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INSTRUMENTATION OF THE YAMAHA R-50/RMAX HELICOPTER TESTBEDS FOR AIRLOADS IDENTIFICATION AND FOLLOW-ON RESEARCH

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ABSTRACT

The School of Aerospace Engineering of the Georgia Institute of Technology (GIT) has been using two Yamaha R-50 remote controlled helicopters (RPHs) as testbeds for flight controls research in the Center of Excellence in Rotorcraft Technology (CERT) over the past two years. A larger and more capable version of the Yamaha R-50 RPH, the RMAX, is being purchased by Georgia Tech as a testbed to support the DARPA Software Enabled Control (SEC) project as well as to serve as a generic testbed for other research being conducted at Georgia Tech. The objective of this paper is to describe the planned instrumentation for the testbed and how we plan to identify the loads on the baseline RMAX RPH.

Instrumentation requirements for the described Load Identification Method include the use of strain, accelerometer, tilt (angle) and position sensors totaling 50 channels of measurements obtained on the rotating rotor system. Data will be collected by a micro miniature signal conditioner/PCM encoder placed on the helicopter rotor hub. The data will be transmitted to the ground by a wideband telemetry microwave transmitter. The data acquisition system located on ground consists of a PC-compatible format synchronizer/decommutator and a PC compatible bit synchronizer decoding the data cards connected to a Model S5200 personal telemetry computer.

1- INTRODUCTION

1.1 General Scope of the Study

It is generally recognized that Uninhabited Aerial Vehicles (UAVs) may serve the Department of Defense (DoD) community effectively and affordably by accomplishing such critical mission functions as reconnaissance and strike with minimal human invention and logistics support The Army, Navy, and Marines all have expressed strong interest in the unmanned Vertical Take-Off and Landing (VTOL) concept. It also has attracted attention from other government agencies, including the Border Patrol and police departments, as well as from commercial operations, from pipeline and power line inspection to charting of fish.

The current state-of-the-art in Software Enabled Control (SEC) technologies is incapable of supporting these functions for demanding military missions, such as Urban Warefare (UW) and Suppression of Enemy Air Defense (SEAD). Autonomous UAVs performing extreme performance maneuvers are currently impractical and intractable using today's control engineering approaches. As stated in the DoD Uninhabited Combat Air Vehicle (UCAV) Operation System (UOS) System Capability Document (SCD) [1].

> "The flight control function should perform the actual mechanical operations of the vehicle to accomplish the mission and should be highly automated. This function continually implements the collision avoidance, terrain avoidance, and attack maneuvering to the accuracy required by the Mission Management System (MMS)"

Extreme performance maneuvers for two types of aircraft, a helicopter and a fighter, are illustrated in Figure 1. As can be seen the helicopter has high agility in low speed with turn rates of up to 80 degs/sec, which allows it to perform Nap of the Earth (NOE) flight. On the other hand, the fixed wing fighter has excellent maneuvering capability at its "corner speed" with approximately 40 degs/sec turn rates. While these extreme performance capabilities can be achieved in piloted aircraft, they can't be achieved on UAVs without robust new SEC technologies and an Open Control Platform (OCP) environment for on-line customization.

The SEC program is based on providing the mission intelligence flow illustrated in Figure 2. *Situation Awareness* is used for *Mission Planning and Flight Mode Selection* which constitutes the *high level* control elements. For inhabited aircraft the pilot and other crewmembers provide the intelligence for interpreting the data from a variety of sources to execute these functions. Much of this data is used in pre-flight or pre-mission planning and is updated on-board as the mission proceeds. As the mission segments are executed and abnormal events are encountered, flight *Mode Switching* takes place which constitutes *the mid level* control element. On an inhabited aircraft the pilot flies the aircraft and makes necessary mode switching and control reconfiguration decisions for implementation through the use of the *Flight Control System.* This constitutes the *low level* control element and is used to execute the smooth transition between modes of flight, i.e., transition from hover or takeoff to level flight, etc., and stay within the flight envelope of the UAVs. *External Abnormal Conditions* cause the pilot to take corrective action, such as avoiding an obstacle or evading a target or threat. *Internal Abnormal Conditions* can also occur, such as the failure or malfunction of a component on board the aircraft. Once again the pilot provides the intelligence to take the corrective action by reconfiguring his/her set of controls to safely continue to fly or land the aircraft.

