DESIGN AND DEVELOPMENT OF A FACILITY FOR COMPRESSIBLE DYNAMIC STALL STUDIES OF A RAPIDLY PITCHING AIRFOIL

M.S.Chandrasekhara[1]
Navy - NASA Joint Institute of Aeronautics, Department of Aeronautics and Astronautics
Naval Postgraduate School, Monterey, CA, 93943, U.S.A.
and
L.W.Carr[2]
Aeroflightdynamics Directorate, U.S. Army ARTA and Fluid Dynamics Research Branch
NASA Ames Research Center, Moffett Field, CA, 94035, U.S.A.

Abstract

A facility for the study of dynamic stall of an airfoil undergoing a transient ramp type pitching motion is described. The facility can produce pitch rates of 3600 degrees/sec, to an angle of attack of 60 degrees by using a specially designed hydraulic drive with feedback control. A unique airfoil support system allows unobstructed flow visualization including the complete airfoil contour, thus permitting the use of non-intrusive optical diagnostic methods for flow measurement close to the surface as well as simultaneous far field measurements. Schlieren results obtained with this facility are presented.

1. INTRODUCTION

The phenomenon of dynamic stall is responsible for the production of lift well beyond the static stall angle by airfoils experiencing rapid pitching motion. In fact, lift coefficients twice as large as the static maximum value have been produced by unsteady motions (see Carr [1]). In all cases of unsteady motion, a large dynamic stall vortex is generated, which is a significant contributor to the dynamic lift that is observed.

The effective use and control of dynamic lift on helicopter rotors and aircraft wings will depend on manipulation of the vorticity being shed into the flow during the dynamic stall process. In the case of the helicopter, the dynamic stall vortex remains close to the rotor blade; the rotor blade pitch rate is decreasing even as the vortex is forming near the leading edge. The resulting vortex is swept off the blade by the free stream flow. In contrast, aircraft motion is essentially a constant-rate pitch-up condition, to angles of attack as high as 60 deg, followed by a condition where the wing is then held at a constant angle relative to the oncoming flow. In this case, the goal is to to trap the vortex to retain its effect on the aircraft, inducing the high lift that is so important to aircraft maneuvers. In contrast to the helicopter condition, where the task is to alleviate the effects of the vortex as it is swept over the airfoil, on an aircraft the question becomes one of retaining the vortex structure in such a way that the lift will remain high for sufficiently long time for the the aircraft to complete the required maneuver. Since this flight condition is significantly different form that of an oscillating airfoil associated with helicopter flight, a new drive system has been developed to complement an existing oscillating drive in the Compressible Dynamic Stall Facility at NASA Ames Research Center.

Over the past 15 years, many attempts have been made to study the dynamic stall of ramp-type pitching airfoils, e.g. Francis et al [2], Lorber and Carta [3,4], Robinson and Wisler [5], Walker et al. [6], Jumper et al. [7], Albertson et al. [8], Favier et al. [9], Harper and Flanigan [10]. Most of these were limited to low speed flows, with the exception of [3,4,10]. Harper and Flanigan [10] observed a complete loss of the dynamic lift as the Mach number was increased to the compressible regime. Lorber and Carta [3,4] found that increasing the pitch rate had a mitigat-

---

[1] Assistant Director and Adjunct Professor, *Mailing Address: M.S.260-1, NASA Ames Research Center, Moffett Field, CA 94035, U.S.A.*

[2] Research Scientist; Group Leader, Unsteady Viscous Flows

ing effect on this loss. Chandrasekhara and Carr[11] have conducted similar studies when compressibility effects are present on an oscillating airfoil and concluded that increasing the unsteadiness helped in retaining the dynamic stall vortex on the airfoil surface.

It is now known (ref.[1]) that the local flow velocities over an airfoil in rapid unsteady motion can exceed sonic values, even when the free stream Mach number is only 0.2. Thus, compressibility effects are present in the local flow, which are further amplified as the free stream Mach number is increased above this value. The presence of the local supersonic flow and the shock that forms on the airfoil upper surface can adversely affect the process of vortex formation and may even *negate* the benefits of dynamic stall delay.

