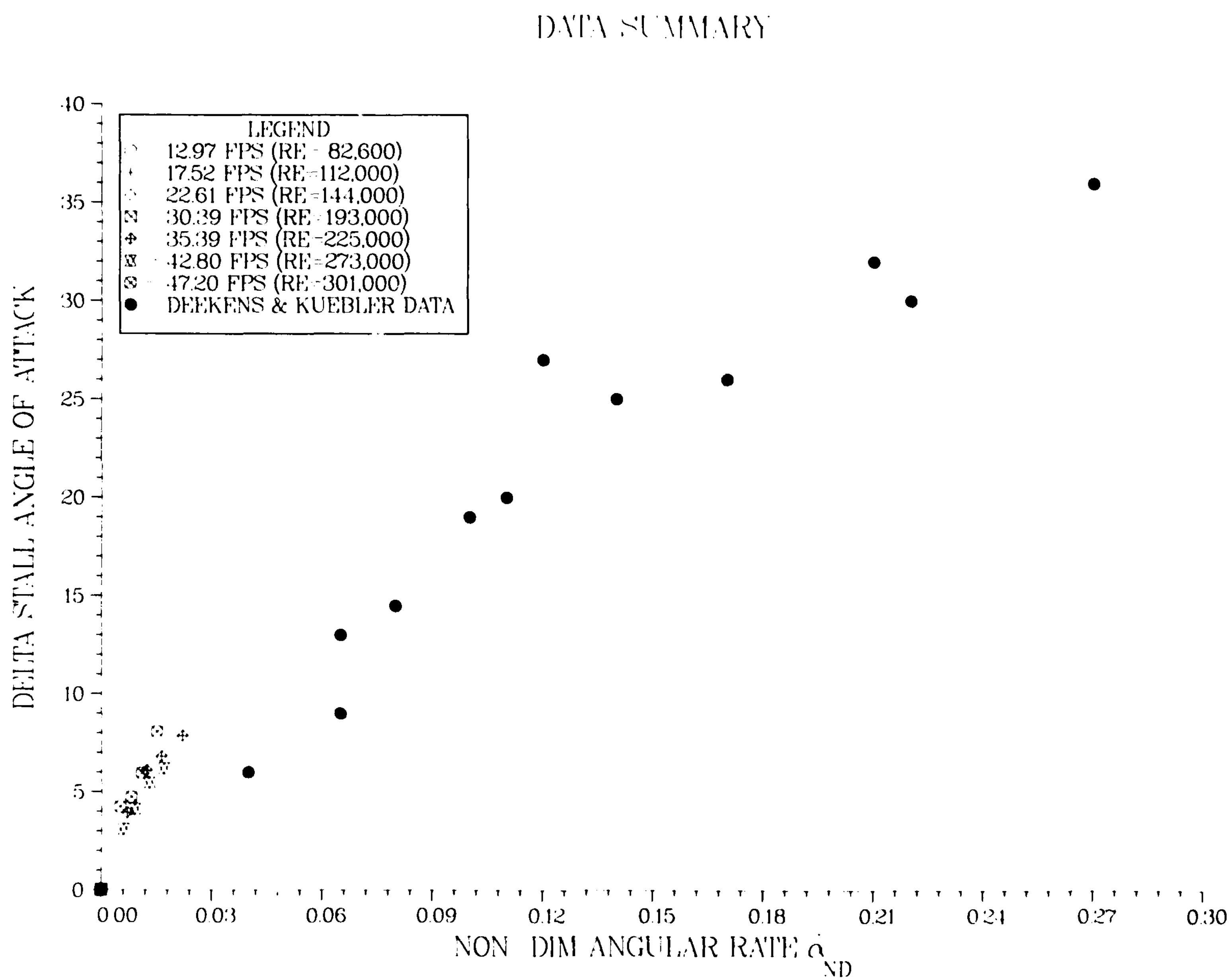

Figure 24. Data Summary With Deekens and Kuebler Data

The data from this experiment agrees well with data from Deekens and Kuebler. The figure shows that as the non-dimensional angular rate increases, the difference between the static-stall and dynamic-stall angle of attack increases. The figure also shows a decrease in this difference as the airflow velocity increases. These were the same observations as Kuebler and Deekens and Kramer.

It was possible to review the data acquisition system information and obtain a time interval for the time from 0° angle of attack to the angle of attack at flow separation (at the quarter chord). When this time interval was compared with the time interval obtained from the film, there was excellent correlation. For example for run #23, analysis of the data acquisition system information indicated that the time interval between 0° and the dynamic-stall angle of attack was 0.837 seconds. When the film was reviewed, the actual time between 0° and the dynamic-stall angle of attack was 0.846 seconds, an error of only one part in 84 or 1.2%.

