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A UNIQUE APPROACH TO AEROELASTIC TESTING OF SCALED ROTORS

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ABSTRACT

In 1982 the U.S. Army Research Office commissioned the Georgia Institute of Technology to design and construct a unique testing facility for the purpose of acquiring a comprehensive data base of aeroelastic response characteristics for scaled model helicopter rotors. This data base could then be used in subsequent correlation studies to establish the validity or deficiencies of available analytical methods for the prediction of structural dynamic and/or unsteady aerodynamic phenomena. This paper presents detailed descriptions of the facility which resulted from this effort, the testing philosophy behind its design and use, and current and future test programs conducted in the facility.

1. INTRODUCTION

The Assistant Secretary of the U.S. Army, Dr. Percy A. Pierre, convened a team of experts to assess the Army's Vertical Lift Technology, Missions, and Management. This review team, which included representatives from the Army, Department of Defense, NASA, industry and academia, completed a report on their findings in 1980. One of the team's major recommendations was to establish a small number of centers of excellence in rotary wing technology among respected U.S. universities. The following year the U.S. Army Research Office requested proposals from U.S. institutions of higher learning with graduate-level programs to establish one or more such centers. The specific proposals were to include original and fundamental research programs in numerous areas of solid and fluid mechanics as related to rotary aircraft. In addition plans were requested for updating or developing experimental facilities which would significantly extend the capabilities of researchers in rotorcraft technology. These facilities were to complement the proposed research programs. A third aspect of the proposed effort was to provide graduate study programs in rotorcraft technology which would lead to advanced degrees.

In 1982 Georgia Tech was one of three schools chosen to participate in the development of the rotorcraft centers. One facet of the many research programs to be undertaken dealt with aeroelastic phenomena of rotor systems and in particular with the development of comprehensive aeroelastic analyses for the prediction of vibration levels. The underlying objective was to evaluate and possibly improve on the various methods of vibration suppression. As an adjunct to this program of analytical development, it was also proposed to design and construct a rotor test facility which could be used to measure dynamic response characteristics under known controlled conditions. The information compiled with this facility would thus form a valuable data base with which to correlate the predictions obtained from the aeroelastic analyses. It is the design and use of this facility which is the subject of this paper.

Since the primary purpose of the facility was to experimentally simulate and record various aeroelastic phenomena associated with contemporary helicopter rotor systems, it seemed appropriate to call it the Aeroelastic Rotor Test Chamber (AeroTech). As mentioned above, the funding for its initial design and development was appropriated by the U.S. Army Research Office. In 1984 a grant was awarded to Georgia Tech by the Department of Defense which permitted the installation of a hydraulic excitation system and a significant expansion to the data acquisition system. To understand and appreciate the usefulness of AeroTech to advances in the field of aeroelastic analyses of rotor systems, a few comments will now be made with respect to the philosophy which led to the final design.

2. FACILITY DESIGN

In order to establish a data base of experimental aeroelastic response characteristics for subsequent correlation and evaluation of analytical predictive methods, it was concluded that the testing conditions must be known and controlled with the greatest possible accuracy. During normal forward flight operations of a helicopter there are many uncontrolled perturbations introduced into the dynamic environment such as pilot inputs, atmospheric disturbances, weight and balance fluctuations and many others. These uncontrolled perturbations can be eliminated in a facility which has a closed environment and programmed operating conditions. In addition to uncontrolled perturbations, forward flight is characterized by various flow phenomena which are not readily amenable to analytical simulation. Such flows are associated with interactions between the blade airflow and tail boom, fuselage canopy, tail rotor and other empennages. Other phenomena which are also difficult to analytically predict include dynamic stall, reverse flow and blade-vortex interaction. Although each of these phenomena is of prime importance in validating the operational capability of a helicopter system, most of them only represent an input of dynamic excitation to the analyst. For this reason it is desirable to eliminate or significantly suppress their influence on the rotor dynamic response. Based on this premise the facility was conceived as a stationary test chamber contained within a large enclosure.

2.1 Aerodynamic Considerations

The concept of a stationary test chamber with the absence of an external uniform flow field as associated with a conventional wind tunnel, suggests that the chamber appears as a static thrust facility. This is not the case, since there is no intention to measure thrust nor other performance parameters. Another feature which distinguishes the chamber from a thrust facility is the incorporation of a conventional swashplate mechanism to simulate control inputs associated with forward flight operations.