The development of high lift on aircraft will depend on proper management of the vorticity which is generated during the unsteady delay. Since the stall process is strongly influenced by compressibility, proper representation of this flow must include match of free stream Mach number. The constant-pitch-rate condition associated with aircraft motion also introduces significant changes in the driving mechanism producing the vorticity, since the constant pitch rate condition maintains the pitch rate without change in the rate as the airfoil passes through the static and dynamic stall angles, thus removing a source of premature stall inception (the pitch rate of the oscillating airfoil is decreasing as soon as the mean angle is passed). In addition, the constant-pitch-rate motion concludes with a long duration of very high angle of attack flight, which results in development of the dynamic stall vortex in the wake of the airfoil. This condition is dramatically different from the oscillating airfoil case and requires a separate study, particularly under conditions where compressibility effects may have altered the character of the stall process.

The research effort being reported is directed towards documentation of the flow under conditions conducive to dynamic stall, and identification of the appropriate flow physics when compressibility effects are present. This will lead to a better understanding of the dynamic stall process and will aid in exploitation of dynamic lift in aircraft applications.

To achieve this goal, a Compressible Dynamic Stall Facility (CDSF) was built and installed in the Fluid Mechanics Laboratory at the NASA Ames Research Center, under the Navy-NASA Joint Institute of Aeronautics. The CDSF presently uses a drive mechanism to oscillate an airfoil and is described in Carr and Chandrasekhara [12]. A new drive has just been installed to rapidly pitch an airfoil at a constant rate in a ramp type motion up to very high angles of attack. This is described in the following sections.

2. DESCRIPTION OF THE FACILITY

2.1.General

The Compressible Dynamic Stall Facility is an indraft wind tunnel, with a test section of 25 cm X 35 cm, connected to an evacuation compressor. The inlet flow passes through a bell mouth, six turbulence suppression screens and a contraction with 3:1 area ratio. The flow in the tunnel is controlled by a variable-throat-area choked diffuser immediately downstream of the test section. The compressor runs continuously and produces suction pressures sufficient to maintain steady flow in the tunnel at a Mach Number of 0.5.

The uniqueness of the CDSF is that it provides an unobstructed view of the entire flow field, including the airfoil surface. The airfoil is supported between 2.54cm thick optical galss windows by pins located at 25% and 70% chord. The pins are made from high strength steel, have spherical tips to provide self-alignment and are smaller than the local airfoil thickness. This allows complete optical access down to the airfoil surface. This is especially valuable near the leading edge, where the dynamic stall vortex forms and a supersonic flow region exists. Fig. 1 [12] shows the details of the model support in the window along with the test section walls. The facility has been operated in sinusoidal motion for the study of dynamic stall on helicopter rotor blades. For details of the oscillating drive mechanism, see ref.[12]; for analysis of the compressibility effects on oscillating airfoils, see ref. [11].

2.2. Specifications for the Constant Pitch Rate Drive

In order to properly represent aircraft maneuvers, the following specifications were prescribed for the drive mechanism to pitch the airfoil.

angle of attack, α:	0-60^o
pitch rate, $\dot{\alpha}$:	0-3600 ^{o}/sec
acceleration rate:	600,000 $^o/sec^2$
change in α during acceleration:	$\leq 10^o$ of pitch
acceleration time:	0.006 sec
free stream Mach number:	0.1-0.5
airfoil chord:	7.5cm
Reynolds number:	$2x10^5$ - $1x10^6$

A pitch rate of 3600 °/sec on a 7.5 cm chord airfoil corresponds to a 90°/sec pitch of a 3m chord airplane wing, (the model scaling being the ratio of the aircraft wing chord to the airfoil chord at any given Mach number). Thus, the rates obtainable from the design are directly applicable to flight conditions. In order to limit or isolate the effects of transients on separation, the change in angle of attack during acceleration and the acceleration time were limited to less than 10° and 6 millisec respectively. To properly simulate a maneuver, an angle of attack range of 0-60 ° has been selected.

These are exacting specifications and require a very powerful prime mover capable of operating intermittently, and starting and stopping rapidly. To provide reasonable experiment times, it was decided to have a short recycle time of 2 seconds (30 runs/minute). After analyzing various drives and mechanisms, a hydraulic drive was chosen to be the power source for the facility. Fig. 2. shows the arrangement of the system. Its details are given below.