V Conclusions and Recommendations

Conclusions

There are three major conclusions which can be drawn from this experimental work. First, based on the excellent agreement between film-derived information and data acquisition system information, it can be stated that the data acquisition system is working and giving reliable information on angular rates, positions, and dynamic-stall angle of attack. Second, the dynamic-stall angle of attack appears to be dependent upon angular rate. The trend is for increasing dynamic-stall angle of attack with increasing angular rate. The difference between static-stall angle of attack and dynamic-stall angle of attack decreases with increasing airspeed. A properly located pressure transducer is a reliable indicator of the angle-of-attack at which dynamic stall occurs. And finally, because the results reported here agree so closely to the Deekens and Kuebler results, Reynolds number effects do not appear to be important over the range of Reynolds number from 15,000 to 300,000.

Recommendations

It is recommended that this work be continued; however, some improvements should be made. First, the number of transducers should be expanded to get a pressure distribution for the airfoil. When using additional transducers, the problems leading to the use of batteries must be eliminated or each transducer should be powered by a separate battery power source. The amplification of the transducer signals can be handled by building separate small amplifiers that are designed for good linearity in the operating range of the transducers. Another approach is to try to use the instrumentation amplifier of the AIM-12 board set at a gain of 100. If the latter approach is tried, one would have to use another A/D conversion board for the position potentiometer because of the different voltage ranges between position signals and transducer signals. When using more transducers, the memory storage space of the data acquisition system will have to be increased. To allow the storage of more elements in the IDATA array of the computer programs, the data type of IDATA should be changed to INTEGER*2.

Secondly, to help prevent irregular curves like that of Figure 23, small braces should be used between the glass panes. Another approach would be to cut down the width of the airfoil; however, care must be taken to maintain a good seal between the airfoil and the smoke tunnel walls to assure 2-D flow.

Third, in order to expand the non-dimensional angular rate range, a rotation drive motor with higher velocity should be used.

Fourth, the operation of the data acquisition system would allow the elimination of filming in further studies. However, if filming is still desired, the quality of the smoke traces might be able to be enhanced by removing the present smoke ejectors and constructing a set in front of the smoke tunnel as used by Brown in the Notre Dame University smoke tunnel (Ref 11:53). This would eliminate the injection rake from adding to the disturbance in the test section and might make possible more dense smoke traces at the higher velocities. To analyze the films, a film analyzer projector should be purchased.

Finally, for ease in operating the data acquisition system, the operator should be familiar with the microcomputer operating system CP/M, Microsoft Fortran (Fortran IV), and the text editor Wordmaster (the H-19 video terminal is required to use Wordmaster).

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Appendix

Computer Programs

1. The voltage value program (Program VALU) was used for voltage values of the 0^{o} and 90^{o} airfoil positions and for general testing. The operator enters the desired channel number of the A/D board and the output is the converted integer value and the voltage value. Five values of the desired channel are displayed. Inputs to the A/D board must be in the plus or minus five volts DC range.
2. The initial values program (Program DOS) was used to enter the 0^{o} and 90^{o} airfoil positions voltage values, check airfoil angular position, and to obtain the 0^{o} angle-of-attack pressure readings. The 0^{o} angle-of-attack voltage value, volts per degree value, and transducer 0^{o} pressure readings are stored on data file Fort 06.Dat for use by other programs.
3. The data gathering program (program UNO) was used to gather data during test runs. General run information was stored on data file Fort08.Dat and time, position, and pressure information was stored on data file Fort07. Dat. Three subroutines were used in this program. The first, STCLK, was used to start the computer internal clock. The second, GETTIM, was used to get the time value. The last, AD, was used to convert the signal from analog to digital value.