Without a pilot onboard the aircraft a UAV must either be controlled from the ground by a radio control ground pilot or the UAV must have its own intelligence to fly autonomously. Executing a VTOL UAV mission autonomously has been demonstrated, by both the Georgia Tech and Sikorsky Aircraft UAVs in the Army's Advanced Scout Rotorcraft Testbed (ASRT) Project [2]. However, both of the aircraft weren't able to use the entire flight envelope capability of the UAVs, largely limited by the controls algorithms implemented. In addition, the control algorithms were very much customized for the particular vehicle's characteristics and were developed in very much of a trial and error approach. Also, the computing architecture on-board the aircraft did not provide the environment for reusability and reconfigurability, let alone for plug and play of different SEC algorithms.

In addition, a number of technologies are being developed for implementation in the rotating system on rotorcraft, both manned and unmanned, that include the use of smart materials, flow control, individual blade control, and health usage monitoring systems. A low cost generic testbed that was properly instrumented could go a long way to furthering the development of these high payoff technologies. To properly develop and use a generic rotorcraft UAV testbed requires an integrated rotor design, analysis, and test approach through virtual prototyping to predict, verify, and document the rotor loads on the baseline aircraft. The planned approach is to use a previously developed load determination methodology, including load identification and modification, based on the inverse method to calculate the rotor loads from the measured blade response.

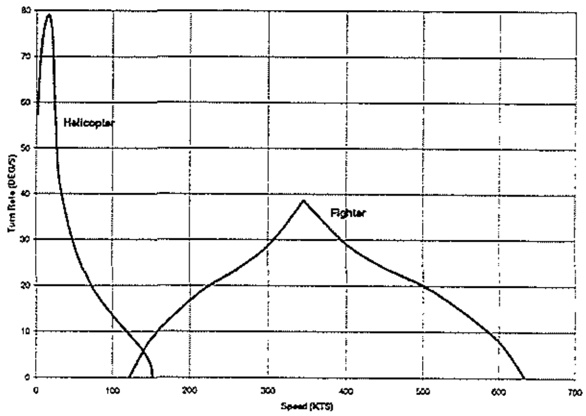


Figure 1. Extreme Performance Capabilities

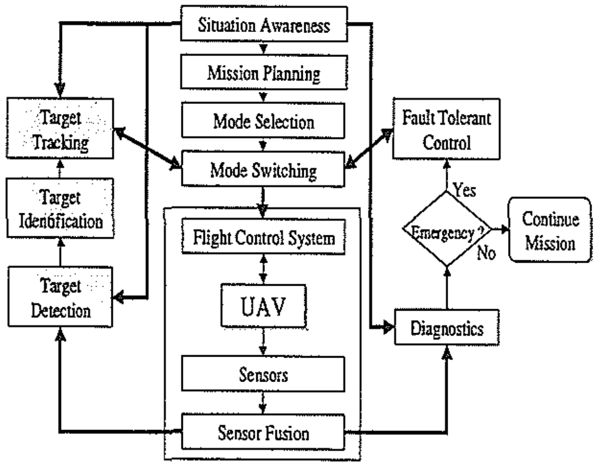


Figure 2. Mission Intelligence Flow

1.2 Rotor Load Determination Method

The determination of rotorcraft rotor loads, including the airloads on the rotor blade, the structural loads (or internal forces) of the blade, and the rotor hub loads (hub forces and moments) continues to be of primary importance and is still considered the " Achilles' Heel " for rotorcraft design, operation and technology development.

Prediction, known as the "direct" problem, is the common approach to determine the rotor loads. Although a long-term effort has been made to improve and advance the technology, the accuracy of predicting the rotor loads in many cases is still unsatisfactory. In view of the problems which still exist for predicting rotor loads the Georgia Tech Center of Excellence in Rotorcraft Technology (CERT) has conducted research work on the "inverse" problem for the determination of rotor loads. In the most general inverse problem, the response is known but either the equations describing the process or the system are unknown or the inputs themselves are unknown. For the inverse problem of rotorcraft rotor load determination it is the later case. This research work [3] includes "rotor load identification" and "rotor load transformation". The two concepts will now be briefly addressed:

Rotor Load Identification: It is an approach for the determination of rotor loads from measured structural response data such as measured strains at specific stations on the blade, local accelerations or strains at points on the fuselage structure. This is a typical inverse problem. All of the response data are measured on the rotor or rotorcraft itself.