2.3. Mechanical Aspects

The test section of the wind tunnel is the same as described in ref. 11. However, the drive is different and consists of a four-bar linkage, connected to a hydraulic piston/cylinder through a truss and bell crank assembly. The bell cranks are attached to a connecting rod on either side of the test section, which are in turn pinned to the magnesium frames that hold the glass windows. The airfoil, the connecting rods, and the linkage between the bell cranks constitute the four bar arrangement as can be seen from Fig.3. The pivoting of the bell cranks on precision bearings causes a linear change in the airfoil angle of attack. The truss is machined from a single block of steel to prevent any misalignment and the concomitant torsional moments. The hydraulic cylinder/piston driving the truss has the stroke necessary to produce the specified change in angle of attack. Mechanical stops are provided at either end of the cylinder assembly to arrest the motion in case of a control system malfunction. The entire drive system, including the hydraulic assembly is mounted on a support platform, Fig. 4 provides the details of this assembly. This design permits easy interchange with the oscillating airfoil drive mechanism.

2.4. Hydraulic System and Its Control

The hydraulic system consists of a 80 liter/min, 200 kgf/cm^2, pump to charge a 10 liter accumulator. The hydraulic circuit consists of the accumulator, a servo valve, a manifold and the hydraulic-piston and flow control valves. A pilot stage circuit consisting of a small 1 liter accumulator and a servo valve helps control the main servo valve by absorbing the flow fluctutaions. The stroke of the cylinder necessary for the range of the facility is 7.5 cm in each direction. However, it has a maximum range of 10 cm before the cylinder motion is stopped by hydraulic snubbers. Fig. 5 shows the hydraulic manifold sub-assembly and the schematic of the flow line is represented in Fig. 6. The average flow through the cylinder is less than 1 liter/sec; however, the peak rates could reach 10 liters/sec. The cylinder pressures vary from 60 kgf/cm^2 to 75 kgf/cm^2.

A sophisticated control system is necessary to govern the motion of the system to maximize the performance of the system. Both the mechanical and hydraulic systems were modelled on the computer by properly representing the various components and their transfer functions before designing the controls. The complete details of the design are presented in Andrews [13]; only the salient fatures are described here.

A digital controller is used for controlling the position of the pitching mechanism. The angular position of the airfoil is provided by a digital incremental encoder attached to the pitching windows. The controller can calculate the command input (ramp motion in this case), compare with the encoder information, and act to correct any differences by using proper lead and lag filters. An analog servo valve controller is used for controlling the system dynamic response. A linear velocity transducer (LVT) mounted on the piston of the hydraulic cylinder produces the necessary feed back analog signal. The feed back system ensures that the cylinder will track the velocity command input during a run. Leakage in the hydraulic valve assembly was estimated to be ≈3% and was modelled together with the rest of the system. Proper compensation was used in the control software to reproduce the additional damping induced by the leakage.

In addition to the above linear elements, non linear aspects such as amplifier saturation and changes in acceleration rates during starting and stopping were also modelled. The estimated theoretical response curves are shown in Fig. 7 and a comparison of the command input and the window position curves in it shows that the control system meets the design specifications.

2.5. Associated Instrumentation

The facility is equipped with instrumentation for non-intrusive optical diagnostic techniques. These presently include a stroboscopic schlieren system and a two component LDV system as shown in Fig. 8.

The stroboscopic schlieren system consists of an arc lamp light source, two spherical mirrors with 3m focal length, a knife edge and a photographing apparatus. The light source can be triggered instantaneously at any desired angle of attack by using electronic hardware developed for this application either manually or with a computer. The quadrature pulse output from an incremental position encoder is used for this. The encoder has a resolution of 0.03° angle of attack/count. Based on the previous experiments [11], it is known that the initiation of the dynamic stall process occurs very rapidly and over a small range of angle of attack. The fine resolution of the encoder will thus permit studies of the flow with the necessary detail. The schlieren system has been fully exercised in studies on oscillating airfoil dynamic stall[11].

The LDV uses standard optics and processors, and transfers data in the DMA mode to a microVAX II Workstation. The hardware for LDV instrumentation includes latches to "freeze" the encoder information when a coincident LDV signal is present in the U and V channels.

Static pressures along the tunnel walls including the contraction and diffuser walls are read by a 6-barrel, 24-port scanivalve system connected to sensitive pressure transducers by digitizing the voltages using a computer. Provision has also been made in the test section top and bottom walls for introducing pressure transducers to quantify wall effects while moving the airfoil.

3. RESULTS AND DISCUSSION

Fig. 9 shows stroboscopic schlieren pictures taken with an oscillating airfoil in the CDSF. The phase angles in the oscillation cycle were selected manually, and the strobe light source triggered by the control circuit. These pictures are snap shots of the flow and reflect the instantaneous density gradient field, unlike other methods of flow visualization in which time history effects are present. The present system is very effective for revealing the fluid phenomena on the airfoil.