Containment of the test chamber within a surrounding large enclosure can have a significant influence on the flow characteristics of the wake and can potentially induce an undesirable recirculation of this wake. In an effort to simulate an unperturbed free-air flow environment without wake distortion and recirculation of vorticity, the test chamber was constructed as a honeycombed enclosure. This enclosure is essentially a cylinder whose axis is coincident with the rotor shaft and whose diameter is twice that of the rotor. The upstream portion of the enclosure ahead of the rotor disk is hemispherical with a center at the hub. The downstream portion of the enclosure is terminated with a flat honeycomb surface normal to the axis of rotation. This surface contains a circular opening which is concentric with the rotor disk to facilitate passage of the rotor wake from the honeycomb chamber to the containment room. Once the wake flow is in the containment room it is free to recirculate back around the chamber and reenter the test region through the honeycomb surfaces. In this manner the vorticity contained in the wake will be destroyed by the filtering effect of the honeycomb as it is recirculated through the rotor disk. The general configuration of the chamber within the containment room is illustrated in Figures 1 and 2.

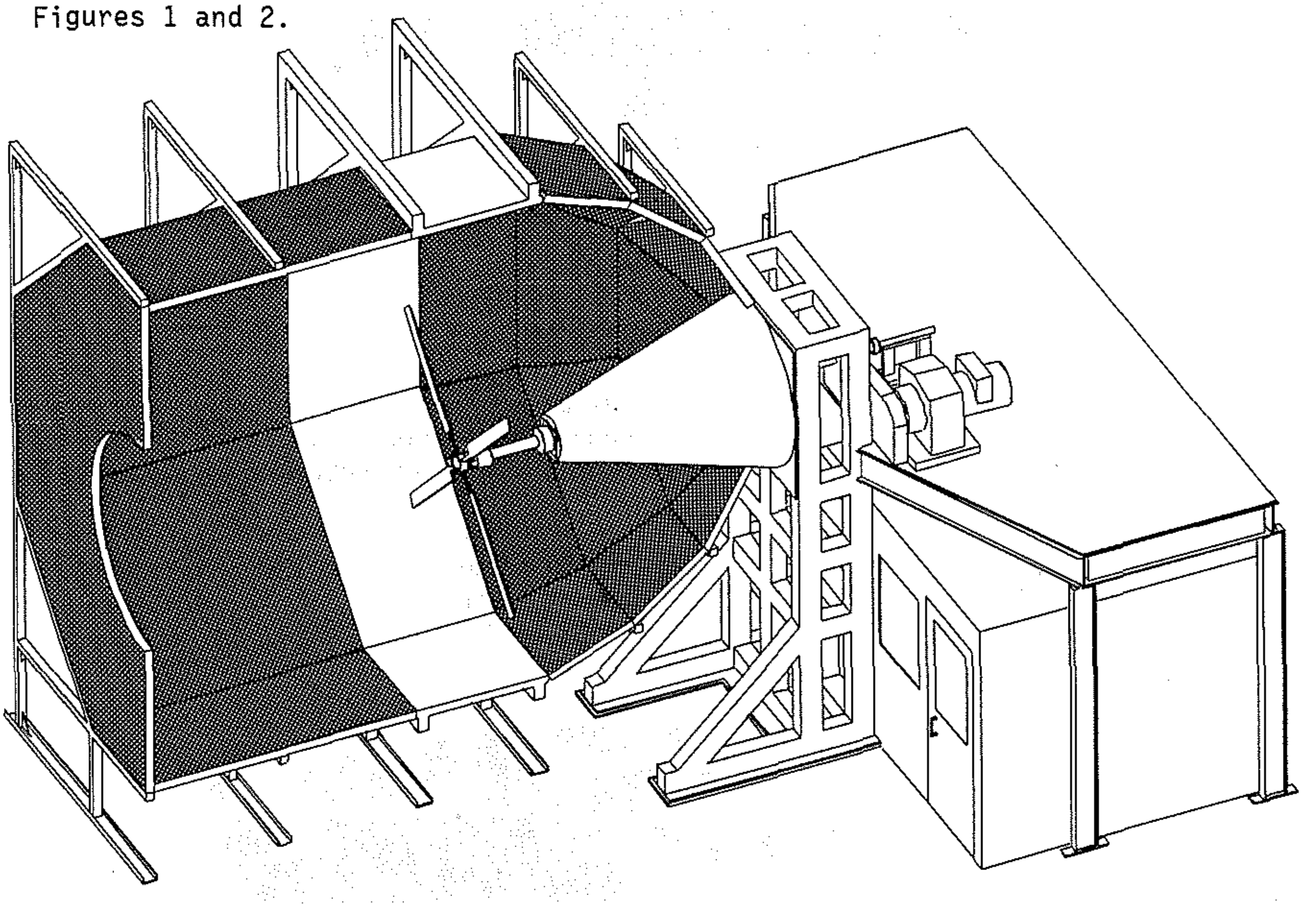

Figure 1. Aeroelastic Rotor Test Chamber (Cutaway View).