Rotor Load Transformation: It is an approach for the determination of rotor loads from measured structural response data; however, the response data utilized in the analysis are measured on another (not the same) rotor or rotorcraft. This is the primary difference from rotor load identification as described above. This approach is actually a combination of the inverse problem and the direct problem, not just an inverse problem.

Rotor Blade Displacement and Load Identification Method

The concept of load or force identification is not a new concept. In essence, the system becomes its own force sensor. Some successful applications of the force identification process have been achieved for mechanical, civil, automotive, and aerospace engineering. With respect to the helicopter, much work regarding this subject has also been performed and certain achievements have been made.

In the Georgia Tech CERT, some rotor blade displacement and load identification methods have been developed or used and they form the basis for rotor load determination. The research work is continuing and the methods are planed for validation and further development on the YAMAHA R-50/RMAX helicopter testbeds. Two approaches, based on the modal analysis and force analysis respectively, for rotor blade load identification will now be briefly discussed:

Modal Analysis Method

The modal analysis method has been used previously for the flapwise case of rotor blade displacement and load identification. This modal analysis method is based on the principle of modal superposition. The modal bending moments (and the slopes of the modal displacements) are used in conjunction with the measured bending moment (and flap angle) data to identify the generalized coordinates. With the generalized coordinates identified and the other modal parameters, the displacement, slopes, shears and the airloads can be determined. The details of the procedure is given in detail in Reference [4].

In Reference [4], this technique for rotor blade displacement and load determination has been applied using a flight test case of a light helicopter in forward flight with and without High Harmonics Control (HHC). The process of determining blade displacement and loads (structural loads, airloads and hub loads) from measured blade bending moments is systematically described. Some practical problems such as the ill-conditioned problem and the underdetermined problem have been investigated, analyzed and solved. For calculation of the generalized coordinates, the Single Value Decomposition (SVD) method is a powerful tool and was for the first time, applied successfully in the rotor blade displacement and load determination process to explore the ill-conditioned problem. For the articulated rotor, it is necessary to use the measured flap angle in conjunction with an iterative process to determine the generalized coordinate of the first flapwise mode and a recurrence formula in matrix form for this process has been developed.

Force Analysis Method

It is obvious that the calculation of the generalized coordinates is the key in the modal analysis approach and much attention should be paid to ill-conditioned problem. This modal analysis method is simple and works well for flapwise blade load identification. But when we extend this method to the coupled flap-lag and/or coupled flap-lag-torsion rotor blade load identification, certain computational problems can occur. In this method, the ill-conditioned problem becomes serious. The disadvantage of modal superposition which exists in other rotor dynamic analysis methods also appear in this method. Therefore, another approach so called the " Inverse Transfer Matrix Method" has been developed.

Inverse Transfer Matrix Method (ITMM):

This method is based on the force analysis and basically is an inverse process based on an extension of the Myklestad method. In this method a transfer matrix equation relating blade station n with n+1 is established. After determining the bending moment distribution at all stations along the blade from the measured bending moments, and by using these bending moments in conjunction with the measured flap angles, lead-lag angles, damper moment at the blade root and the displacement boundary condition, moving from the root toward the tip of the blade, the displacements, slopes and shears at all of the stations along the blade can be obtained. Based on the results from ITMM, the airloads on the blade can be calculated. The developed methodology has been applied to the coupled flap-lag rotor blade load identification [5] and coupled flap-lag-torsion rotor blade load identification [6,7].

In this research work an articulated rotor is considered. The response data used in the coupled flap-lag case are the flapwise and chordwise bending moments at specific radial stations on the blade including the lead-lag damper moment at the root, the flap angles, lead-lag angles and pitch angles at the blade root. Based on these response data, the displacements and loads of the blade in both flapwise and chordwise directions can be determined. The procedure is schematically described in Figure 3.