Fig. 9a is a schlieren picture for steady flow over a NACA 0012 airfoil at an airfoil angle of attack of 10°; a Mach number of 0.4. At this condition, an audible tone was detected. Well defined cylindrical acoustic waves travelling upstream can be seen in the photograph. A small shock appears to be present for this flow condition on the upper surface. The details of the vortical flow in the boundary layer downstream of the shock can also be seen clearly. The long focal length of the schlieren mirrors resulted in a very sensitive system which enabled the capturing of these small scale details of the flow. Because of this, it was also possible to detect the density gradients at very low free stream Mach numbers, where the flow is normally considered to be incompressible. It is to be noted that the density gradients that produced this picture are about 2%. Fig. 9b presents a schlieren picture of the flow over the oscillating airfoil at a Mach number of 0.1, a reduced frerquency of 0.15 at an instantaneous angle of attack of 19.23°. The shear layer/vorticity layer separating from the leading edge is clearly visible as also the structure of the separated flow at this high angle of attack. The shear layer thickness is $\approx$ 2-3 mm and the gradients across it are very large. This information will be useful during grid generation for modelling the fully separated flow over the airfoil.

Fig. 9c represents a fully developed dynamic stall vortex at a Mach number of 0.3, reduced frequency of 0.05, and an angle of attack of $\approx$15 °. The scale of the vortex and the structure of the flow on the upper surface as well as the lower surface attached flow and the fine scales the trailing edge flow may be clearly seen. The gross differences in the scales on the two surfaces imply that the wake development is significantly affected, which has to be considered in the computer modelling of the flow.

4. CONCLUDING REMARKS

A unique Compressible Dynamic Stall Facility has been designed and installed to study the compressibility effects on dynamic stall of airfoils. The facility permits pitching an airfoil in either a harmonic oscillation or in a transient ramp-type motion at realistic flight conditions and rates by use of suitable drive systems. The ramp motion generator can also generate arbitrary motion of the airfoil and thus can simulate an arbitrary aircraft maneuver. The unique model mounting method used in the facility provides optical access for non-intrusive flow diagnostic techniques to be used for flow mapping. Many schlieren pictures have been obtained during the study which reveal the instantaneous density gradients associated with dynamic stall, even under conditions of very low Mach numbers.

Acknowledgements

This work was initiated by the late Professor Satya Bodapati, who was instrumental in developing the unsteady aerodynamics program in the Navy - NASA Joint Institute of Aeronautics.

The project was funded by AFOSR-MIPR-88-0010 (monitored by Capt. H.Helin). Additional support was provided by ARO-MIPR-137-86 (monitored by Dr. T. Doligalski) and NAVAIR (monitored by Mr. T. Momiyama). The support and encouragement of Dr. S.S.Davis, Chief, Fluid Mechanics Branch during the course of this project and the technical support of Mr. Michael J. Fidrich are greatly appreciated. The design efforts of the NASA Design Group are gratefully acknowledged.

References

[1] L.W.Carr, "Progress in Analysis and Prediction of Dynamic Stall", JL. AIRCRAFT, Vol.25, No.1, pp. 6-17, Jan. 1988.

[2] M.S.Francis and J.E.Keese, "Airfoil Dynamic Stall Performance with Large-Amplitude Motions", JL. AIRCRAFT, Vol.23, No.11, pp. 1653-1659, Nov. 1985.

[3] P.F.Lorber and F.O.Carta, "Airfoil Dynamic Stall at Constant Pitch Rate and High Reynolds Number", JL. AIRCRAFT, Vol.25, No.6, pp. 548-556, June 1988.

[4] P.F.Lorber and F.O Carta, "Unsteady Stall Penetration Experiments at High Reynolds Numbers", UTRC Report R87-956939-3, April 1987.

[5] M.C.Robinson and J.B.Wissler. "Pitch Rate and Reynolds Number Effects on a Pitching Rectangular Wing", AIAA Paper No. 88-2577-CP.

[6] J.M.Walker, H.E.Helin and J.H.Strickland, "An Experimental Investigation of an Airfoil Undergoing Large-Amplitude Pitching Motions", JL. AIRCRAFT, Vol. 23, No. 8, pp. 1141-1142, Aug. 1985.