2.2 Mechanical Considerations

It can be noted in Figure 1 that the rotor shaft is supported within a steel cone in a horizontal rather than the more conventional vertical position. This orientation was necessitated by the availability of laboratory space, the aerodynamic requirement for recirculation, simplification of the drive system mechanics and suitability of the control room location. The major detriment of the horizontal drive shaft and associated vertical tip path plane is the asymmetric rotor loading imposed by gravity. Since this one per Rev inertial excitation will be present during all testing, it must also be simulated in any analytical method whose results are to be correlated with the data base generated in this facility.

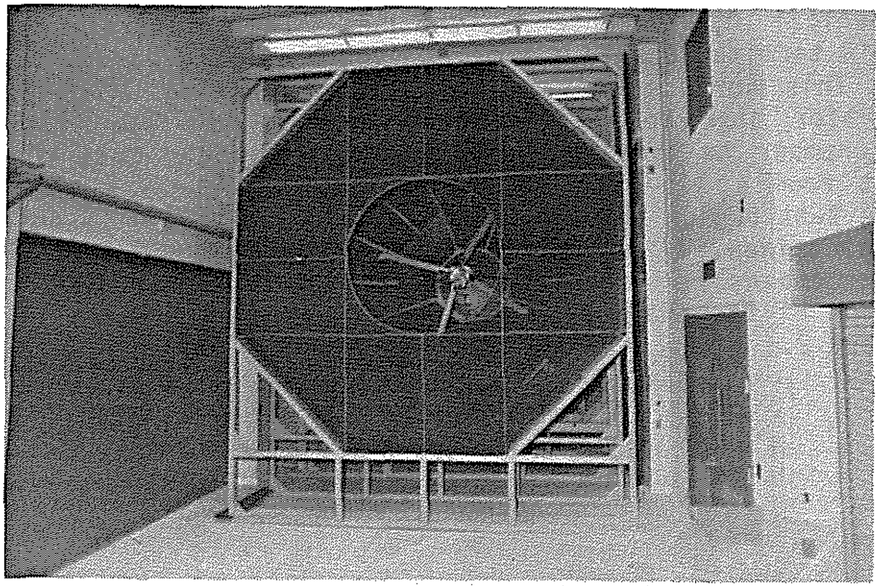

Figure 2. AeroTech Within the Containment Room.

In order to statically and dynamically control pitch attitude of the rotor blades during tests, a conventional swashplate mechanism was installed on the rotor drive shaft. To control orientation of the swashplate three hydraulic actuators have been mounted on the end of the cone which supports the drive shaft. These actuators have relatively high frequency response characteristics and can therefore be used to excite the structural dynamic rotor modes. Figure 3 illustrates the installation of the actuators, swashplate and pitch links with an articulated model rotor.

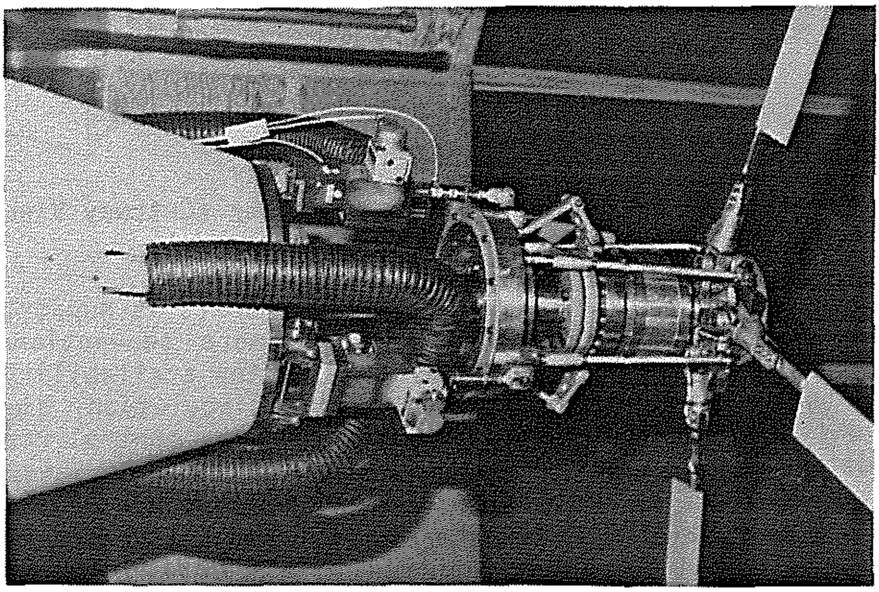

Figure 3. Hydraulic Actuators with Swashplate and Pitch Links.

Although the hydraulically operated swashplate system can be effectively used to dynamically excite the rotor, an alternate excitation system is also available. This system consists of stationary air jets which are directed normal to the tip path plane and located a short distance upstream of the rotor as illustrated in Figure 4. These jets have individually controllable air supplies and can be easily reoriented to different azimuthal locations. Since the jets are stationary, their greatest asset for dynamic excitation is absolute control of both frequency and phase with respect to the rotor speed and position.