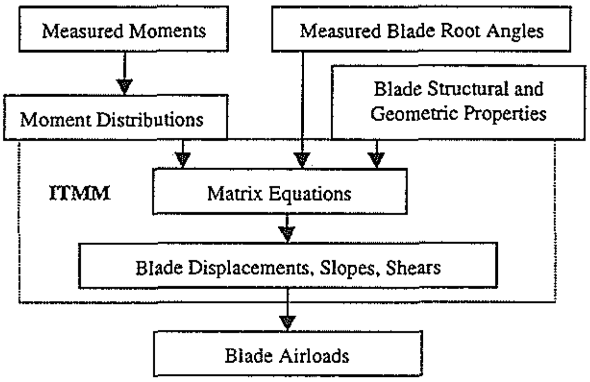


Figure 3. Inverse Transfer Matrix Method (ITMM) Calculation Procedure.

In the coupled flap-lag-torsion case, the measured response data should include torsional moments. The procedure is identical as shown in Figure 3 [6].

The method and process are verified in Reference [5] using simulated flapwise and chordwise bending moments and other response data that have been calculated using the measured airloads obtained during the NASA/Army UH-60A Airloads Program. The flight test airloads are measured at 9 stations and fitted airloads distributions at 49 blade locations are obtained by a third order B-spline interpolation.

The fitted airloads, the calculated displacements, slopes, shears and bending moments referred as the "measured" data and marked as "data" in the following figures. The bending moments at certain locations, lead-lad damper moments, flap and lead-lag angles of this "measured" data are chosen as "experimental data" for the identification calculations and marked by "exp" in the following figures. From these "experimental data" the bending moment distributions, the displacements, slopes, shears and airloads are determined and marked as " id" in the following figures.

Figures 4 to 8 show the comparison of the first harmonic cosine components of the determined flapwise and chordwise bending moment distributions, displacements, shears and airloads with the corresponding "measured" data. Presented results are taken from Reference [5]. Three different cases presented in these figures correspond to 9, 12 and 16 "experimental" data points are considered, respectively.

In Figure 4 the first harmonic cosine component of M_y (lead-lag) and M_z (flap) bending moment distributions are presented and very good agreements have been obtained between the identified moment distributions and the measured data. Similar results for the first harmonic cosine of the flapwise (w) and lead-lag (v) displacements are presented in Figure 5 where results have shown excellent agreements.

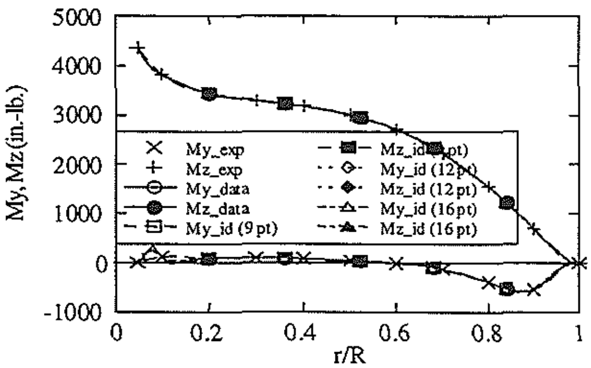


Figure 4. Comparison of Determined and Measured Bending Moments (First Harmonic Cosine Component).

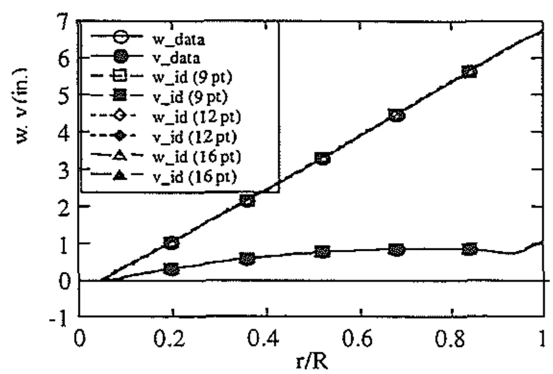


Figure 5. Comparison of Determined and Measured Displacements (First Harmonic Cosine Component).