4. The preliminary reduction program (Program REDUCE) reduced information stored by the initial value and data gathering programs. The information outputs were: 0° angle-of-attack pressure readings, angular rate, non-dimensional rate, Reynolds Number, run velocity, time, position (up to 40°), and pressure readings.
5. The comparison reduction program (Program REDUC2) was used to get individual and average values from the film and the data acquisition system for run velocity, angular rates, non-dimensional rates, and stall angle of attack. The printouts of the preliminary reduction program were required for this program.
6. The normalized pressure program (Program PRESS) was used to get normalized pressure for transducers #2 and #3.
7. The calibration program (Program TEST) was used to get a continuous readout of the A/D channel 0 integer value. It was used in testing and calibration.

```
      PROGRAM VALUE
C     FOR OBTAINING VALUES OF SELECTED CHANNELS OF THE AIM-12 BOARD,12 OCT 82
C     LINK VALU,ADIO,FORLIB/S,VALU
C     LATEST MOD: 4 APR 83
      IMPLICIT INTEGER (A-Z)
      INTEGER CHAN,VALUE
      REAL VALUE1
C
C***********************************************************************
C     CHAN=AD CHANNEL SELECTED        VALUE=AD CONVERTED VALUE(INTEGER)   *
C     VALUE=VOLTAGE VALUE(REAL)                                           *
C***********************************************************************
C
 10   WRITE(1,100)
 100  FORMAT(' ENTER CHANNEL NUMBER DESIRED FOR READING',/,
    + ' (CONTROL C TO EXIT)',/)
      READ(1,200)CHAN
 200  FORMAT(I2)
      WRITE(1,300)CHAN
 300  FORMAT(' CHAN=',I2,/)
      DO 500 I=1,5
      CALL AD(VALUE,CHAN,80)
      WRITE(1,400)VALUE
 400  FORMAT(' VALUE=',I7)
      VALUE1=VALUE*10./4096.-5.
      WRITE (1,50)VALUE1
 50   FORMAT (' VALUE1=',F12.4,/)
 500  CONTINUE
      GO TO 10
      STOP
      END
```

```
      PROGRAM DOS
C     TO GET Ø DEGREE ANGLE OF ATTACK INFO FOR RED1 PROGRAM, 24 MAR 83
C     LATEST MOD: 2 APR
C     LINK DOS,ADIO,FORLIB/S,DOS/N/E
      IMPLICIT INTEGER (A-Z)
      REAL PØ,P9Ø,VPD,POS
      INTEGER VALUE,CHAN,A,B
      DIMENSION IDATA(16),SUM(4),TØ(4)
C*****************************************************************************
C     CHAN=CHANNEL NUMBER                    TØ(4)=AVERAGE TRANSDUCER VALUE*
C     IDATA(16)=TRANSDUCER VALUE ARRAY       VALUE=AD CONVERTED VALUE      *
C     PØ=Ø ALPHA VOLTAGE VALUE               VPD=VOLTS PER DEGREE          *
C     P9Ø=9Ø ALPHA VOLTAGE VALUE                                           *
C     POS=ANGULAR POSITION                                                 *
C     SUM(4)=SUM STORAGE ARRAY                                             *
C*****************************************************************************
      WRITE(1,1Ø)
 1Ø   FORMAT(' NEW POSITIONS?(Y=1)',/)
      READ(1,2Ø)A
 2Ø   FORMAT(I1)
      IF (A.NE.1) GO TO 6Ø
C
C     ENTER Ø AND 9Ø ALPHA VOLTAGE VALUES
C
      WRITE(1,3Ø)
 3Ø   FORMAT(' ENTER PØ AND P9Ø(2F7.4)',/)
      READ (1,4Ø)PØ,P9Ø
 4Ø   FORMAT(2F7.4)
      VPD=(P9Ø-PØ)/9Ø.
C
C     WRITE PØ AND VPD TO FORTØ9.DAT TO GET POSITION BASED ON LAST
C     PØ AND P9Ø ENTERED
C
      WRITE(9,5Ø)PØ,VPD
 5Ø   FORMAT(F7.4,F8.5)
      GO TO 7Ø
 6Ø   READ (9,5Ø)PØ,VPD
C
C     CHECK POSITION TO OBTAIN Ø ALPHA PRIOR TO TAKING TRANSDUCER VALUES
C
 7Ø   CALL AD(VALUE,Ø,8Ø)
      POS=VALUE*1Ø./4Ø96.-5.
      POS=(POS-PØ)/VPD
      WRITE(1,8Ø)POS
 8Ø   FORMAT(' POSITION IS',F9.4,' DEGREES',/)