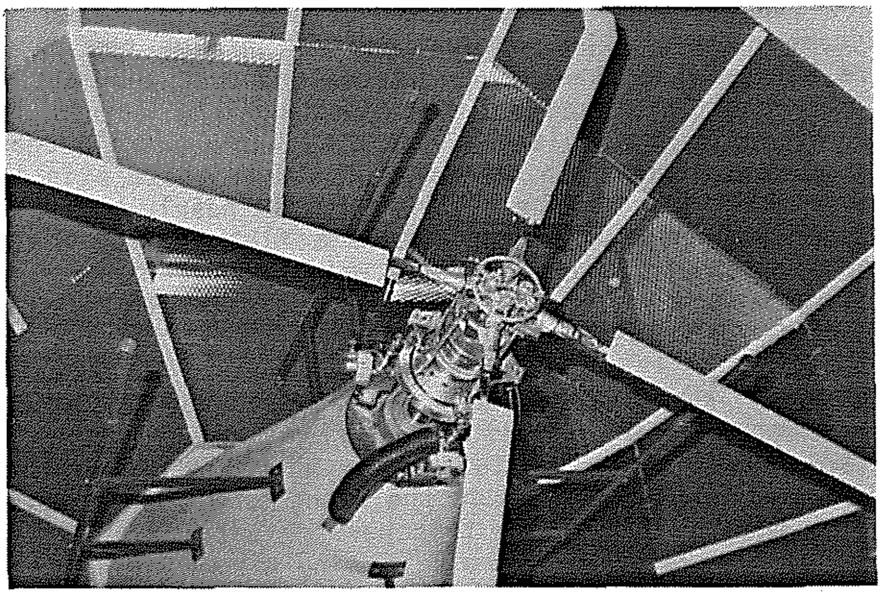

Figure 4. Articulated Rotor with Three of Four Air Jets.

2.3 Data Acquisition

Since the purpose of the test facility is to compile an extensive database of dynamic response characteristics, a primary requirement of the data acquisition system is to provide data storage and retrieval capabilities. Consequently the data handling system has been designed around a digital computer which has significant storage capability. This computer permits programming of both the test procedures and data analysis. The great majority of data to be recorded originates as analog signals in the rotating reference frame of the rotor. It was therefore necessary to transmit these signals through an appropriate slip ring assembly and thence through an analog-to-digital converter to the computer. Programmed test parameters established in the computer had to be conversely processed by a digital-to-analog converter before they could be used to control mechanical test devices.

It can be observed in Figure 1 that the control room which contains both the data acquisition and test control systems is located directly below the drive motor and immediately adjacent to the test chamber. The primary reason for this location is to minimize the length of data signal leads and thus maximize signal-to-noise ratios. Other benefits include shortened test control lines, minimal aerodynamic interference by the control room and direct visual access to the test specimen.

3. FACILITY DESCRIPTION

The design of AeroTech as described above has resulted in a complex dynamic testing facility which consists of four identifiable subsystems whose interaction is essential to the effective operation of the overall installation. These subsystems which include the test chamber, drive system, data acquisition system and the control & excitation systems will now be individually described.

3.1 Test Chamber

The test chamber within which the rotor models are tested is constructed of a tubular steel framework which supports 3 inches (7.6cm) thick paper honeycomb panels. The honeycomb voids through the panels equalize the pressure between the chamber and the exterior containment room. These voids are hexagonal in shape and 0.8 inches (2cm) across the flats to effectively eliminate recirculating vorticity. The overall chamber configuration can be described as an octagonal cylinder whose axis is coincident with the rotor drive shaft. The upstream end is nearly hemispherical about the rotor hub, and the downstream end is a flat surface with a centered circular opening through which the rotor wake is convected. The chamber is 16 feet (4.9m) between the flats of the octagonal cross section, and the overall length is 20 feet (6.1m).

A section of the chamber wall which surrounds the tip path plane consists of composite panels constructed from 3/4 inch (19mm) plywood and 5/16 inch (8mm) steel plate. This section which is 4 feet (1.2m) long is intended as a containment barrier in the event of a catastrophic structural failure of the model. Built into this barrier section of the chamber wall in the plane of the rotor is a small viewing window of clear Lexan (polycarbonate) and a high intensity strobe light. This optical system is used to evaluate the tracking accuracy of the test rotor.

3.2 Drive System

The electrically powered system which is used to drive the model rotors at speeds from 100 to 2,000 RPM consists of a 30 horsepower constant speed alternating current motor whose output is governed by an eddy current clutch. The output shaft speed of this system is maintained to within an accuracy of 0.1% by a feedback tachometer. The small electronic speed controller for the eddy current drive is located in the control room together with an electronic counter to provide the operator of the facility with a visual indication of the rotor RPM. The drive motor and clutch are located on a platform immediately above the control room as illustrated in Figure 1.