[7] E.J.Jumper, S.J.Schreck and R.L.Dimmick, "Lift-Curve Characteristics for an Airfoil Pitching at Constant Rate", JL. AIRCRAFT, Vol. 24, No. 10, pp. 680-687.

[8] J.A.Albertson, T.R.Troutt and C.R.Kedzie, "Unsteady Aerodynamic Forces at Low Airfoil Pitching Rates", AIAA Paper No. 88-2579-CP.

[9] D.Favier, A.Agnes, C.Barbi and C.Maresca, "Combined Translation/Pitch Motion: A New Airfoil Dynamic Stall Simulation", JL. AIRCRAFT, Vol. 25, No. 9, pp. 805-814, Sep. 1988.

[10] P.W.Harper and R.E.Flanigan, "The Effect of Rate of Change of Angle of Attack on the Maximum Lift of a Small Model", NACA TN 2061, March 1950.

[11] M.S.Chandrasekhara and L.W.Carr, "Flow Visualization Studies of the Mach Number Effects on the Dynamic Stall of an Oscillating Airfoil", AIAA Paper No. 89-0023, Jan. 1989.

[12] L.W.Carr and M.S.Chandrasekhara, "Design and Development of a Compressible Dynamic Stall Facility", AIAA Paper. No. 89-0647, Jan. 1989.

[13] D.R.Andrews, "An Airfoil Pitch Apparatus: Modelling and Control Design", presented at the 35th ISA International Instrumentation Symposium, Orlando, Florida, U.S.A., May 1989.

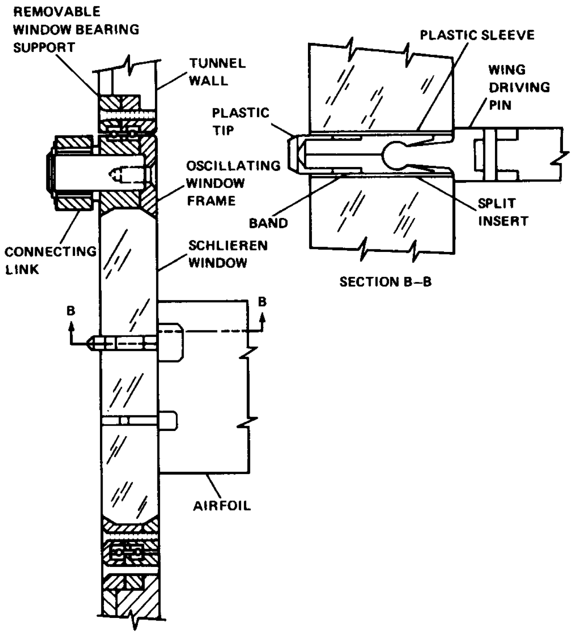

Fig. 1. Details of Airfoil Support at Window.

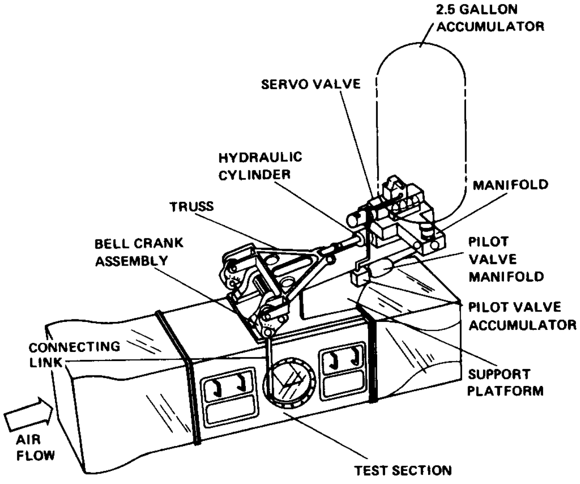

Fig. 2. Schematic of the Constant-Pitch-Rate Drive.