      WRITE(1,9Ø)
 9Ø   FORMAT(' TRY ANOTHER POSITION?(Y=1)',/)
      READ(1,2Ø)B
      IF (B.EQ.1) GOTO 7Ø
C
C     RUN THRU TRANSDUCERS TO GET AVERAGE VALUES
C
      DO 11Ø K=1,16,4
      DO 1ØØ J=1,4
```

```
      CHAN=J
      CALL AD(VALUE,CHAN,80)
      DI=K+J-1
      IDATA(DI)=VALUE
 100  CONTINUE
 110  CONTINUE
      SUM(1)=IDATA(1)+IDATA(5)+IDATA(9)+IDATA(13)
      SUM(2)=IDATA(2)+IDATA(6)+IDATA(10)+IDATA(14)
      SUM(3)=IDATA(3)+IDATA(7)+IDATA(11)+IDATA(15)
      SUM(4)=IDATA(4)+IDATA(8)+IDATA(12)+IDATA(16)
      DO 120 L=1,4
      T0(L)=SUM(L)/4
 120  CONTINUE
      WRITE(1,130)(SUM(I),I=1,4)
 130  FORMAT(4I8)
      WRITE(1,140)P0,VPD,(T0(I),I=1,4)
 140  FORMAT(F7.4,F8.5,4I6)
C
C     WRITE TO FORT06.DAT FOR USE BY THE REDUCTION PROGRAM
C
      WRITE(6,140)P0,VPD,(T0(I),I=1,4)
      WRITE(1,150)
 150  FORMAT(//)
      STOP
      END
```

```
      PROGRAM UNO
C     TO GATHER AND STORE DATA FOR FURTHER PROCESSING, 15 FEB 83
C     LATEST MOD: 3 APR
C     LINK:UNO,STCLK,GETTIM,ADIO,FORLIB/S,UNO/N/E
C
      IMPLICIT INTEGER (A-Z)
      REAL PØ,VPD,VEL,MV,DTIM,DPOS,DPOSD,RATE
      INTEGER IDATA(172Ø),A,NS,KOUNT,B,L,I,J,RN,TØ(4),TIME,VALUE,CHAN,
     + N,AA,C
C
C**********************************************************************
C     CHAN=CHANNEL NUMBER                     PØ=Ø ALPHA POSITION         *
C     DPOS=DELTA POSITION(VOLTAGE)            RATE=ANGULAR RATE           *
C     DPOSD=DELTA POSITION(DEGREES)           RN=RUN NUMBER               *
C     DTIM=DELTA TIME                         TØ(4)=Ø ALPHA TRANSDUCER VALUE*
C     IDATA(172Ø)=DATA STORAGE ARRAY          TIME=INTERNAL CLOCK TICKS   *
C     MV=MOTOR VOLTAGE                        VALUE=AD CONVERTED VALUE    *
C     N=NUMBER OF IDATA ELEMENTS              VEL=RUN VELOCITY            *
C     NS=NUMBER OF SAMPLES                    VPD=VOLTS PER DEGREE        *
C**********************************************************************
C
C     INITIAL COUNT OF PASSES TO Ø
 1Ø   KOUNT=Ø
C
C     INPUT POSITIONS FROM DOS PROGRAM
C
      READ(6,2Ø)PØ,VPD,(TØ(I),I=1,4)
 2Ø   FORMAT(F7.4,F8.5,4I6)
      WRITE (1,2Ø)PØ,VPD,(TØ(I),I=1,4)
      WRITE (1,3Ø)
 3Ø   FORMAT(' ENTER VELOCITY, MOTOR VOLTAGE, AND RUN NUMBER:
     + (2F5.1,I3)',/)
      READ(1,4Ø)VEL,MV,RN
 4Ø   FORMAT(2F5.1,I3)
      IF (MV.EQ.6.) NS=17Ø5
      IF (MV.NE.6.) NS=12Ø5
      WRITE (1,5Ø)NS
 5Ø   FORMAT (' ',25X,'NS=',I5,//)
C
C     GET READY TO START TAKING DATA
C
      WRITE (1,6Ø)
 6Ø   FORMAT (' ENTER 1 TO START',/)
      READ (1,7Ø)A
 7Ø   FORMAT (I1)
      IF (A.EQ.1) GO TO 8Ø
C
C     START THE TIMER
C
 8Ø   CALL STCLK
C     READ AND STORE THE TIME AND INTEGER VALUES OF THE A/D OUTPUT
      WRITE(1,9Ø)
 9Ø   FORMAT(' ',2ØX,'STARTING TO TAKE DATA',////)
      DO 12Ø J=1,NS,6
      KOUNT=KOUNT+1
```

```
      CALL GETTIM(TIME)
      IDATA(J)=TIME
      DO 11Ø K=1,5
      CHAN=K-1
      CALL AD(VALUE,CHAN,8Ø)
      DI=K+J
      IDATA(DI)=VALUE
      DO 1ØØ L=1,25
 1ØØ  CONTINUE
 11Ø  CONTINUE
 12Ø  CONTINUE
      WRITE (1,13Ø)
 13Ø  FORMAT (' ',2ØX,'DATA GATHERING COMPLETE',//)
      WRITE (1,14Ø)KOUNT
 14Ø  FORMAT (' NUMBER OF PASSES = ',I6,/)
C
C     DETERMINE LIMIT OF IDATA ELEMENTS
C
      N=KOUNT*6
      WRITE(8,15Ø)N,NS,VEL,MV,RN
 15Ø  FORMAT(2I6,2F5.1,I3)
      DTIM=(IDATA(1Ø81)-IDATA(115))*.ØØ1ØØ46
      DPOS=(IDATA(1Ø82)*1Ø./4Ø96.-5.)-(IDATA(116)*1Ø./4Ø96.-5.)
      DPOSD=DPOS/VPD
      RATE=DPOSD/DTIM
      WRITE(1,16Ø)RATE
 16Ø  FORMAT(' ANGULAR RATE=',F7.3,' DEGREES PER SECOND',/)