Power is transmitted from the motor-clutch system to the rotor drive shaft by conventional belts and sheaves. The drive shaft which is 11.3 feet (3.5m) long is mounted on three bearings. Two of these bearings are fastened to a massive steel superstructure which extends from the laboratory floor, while the third is a flange mounted bearing on the end of the cone which can be seen in Figure 4. In order to maintain a critical shaft speed in excess of the 2,000 RPM rated operating speed of the facility it was necessary to have a drive shaft diameter of 4.7 inches (11.9cm). The machining of this large drive shaft was complicated by the requirement that a cable of 55 electronic leads had to threaded down its center. It was therefore necessary to bore a 2.5 inch (6.4cm) hole the full 11.3 feet length of the shaft. After this complex machining job was completed and the electronic cable with connectors was installed, the shaft was dynamically balanced to a speed of 2,000 RPM. Figure 5 is a photograph of the motor and drive shaft installation as viewed from above the control room.

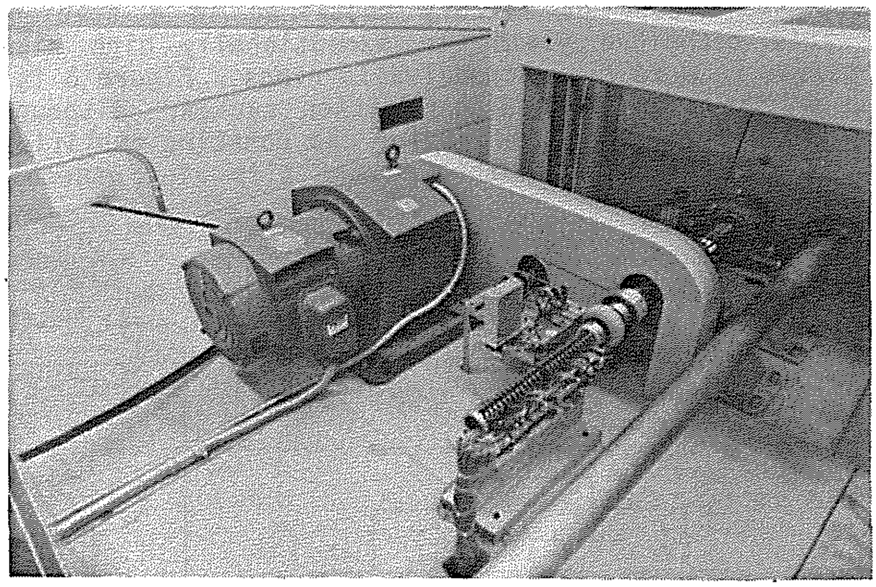

Figure 5. Motor and Drive Shaft with Slip Ring Assembly.

3.3 Data Acquisition System

As previously mentioned, the data handling system has been designed around a digital computer to permit efficient storage and retrieval capabilities. The computer chosen for the facility is a Hewlett Packard HP 1000 A700 system containing a floating point processor with scientific and vector instruction sets. It has 4 megabytes of memory and a hard disk storage capacity of 200 megabytes. This configuration was chosen for its high speed (1,000,000 instr/sec and 204,000 oper/sec) and its user-microprogammable capability. In addition to its Real-Time Executive operating system and interactive screen editor, the system includes a FORTRAN 77 compiler and an interactive three-dimensional graphics package. The availability of these software systems has greatly broadened the versatility of the computing facility to include usage in purely analytical studies as well as the intended data acquisition and test control rolls.

The data acquisition system has been designed to retrieve and store both response signals and environmental operating parameters. The environmental parameters which include such things as rotor speed, pitch angle, air temperature and many others are measured in the nonrotating system of the motor platform or control room. In contrast to these, the response signals are generally measured by transducers mounted on the rotating model. Before these signals are converted to the stationary system of the control room, they are first amplified by a gain of 100 to minimize the effects of potential noise sources during this conversion. The amplification is provided by forty DC differential amplifiers contained in a package which rotates with the drive shaft just upstream of the rotor hub. From these amplifiers the response signals are then transmitted through the cable which was threaded down the center of the drive shaft.

Coupled to the end of the drive shaft is a 52 channel slip ring assembly which converts the response data from the rotating to the nonrotating system. The design of these slip rings is unique in that the signals are not transmitted through sliding contacts. The electrical connection between the rotating and nonrotating elements is achieved by a disk rotating in a pool of mercury contained in a stationary annular container. This technique yields an exceptionally high signal-to-noise ratio in contrast to more conventional slip rings. Figure 6 is a schematic illustration of the overall data acquisition system. Although it is not indicated in the figure, the DC power for the rotating amplifiers and blade transducers is also transmitted through the slip ring assembly and drive shaft cable.