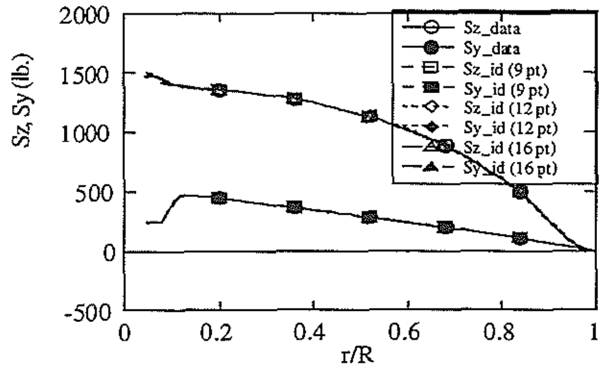


Figure 6. Comparison of Determined and Measured Shear Forces (First Harmonic Cosine Component).

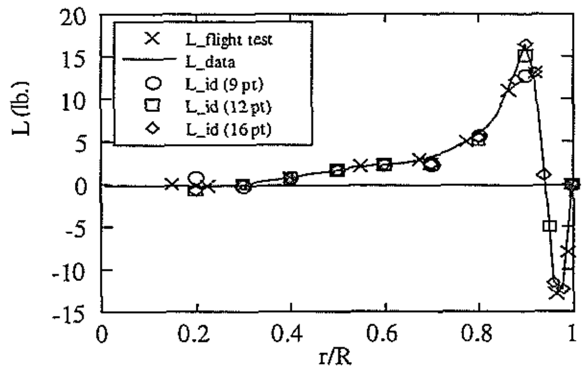


Figure 7. Comparison of Determined and Measured Aerodynamic Lifting Force (First Harmonic Cosine Component).

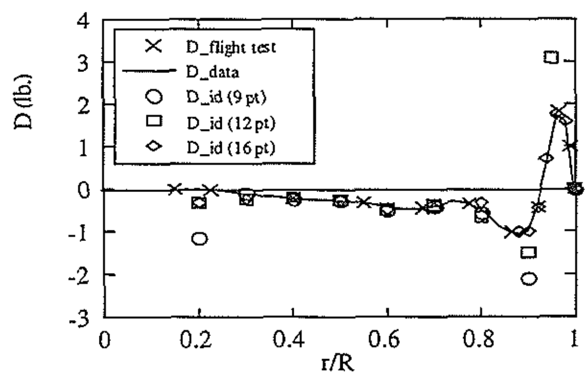


Figure 8. Comparison of Determined and Measured Aerodynamic Drag Force (First Harmonic Cosine Component).

Flapwise (S_z) and chordwise (S_y) shear forces identified by the developed methodology are compared with the measured data in Figure 6 where very good agreements have been obtained for all three cases considered. Figures 7 and 8 depict the blade aerodynamic lift and drag force distributions. As seen from these figures similarly good agreements have been observed for the case of 16 data points considered for the blade aerodynamic loads identification process.

Although a lot of the research work on rotorcraft rotor load determination has been accomplished in the Georgia Tech CERT, the verification, validation, modification and development of the methodology on the testbed are very important. It is not only for the methodology itself, but also to establish baseline loads for other research projects and; finally, should be of enormous benefits to rotorcraft community.

1.3 Testbed Aircraft Description

The CERT in the School of Aerospace Engineering, at the Georgia Institute of Technology (GIT) has been using two Yamaha R-50 remote controlled helicopters, for flight controls research. This research work has resulted in a DARPA contract for Software Enabled Control (SEC) for intelligent UAVs as a joint project with School of Electrical and Computer Engineering and Boing Phantom Works. Thus, the Yamaha R-50/RMAX are quickly becoming testbeds for a variety of research efforts at GIT. Since Georgia Tech Research Institute (GTRI) had stopped using their fixed wing avionics integration aircraft the Yamaha R-50 will be the only aerial platforms at GIT that can be used as testbeds for evaluating emerging technologies like MicroElectroMechanical Systems (MEMS), Health Usage and Monitoring Systems (HUMS), Smart Materials and Structures, Real Time High Speed Chip and Processor Design, etc.

Figure 9. RMAX Remote Controlled Helicopter In Agriculture Spraying Configuration.