      WRITE(1,17Ø)
 17Ø  FORMAT(' LIST IDATA ARRAY?(Y=1)',/)
      READ(1,7Ø)AA
      IF (AA.NE.1)GO TO 18Ø
      WRITE (1,2ØØ)(IDATA(L),L=1,N)
 18Ø  WRITE(1,19Ø)
 19Ø  FORMAT(' WRITE TO DISK(N=1)?',/)
      READ(1,7Ø)B
      IF (B.EQ.1) GOTO 21Ø
      WRITE(7,2ØØ)(IDATA(L),L=1,N)
 2ØØ  FORMAT(6I7)
 21Ø  WRITE (1,22Ø)
 22Ø  FORMAT(' ANOTHER RUN?(Y=1)',/)
      READ (1,7Ø)C
      IF (C.EQ.1) GOTO 1Ø
      WRITE(1,23Ø)RN
 23Ø  FORMAT(' ',1ØX,'**********NOTE***********'
     + ,//,1ØX,'SUBMIT RUN ',I3,' FOR NAME CHANGE PRIOR TO NEXT RUN',//,
     + 1ØX,'**********NØTE**********',//)
      STOP
      END
```

```
ENTRY STCLK
STCLK:  LD A,Ø17H   ; CHANNEL 1 CTRL WD =TIME/16
        OUT (Ø79H),A
        LD A,Ø9AH   ;TIME CONSTANT
        OUT (Ø79H),A
        LD A,Ø57H   ;CHANNEL 2 CNTRL WD=CTR
        OUT (Ø7AH),A
        LD A,ØFFH   ;TIME CONSTANT=256(BASE 1Ø)
        OUT (Ø7AH),A
        LD A,Ø57H   ;CHANNEL 3 CNTRL WD=CTR
        OUT (Ø7BH),A
        LD A,ØFFH   ;TIME CONSTANT
        OUT (Ø7BH),A
        RET
        END
```

```
ENTRY GETTIM
GETTIM:
        PUSH    HL      ;SAVE DEST ADDRESS
        IN      A,(Ø7AH)
        LD      E,A
        IN      A,(Ø7BH)
        LD      D,A
        LD      HL,ØFFFFH       ;MAX COUNT
        XOR     A       ;CLEAR CARRY
        SBC     HL,DE   ;SUBTR CURRENT COUNT FROM MAX COUNT
        EX      DE,HL   ;TIME TO DE
        POP     HL      ;GET ADDRESS
        LD      (HL),E
        INC     HL
        LD      (HL),D
        RET
        END
```

```
        .Z8Ø
        ENTRY   AD
;       A/D SERVICE ROUTINE
;       FORTRAN CALLABLE
;       CALL AD(VALUE,CHAN,BASE)
;
;       GET ONE SAMPLE FROM THE CHAN'TH CHANNEL
;       ON THE A/D BOARD WITH BASE ADDRESS 'BASE'
;
AD:     LD      (VALUE),HL
        LD      (CHAN),DE
        LD      (BASE),BC
        EX      DE,HL   ;HL->CHAN
        LD      A,(HL)  ;GET CHAN NO.
        LD      HL,(BASE)
        LD      C,(HL)  ;GET BASE I/O ADDRESS TO C REG FOR OUTING
        OUT     (C),A   ;MODE Ø TO CHAN NO.
                        ;USES BASE ADDRESS IN C REG
        INC     C       ;POINT TO START CONVERSION PORT
        LD      A,Ø
        OUT     (C),A   ;START CONVERSION
        DEC     C       ;POINT TO BASE REGISTER
NRDY:   IN      A,(C)   ;GET STATUS
        AND     Ø8ØH    ;BIT 7 IS STATUS, =1 IS BUSY
        JR      NZ,NRDY ;NOT ALL Ø'S => BUSY
        INC     C       ;POINT TO BASE ADD+1
        INC     C       ;POINT TO DRL
        IN      A,(C)   ;LOW BYTE OF VALUE
        LD      E,A
        INC     C       ;POINT TO DRH
        IN      A,(C)   ;HIGH BYTE OF VALUE
        AND     ØFH     ;MASK OUT HIGH NIBBLE
        LD      D,A     ;DE=VALUE
        LD      HL,(VALUE)      ;HL->WHERE TO PUT VALUE
        LD      (HL),E  ;PUT LOW BYTE OF VALUE
        INC     HL
        LD      (HL),D  ;THAT GIVES THE CALLER THE VALUE
;
        RET
;
VALUE:  DW      Ø       ;STORAGE FOR ADDRESS OF VALUE
CHAN:   DW      Ø       ;STORAGE FOR ADDRESS OF CHANNEL NO
BASE:   DW      Ø       ;STORAGE FOR ADDRESS OF BASE ADDRESS
;
        .Z8Ø
        ENTRY DA
;       CALL DA(VAL,CHAN,BASE)
;       CHAN IS Ø
;       BASE IS 72(BASE 1Ø)
DA:     LD      A,(DE)          ;GET CHAN
        ADD     A,A             ;DOUBLE IT
        INC     A               ;ADD ONE
        PUSH    HL              ;SAVE VAL
        PUSH    BC              ;
        POP     HL              ;HL=>BASE
```

```
LD      C,(HL)          ;C=LOW BYTE OF BASE