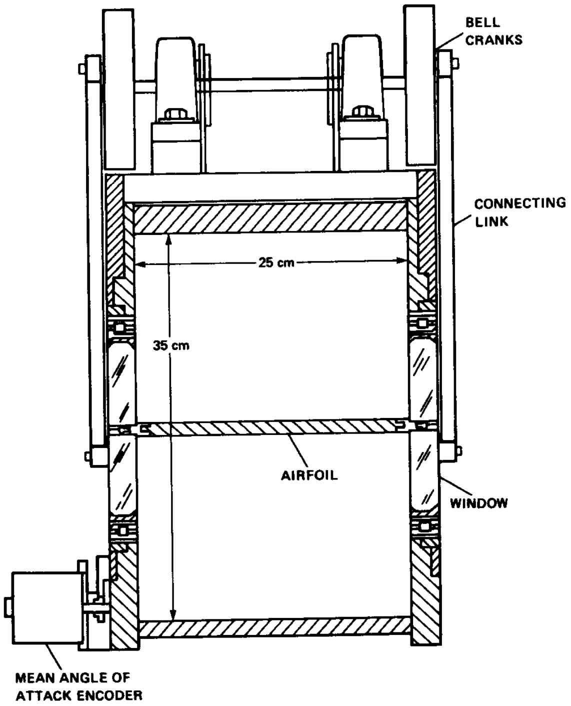

Fig. 3. End View of the Test Section.

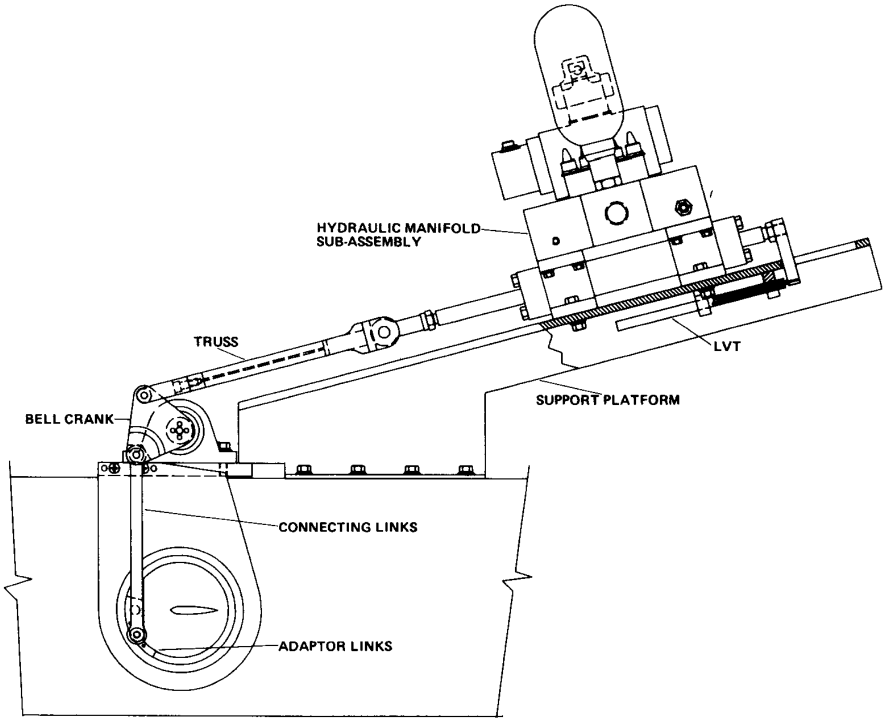

Fig. 4. Mechanical Assembly Details of the Drive System.

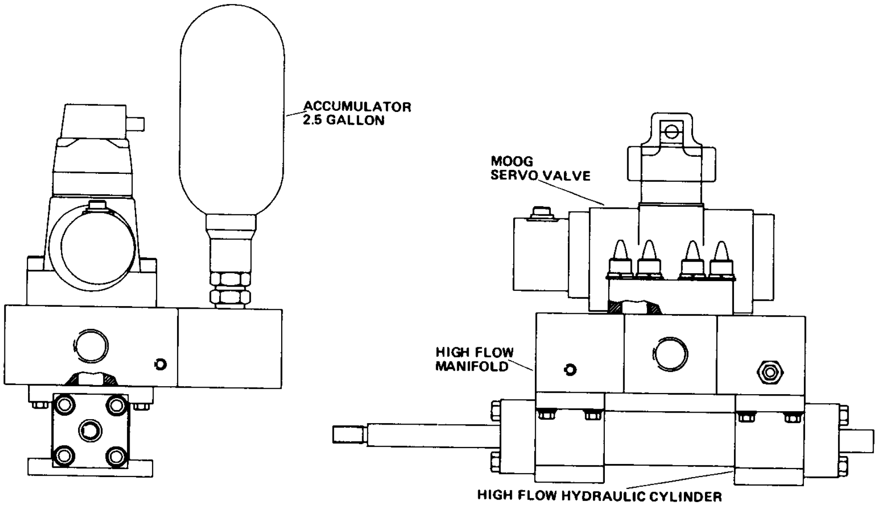

Fig. 5. Details of the Hydraulic Manifold Sub-assembly.