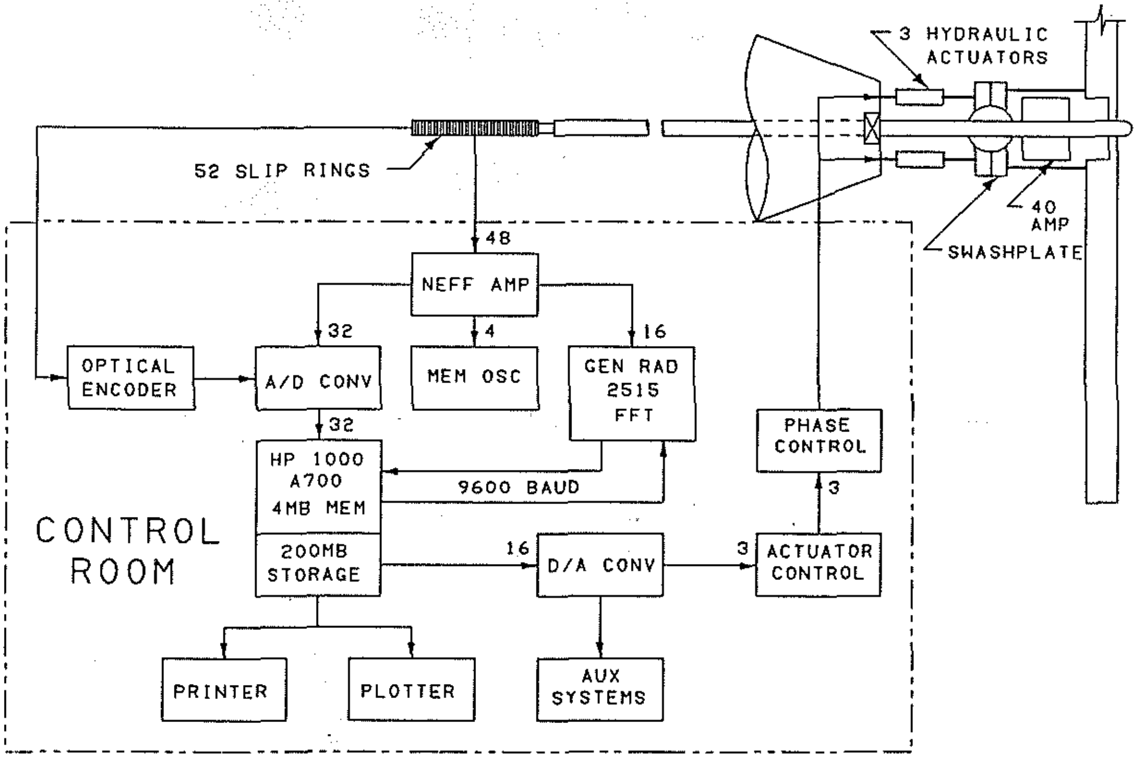

Figure 6. Data Acquisition and Control Systems.

After entering the control room, both the response signals and operating parameters are processed through a bank of 48 NEFF amplifiers. These wideband differential amplifiers have a common mode rejection of better than 120db to 60 Hz and a variable gain from 1 to 2,500 with an accuracy of 0.1%. A digital memory oscilloscope is available to monitor the outputs of any four of these amplifiers. Of the 48 amplifier outputs 32 channels can be processed on-line by an analog-to-digital converter for subsequent transmission to the HP 1000 A700 computer system. This Preston A/D converter has a sampling rate of 312,000 samples per second. It is internally clock driven and has an external start capability. The external start signal is supplied by an optical encoder installed on the rotor drive shaft (See Figure 5). This means of clocking the sampled response data permits a precise correlation between the data traces and the rotor position. All data received by the computer can be conditioned on-line to account for transducer calibrations, amplifier gains and units conversion. These final data traces can then be stored on hard disk for later retrieval and/or be immediately output as hard copy on a printer or plotter. The available dot matrix printer operates at 200 cps and can produce 90x90 dots/inch graphics presentations. Plotted output can be generated using up to six pens of different widths and/or colors on a format up to 11x17 inches or 297x420 mm.