ADD     A,C             ;
LD      C,A             ;C=LOW BYTE VALUE OF PORT
POP     HL              ;GET VAL
LD      A,(HL)          ;GET LOW BYTE
OUT     (C),A           ;PUT LOW BYTE
DEC     C               ;C=HIGH BYTE PORT
INC     HL              ;HL=>HI BYTE
LD      A,(HL)          ;GET HI BYTE
OUT     (C),A           ;PUT HI BYTE
RET
END
```

```
      PROGRAM REDUCE
C     TO PROCESS DATA GATHER BY THE GET DATA PROGRAM(UNO.FOR ON 09)
C
      IMPLICIT INTEGER (A-Z)
      REAL SENS(4),RATE,VPD,DTIME1,POSI,POSF,DPOS,P0
     +,PRESS(4),POS,DTIM,DPOSD,VEL,MV,NDRATE,RE,TC
      INTEGER IDATA(2000),A
C     LOAD TRANSDUCER SENSITIVITIES
      DATA SENS/119.6,131.0,112.0,112.7/
C
C     PRINT OUT TIME, POSITION, AND PRESSURE INFO
C
C     INPUT DATA FROM GET DATA STORAGE LOCATIONS
      READ(8,100)N,NS,VPD,VEL,MV,TC,P0,KOUNT
 100  FORMAT(2I6,F8.5,2F5.1,F7.0,F7.4,I4)
      WRITE(1,200)N,NS,VPD,VEL,MV,TC,P0
 200  FORMAT(' N= ',I6,' NS= ',I6,' VPD= ',F8.5,/,' RUN VELOCITY=',
     +F5.1,' MOTOR VOLTAGE=',F5.1,' TIMER COUNT=',F7.0,/,
     +' P0=',F7.4,/)
      READ(7,310)(IDATA(L),L=1,N)
 310  FORMAT(6I7)
      WRITE(1,320)
 320  FORMAT(' LIST IDATA ARRAY(N=1)?',/)
      READ(1,330)A
 330  FORMAT(I1)
      IF (A.EQ.1) GO TO 335
      WRITE(1,310)(IDATA(L),L=1,N)
C     DETERMINE RATE,NON-DIMENSIONAL RATE AND RE
C     PICK A TIME INTERVAL OF APPROX 1 SEC IN MID TRAVEL TO GET
C     TIME AND POSITION INFO
 335  WRITE(1,340)IDATA(1081),IDATA(115),IDATA(1082),IDATA(116)
 340  FORMAT(4I8)
      DTIM=(IDATA(1081)-IDATA(115))*.0010046
      DPOS=(IDATA(1082)*10./4096.-5.)-(IDATA(116)*10./4096.-5.)
      DPOSD=DPOS/VPD
      RATE=DPOSD/DTIM
      NDRATE=(RATE*.508)/(57.3*VEL)
      RE=VEL*(.00232*1.016)/3.702E-7
      WRITE (1,400)DTIM,DPOSD,RATE,NDRATE,RE
 400  FORMAT(' TIME INTERVAL= ',F9.6,' SEC',/,
     +' CHANGE IN ANGULAR POSITION= ',F6.2,' DEGREES',/,
     +' ANGULAR RATE=',F7.3,' DEGREES PER SEC',/,
     +' NON-DIMENSIONAL RATE=',F6.3,/,
     +' REYNOLDS NUMBER=',E11.4,/)
      WRITE(1,500)
 500  FORMAT(//)
      WRITE(1,331)
 331  FORMAT(' ',2X,'TIME',3X,'POSITION',10X,'PRESSURE READINGS
     +(PSI):')
      WRITE(1,332)
 332  FORMAT(' ',9X,'(DEGREES)',2X,'TRANS1',4X,'TRANS2',4X,
     +'TRANS3',4X,'TRANS4',/)
      DO 800 J1=1,NS,6
        TIME1=IDATA(J1)
```

```
          POS=IDATA(J1+1)*10./4096.-5.
          POS=(POS-P0)/VPD
          K=J1+1
          DO 700 M=1,4
                  N=K+M
                  PRESS(M)=((IDATA(N)*10./4096.-5)/SENS(M))*10.
700       CONTINUE
        WRITE(1,350)TIME1,POS,(PRESS(KI),KI=1,4)
350     FORMAT(' ',2X,I4,3X,F7.4,4X,F7.5,3X,F7.5,3X,F7.5,3X,F7.5)
800     CONTINUE
        WRITE(1,550)
550     FORMAT(//)
        STOP
        END
```

```
      PROGRAM REDUC2
C     TO REDUCE FILM AND COMPUTER INFORMATION,9 APR 83
C     LATEST MOD:9APR
C
      INTEGER RUN(100),A,B,C,J,K,I,CTI,CTF,G
      REAL D,E,F,TI,TF,FRATE(100),VEL(100),AI,AF,CRATE(100)
     +,AVGR(100),CS(100),AVGS(100),FS(100),NDRF(100),NDRC(100),
     + NDRA(100)
C
 1    WRITE(1,10)
 10   FORMAT(' CONTINUE?(N=1)',/)
      READ(1,20)A
 20   FORMAT(I2)
      IF(A.EQ.1) GOTO 255
      I=I+1
      WRITE(1,30)
 30   FORMAT(' ENTER RUN #',/)
      READ(1,20)B
      RUN(I)=B
 35   WRITE(1,40)
 40   FORMAT(' VELOCITY DETERMINATION:',/,' ENTER START TIME',/)
      READ (1,50)D
 50   FORMAT(F7.3)
      WRITE(1,60)
 60   FORMAT(' ENTER END TIME AND DISTANCE',/)
      READ(1,70)E,F
 70   FORMAT(F7.3,F5.2)
      VEL(I)=F/(E-D)
      WRITE(1,80)VEL(I)