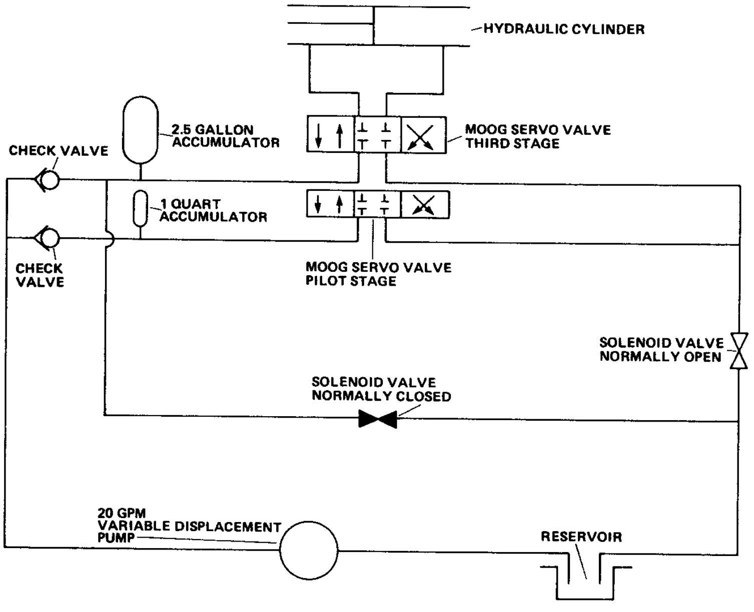

Fig. 6. Schematic of the Hydraulic Actuator.

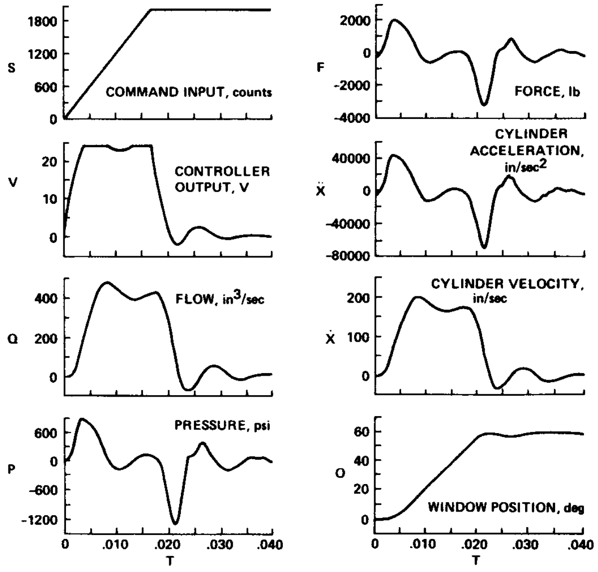

Fig. 7. System Theoretical Response Curves.

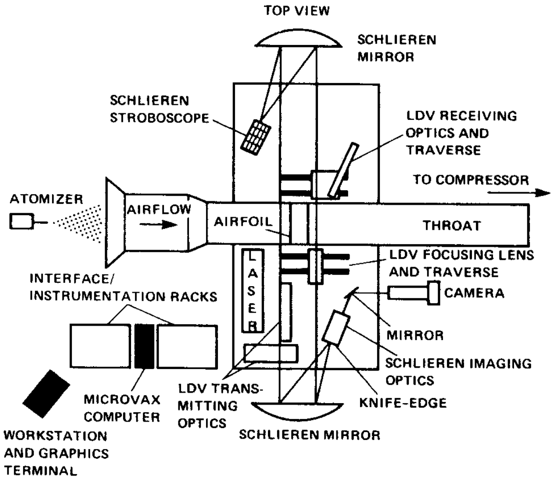

Fig. 8. Schematic of Compressible Dynamic Stall Facility and Instrumentation.

$M = 0.4$
STEADY
$\alpha = 10$

(a)

$M = 0.1$
$k = \dfrac{\pi f c}{U_\infty} = 0.15$
$\alpha = 19.23$

(b)

$M = 0.3$
$k = 0.05$
$\alpha = 15$

(c)

Fig. 9. Stroboscopic Schlieren Pictures of the Flow Over an Oscillating Airfoil.