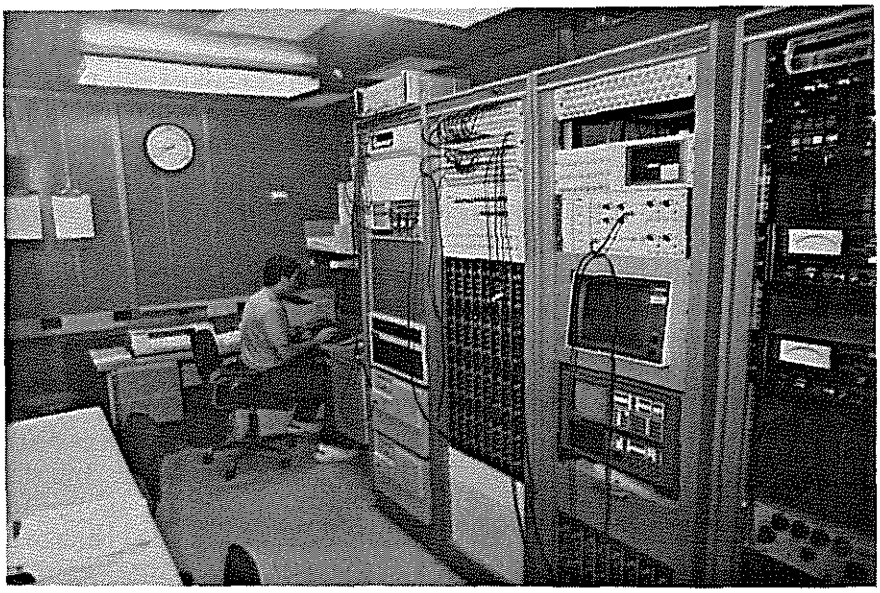

Figure 7. Control Room with Data Acquisition and Control Systems.

The remaining 16 channels of output from the 48 NEFF amplifiers are connected to a Fast Fourier Transform (FFT) analyzer. This unit is a GenRad 2515 Computer-Aided Testing System which has 1 megabyte of memory and a 10 megabyte Winchester disk for data storage. The system includes a high level programming language, specifically designed for signal processing. It can be programmed for on-line time, frequency or amplitude domain analyses of the incoming data or similar post-test data reduction. SDRC's Modal Plus software is also available to support comprehensive modal analysis of the response data and pretest vibration studies of the rotor models. The analyzer system is connected to the HP 1000 A700 computer by GenRad's DataLink, which provides a 9600 baud rate interchange of data between the two systems. This interface permits all results and data obtained by the analyzer to be stored on the larger disk of the HP 1000. It also provides the capability of analyzing, on the GenRad 2515, all data received and stored on the HP 1000 system. Figure 7 is a view of the control room which contains these data acquisition systems.

3.4 Control & Excitation Systems

As previously described, blade pitch control is effected by a conventional swashplate mechanism which is oriented by three hydraulic actuators as illustrated in Figure 3. The hydraulic actuator system was developed by Zonic Technical Laboratories and operates at 3000 psi with a 15 GPM pump. Each actuator has a maximum stroke of 1 inch (2.5cm). The useable stroke is a function of frequency to a maximum of 500 Hz. Each of the three actuators is controlled by a dual-loop servo-controller which consists of independent static and dynamic control loops. The controlled output parameter can be either displacement which is sensed by a linear variable differential transformer (LVDT) or force which is measured by a strain gage load cell. Since pitch angle is the end parameter of immediate concern, the LVDT is used in all current test programs.

Control input signals for the actuators originate in the HP 1000 computer system. All desired operational parameters are preset into the computer by the test engineer, and as a specific test is initiated each phase of the simulation is executed on an interactive basis by the engineer at the computer terminal. Control signals from the computer are processed by a digital-to-analog converter before being transmitted to the actuator controllers. This Preston D/A converter has 16 channels which are sampled at a rate determined by its external clock. The clocking of this conversion is established by a pulse train from an optical encoder mounted on the rotor drive shaft which generates 32,768 pulses per revolution.

The absolute displacements of the three actuators which orient the swashplate are kinematically related to the pitch attitude of each blade in the rotor. These kinematic relations are established for collective, longitudinal cyclic and lateral cyclic modes of the test rotor. They are then programmed into the computer to condition the required input signals for the actuator controllers. In addition to the kinematic relations it is also necessary for the computer to modify the controller inputs to reflect the static and dynamic characteristics of the actuator servo-loops. These characteristics have been obtained by an extensive calibration procedure which relates the true actuator displacement to the controller input voltage. Although the static calibration just entails determining a nonlinear displacement relationship, the dynamic characteristics involve both amplitude and phase which are functions of frequency.

During most typical test programs the steady control input to the rotor will only be collective pitch with the longitudinal and lateral inputs held at zero. Dynamic excitation of the blades can be achieved by an appropriate combination of all three rotor modes with a desired time dependency. As previously mentioned a second means of dynamic excitation is available from a set of four (or less) stationary air jets which are directed normal to the tip path plane from a short distance upstream. The air supply for these jets consists of a 300 SCFM compressor which supplies a 1,000 cubic feet ($28m^3$) reservoir with 125 psi air. Each of the jets is individually controlled by a pressure regulator to permit tailoring of the cyclic gust excitation. The radial position of the jets as illustrated in Figure 4 is 3 feet (0.9m) from the rotor shaft or the 75% radius of an 8 feet (2.4m) diameter rotor. Azimuthal relocation of the jets from their current 90 degree positioning is possible.