 80   FORMAT(' VEL=',F5.1,/)
      WRITE(1,85)
 85   FORMAT(' ANOTHER CALCULATION?(Y=1)',/)
      READ(1,20)C
      IF(C.EQ.1) GOTO 35
 86   WRITE(1,90)
 90   FORMAT(' ',10X,'ANGULAR VELOCITY DETERMINATION:',/
     +' IS 30 DEGREES THE ANGLE INTERVAL?(N=1)',/)
      READ(1,20)G
      IF(G.NE.1)GOTO 115
      WRITE(1,100)
 100  FORMAT(' ENTER ANGLE INTERNAL(F4.0)',/)
      READ(1,110)ANG
 110  FORMAT(F4.0)
      GOTO 120
 115  ANG=30.
 120  WRITE(1,130)
 130  FORMAT(' ENTER FILM TIME FOR 10 AND 40 DEGREES(F7.3)',/,
     +' (OR INITIAL AND FINAL TIMES)',/)
      READ(1,140)TI,TF
 140  FORMAT(2F7.3)
      FRATE(I)=ANG/(TF-TI)
      WRITE(1,150)FRATE(I)
 150  FORMAT(' FILM RATE=',F6.2)
      WRITE(1,85)
      READ(1,20)J
```

```
      IF (J.EQ.1) GO TO 86
155   WRITE(1,160)
160   FORMAT(' ENTER COMPUTER INITIAL TIME&ANGLE,AND FINAL TIME &
     + ANGLE(I5,F8.4)',/)
      READ(1,170)CTI,AI,CTF,AF
170   FORMAT(I5,F8.4,I5,F8.4)
      CRATE(I)=(AF-AI)/((CTF-CTI)*.0010046)
      WRITE(1,180)CRATE(I)
180   FORMAT(' COMPUTER RATE=',F6.2)
      WRITE(1,85)
      READ(1,20)K
      IF(K.EQ.1)GO TO 155
      AVGR(I)=(CRATE(I)+FRATE(I))/2
      WRITE(1,190)AVGR(I)
190   FORMAT(' AVG RATE=',F6.2)
C
C     STALL INFO
C
      WRITE(1,200)
200   FORMAT(' ENTER FILM STALL(F5.1) AND COMPUTER STALL(F5.2)',/)
      READ(1,210)FS(I),CS(I)
210   FORMAT(F5.1,F5.2)
      AVGS(I)=(FS(I)+CS(I))/2
      WRITE(1,220)AVGS(I)
220   FORMAT(' AVG STALL=',F5.2)
C
C     NON-DIMENSIONAL RATE CALCULATION
      NDRF(I)=(FRATE(I)*.508)/(57.3*VEL(I))
      NDRC(I)=(CRATE(I)*.508)/(57.3*VEL(I))
      NDRA(I)=(NDRF(I)+NDRC(I))/2
      WRITE(1,230)NDRF(I),NDRC(I),NDRA(I)
230   FORMAT(' NDRF=',F6.3,' NDRC=',F6.3,' NDRA=',F6.3)
      WRITE(1,240)
240   FORMAT(' RUN  VEL  RATE   NDRATE   RATE   NDRATE   RATE
     +NDRATE  STALL  STALL  STALL',/,10X,'(FILM)   (FILM)  (COMP)
     +(COMP)   (AVG)   (AVG)   (FILM) (COMP) (AVG)',/)
      WRITE(1,250)RUN(I),VEL(I),FRATE(I),NDRF(I),CRATE(I),NDRC(I),
     + AVGR(I),NDRA(I),FS(I),CS(I),AVGS(I)
250   FORMAT(I3,F6.1,F7.2,F8.3,2F9.3,F8.3,F9.3,F7.1,2F7.2)
      GOTO 1
255   WRITE(1,240)
      WRITE(6,260)I
260   FORMAT(I3)
      DO 270 L=1,I
      WRITE(1,250)RUN(L),VEL(L),FRATE(L),NDRF(L),CRATE(L),NDRC(L),
     + AVGR(L),NDRA(L),FS(L),CS(L),AVGS(L)
      WRITE(7,250)RUN(L),VEL(L),FRATE(L),NDRF(L),CRATE(L),NDRC(L),
     + AVGR(L),NDRA(L),FS(L),CS(L),AVGS(L)
270   CONTINUE
      WRITE(1,280)
280   FORMAT(//)
      STOP
      END
```

```
      PROGRAM PRESS
C     TO OBTAIN NORMALIZED PRESSURE FOR TRANSDUCERS 2 AND 3,12 APR 83
C     LATEST MOD: 12 APR
C
      IMPLICIT INTEGER (A-Z)
      REAL SENS(4),VPD,PØ,PRESS(4),POS,PMAX2,PMAX3,PN2,PN3,MV,VEL,
     + TØP(4)
      INTEGER IDATA(18ØØ),A,TØ(4),RN,N,NS,TIME1
C*************************************************************************
C     DPOS=DELTA POSITION (VOLTAGE)          PRESS(4)=TRANSDUCER PRESSURE  *
C     DTIM=DELTA TIME                        RE=REYNOLDS NUMBER            *
C     IDATA(18ØØ)=DATA STORAGE ARRAY         RN=RUN NUMBER                 *
C     MV=MOTOR VOLTAGE                       SENS(4)=TRANSDUCER SENSITIVITY*
C     N=# OF IDATA ELEMENTS                  TØP(4)=Ø ALPHA PRESSURE       *
C     NDRATE=NON-DIMENSIONAL RATE            TIME1=INDIVIDUAL TIME         *
C     NS=NUMBER OF SAMPLES                   VEL=RUN VELOCITY              *
C     PØ=Ø ALPHA VOLTAGE VALUE               VPD=VOLTS PER DEGREE          *
C     POS=POSITION(VOLTAGE & ANGULAR)                                      *
C*************************************************************************
C
C     LOAD TRANSDUCER SENSITIVITIES
C
      DATA SENS/119.6,131.Ø,112.Ø,112.7/
C
C     GET ZERO ALPHA PRESSURE INFO FROM FORTØ6
      READ(6,1Ø)PØ,VPD,(TØ(I),I=1,4)
 1Ø   FORMAT(F7.4,F8.5,4I6)
      DO 3Ø J=1,4
      TØP(J)=((TØ(J)*1Ø./4Ø96.-5.)/SENS(J))*1Ø.
      WRITE(1,2Ø)J,TØP(J)
 2Ø   FORMAT(' ZERO PRESSURE FOR TRANSDUCER #',I2,' IS',F7.5,' PSI')
 3Ø   CONTINUE
C
C     INPUT DATA FROM GET DATA STORAGE LOCATIONS
C
      READ(8,4Ø)N,NS,VEL,MV,RN
 4Ø   FORMAT(2I6,2F5.1,I3)
      WRITE(1,5Ø)N,NS,VPD,VEL,MV,RN,PØ
 5Ø   FORMAT(' N= ',I6,' NS= ',I6,' VPD= ',F8.5,/,' RUN VELOCITY=',
     + F5.1,' MOTOR VOLTAGE=',F5.1,' RUN NUMBER=',I3,/,
     + ' PØ=',F7.4,/)
      READ(7,6Ø)(IDATA(L),L=1,N)
 6Ø   FORMAT(6I7)
C
      WRITE(1,7Ø)
 7Ø   FORMAT(' ENTER MAX TRANS 2 AND MAX TRANS 3 PRESSURE(F8.5)',/)
      READ(1,8Ø)PMAX2,PMAX3
 8Ø   FORMAT(2F8.5)
 85   WRITE(1,9Ø)PMAX2,PMAX3
 9Ø   FORMAT(' MAXIMUM TRANS2 PRESS=',F7.5,' PSI',/,' MAXIMUM TRANS2
     + PRESS=',F7.5,/)
C     PRINT TIME,POSITION,AND PRESSURE READINGS
C
      WRITE(1,13Ø)
```

```
130    FORMAT(' ',2X,'POSITION',5X,'PRESSURE',6X,'NORMALIZED',3X,
     + 'PRESSURE',6X,'NORMALIZED')
       WRITE(1,140)
140    FORMAT(' ',2X,'(DEGREES)',4X,'TRANS2(PSI)',3X,'PRESSURE',5X,
     + 'TRANS3(PSI)',3X,'PRESSURE',/)
       DO 170 J1=1,NS,6
         POS=IDATA(J1+1)*10./4096.-5.
         POS=(POS-P0)/VPD
         K=J1+1
         DO 150 M=1,4
                   N=K+M
                   PRESS(M)=((IDATA(N)*10./4096.-5.)/SENS(M))*10.
                   PRESS(M)=PRESS(M)-T0P(M)
150      CONTINUE
       PN2=PRESS(2)/PMAX2
       PN3=PRESS(3)/PMAX3
       WRITE(1,160)POS,PRESS(2),PN2,PRESS(3),PN3
160    FORMAT(' ',3X,F7.4,7X,F7.5,7X,F8.2,6X,F7.5,7X,F8.2)
       IF (POS.GE.40.) GOTO 180
170    CONTINUE
180    WRITE(1,185)
185    FORMAT(' READY TO PRINT?(N=1)',/)
       READ(1,186)IN
186    FORMAT(I2)
       IF (IN.NE.1)GOTO 85
       WRITE(1,190)
190    FORMAT(/)
       STOP
       END
```

```
      PROGRAM TEST
C     FOR CALIBRATION OF THE AIM 12 IN BIPOLAR, 10 JUL 82
C     CHANNEL USED IS ALWAYS CHANNEL 1
C     LINK: TEST,ADIO,FORLIB/S,TEST/N/E
      IMPLICIT INTEGER (A-Z)
      CHAN=1
10    CALL AD(VALUE,CHAN,80)
      WRITE (1,50)VALUE
50    FORMAT ('+VALUE=',I8)
      GO TO 10
      STOP
      END
```

Vita

Daniel C. Daley was born on 25 May 1948 in Dayton, Ohio. Following graduation from Jeb Stuart High School in Falls Church, Virginia in 1966, he enlisted in the Air Force. In 1967, he received an appointment to the Air Force Academy and graduated from there with a Bachelor of Science Degree in Aeronautical Engineering in 1971. His assignments have been in Air Training Command, Aeronautical Systems Division, and Aerospace Rescue and Recovery Service. He is married to the former Rebecca S. Reining and they have one son.

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This thesis discusses an experimental investigation of dynamic stall for an NACA 0015 airfoil rotated at different constant angular rates. It describes a microcomputer-based automatic data acquisition system capable of acquiring 1000 items of data per second. When this information was used to predict stall and compared with film-data stall indications of the same test runs, there was excellent correlation between them. Results of the investiga-

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