4. TEST PROGRAMS

The current test programs have been associated with the dynamic response characteristics of two aeroelastically scaled rotor models. The first of these models is referred to as the ACR (Aeroelastically Conformable Rotor) model. It is 9 feet (2.7m) in diameter and has been Mach scaled for operation in FREON 12 at a nominal speed of 685 RPM. This model which is illustrated in Figure 4 has a fully articulated hub. It is currently on loan from the NASA Langley Research Center. The second aeroelastic model which is to be tested late this year and early next is known as the HARP (Hughes Advanced Rotor Program) model. It has a diameter of 8 feet (2.4m) and has been Mach scaled for air at a nominal speed of 1,700 RPM. In contrast to the articulated ACR model this configuration has a bearingless hub design. The HARP model will be provided for testing by the McDonnell Douglas Helicopter Co.

4.1 Response Studies

Two types of dynamic response tests are being conducted on the models. The first consists of an experimental determination of the total system damping associated with each of the first few structural dynamic rotor modes. These tests are conducted at various rotor speeds and steady collective pitch settings. In addition to contributing to the overall aeroelastic data base, these damping characteristics will provide a good measure of the test system's aeroelastic stability as operated in the test facility. Excitation of each rotor mode is achieved by an appropriate combination of simple harmonic collective, longitudinal and lateral pitch control. Once the desired mode is excited the simple harmonic perturbations are removed and the resulting transient is recorded. Since these rotor modes have significant coupling it is necessary to use a moving block analysis to determine the damping parameters from the recorded transients.

The second type of response test is similar to the first in that the rotor excitation is again a combination of simple harmonic collective, longitudinal and lateral pitch control. In this case it is the forced response which is of interest rather than the free transient. It is also not intended excite individual rotor modes but rather a combination of them at various operating conditions. Before conducting either type of these response tests it is first necessary to conduct sufficient dynamic response analyses to identify the rotor modes and an efficient means of exciting them.

4.2 Vibration Control

Another type of aeroelastic response testing is currently being developed for use in the facility. This procedure is related to some forms of vibration suppression techniques which are currently being developed for operational helicopters. These techniques are most commonly referred to as higher harmonic control (HHC) and are primarily intended to limit vibration levels at specific points throughout the airframe. The test procedure being developed for use in AeroTech will utilize recorded response data in a control algorithm to minimize the selected response signals obtained from the rotating blade. The control mechanism will be provided by the three actuators to input appropriate amounts of collective, longitudinal and lateral pitch control. Initial efforts will be restricted to control at specific frequencies. In order to install the real time controller on the HP 1000 it will be necessary to program it in machine language rather than FORTRAN which has been used in the other response procedures.

4.3 Future Programs

As stated at the outset, the primary purpose behind the development of the AeroTech facility was to obtain a reliable data base of aeroelastic response characteristics which could be used for correlation with results obtained from analytical methods. As a natural consequence, all of the preceding test procedures have been concerned with the experimental simulation of various aeroelastic phenomena. The versatile capability of this facility suggests that it may be used for many purposes other than just aeroelastic data base gathering. It is quite suitable for evaluating numerous aspects of new rotor designs in the hover mode. The development of flutter suppression techniques and gust alleviation methods in the hover mode are also possible in the facility. One of the broadest areas of potential applications offered by AeroTech is its capability to provide a controlled simulation of numerous unsteady aerodynamic phenomena. Such flows include dynamic stall, blade-vortex interaction, rotor-body interaction and ground plane effects. Installation of pressure instrumented models could provide valuable loading data associated with these flows. With the addition of laser Doppler velocimeter instrumentation detailed unsteady flow field measurements could also be made of these little understood phenomena.

5. SUMMARY COMMENTS

A unique approach to the aeroelastic testing of scaled helicopter rotors has led to the development of the Aeroelastic Rotor Test Chamber or AeroTech as it is called at Georgia Tech. The testing concept is based on the generation of a comprehensive data base of controlled aeroelastic response characteristics for helicopter rotor systems. This data base can then be used for subsequent correlation studies of results obtained from analytical methods. These correlations will then permit an unbiased evaluation of the analytical simulations and should thus lead to significant advances in the current state of aeroelastic predictive techniques.

In addition to the generation of the aeroelastic data base, it has been observed that the AeroTech facility is well suited to conduct other experimental programs which can significantly contribute to rotor technology. Such programs include the development of flutter suppression techniques and gust alleviation schemes, as well as controlled simulation of numerous unsteady aerodynamic phenomena. On the basis of these observations the facility has the potential to greatly enhance our engineering capabilities in the field of rotor phenomena.

6. ACKNOWLEDGEMENT

The development of the AeroTech facility was supported by the U.S. Army Research Office under Grant DAAG29-82-K-0094 and Instrumentation Grant DAAG29-85-G-0072.