A RMAX helicopter, upgraded version of R-50 helicopter shown in agricultural spray configuration in Figure 9, is also being procured as the primary generic testbed.

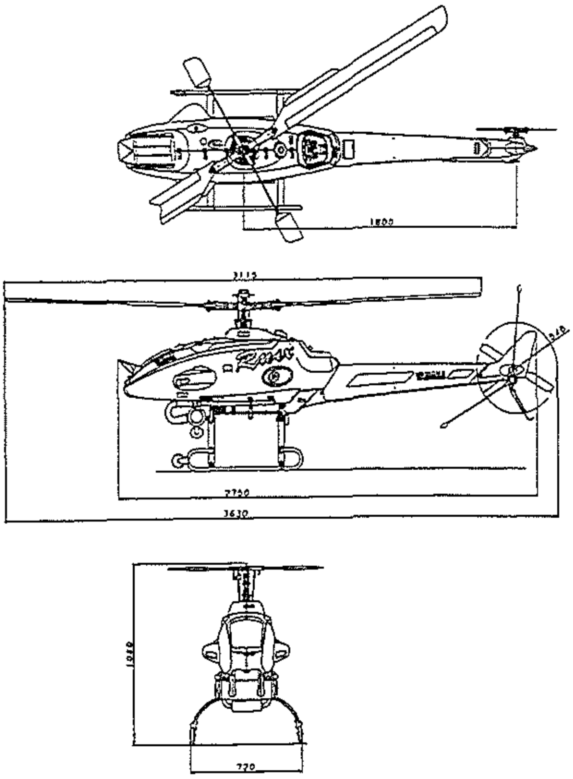


Figure 10. RMAX Top, Side and Front View (Measures in mm)

Both helicopters have two main rotor blades with two stabilizer bars and two tail rotor blades. In Figure 10 the RMAX helicopter is shown in three major views with it's major dimensions.

Table 1. R-50 and RMAX General Data

	R-50	RMAX	UNIT
Empty Weight	47	58	kg
Payload	20	30	kg
Endurance (Full payload)	30	60	min
Control Range	150	150	m
Main Rotor Diameter	3070	3115	mm
Main Rotor RPM	870	830	rpm
Tail Rotor Diameter	520	545	mm
Tail Rotor RPM			
Overall Length	2655	3630	mm
Body Width	700	720	mm
Overall Height	1080	1080	mm
Engine RPM	9330-9550	6350	rpm
Engine Size	98	246	ccm
Installed Power	12	21	PS

The main rotor hub of RMAX helicopter is rigidly connected to blade shaft. There is no teetering or flapping hinge at the rotor hub. The blades attached to the hub with pitch bearing shafts which have pins between hub. Blades do not have a hinged or other kind of degree of freedom in flap (out of plane) direction. Therefore RMAX rotor blades have rigid connections in flapping. A rubber damper attached at the blade root reacts off a fixed pin at the blade grip. Additionally, the blade grip provides friction-based damping in the lead-lag direction. This combined reaction/friction mechanism constitutes the lead-lag damper. RMAX rotor hub assembly is shown in Figure 11.

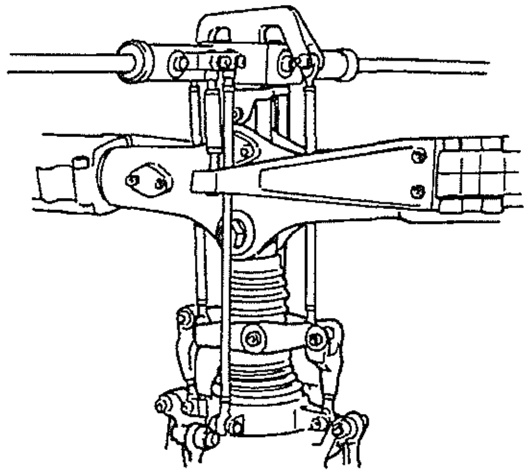


Figure 11. RMAX Rotor Hub Assembly

Both helicopters have two stroke piston engine where R-50 has one cylinder and the RMAX has two cylinder engines. To start the R-50 engine an external device is required, whereas the RMAX has an electrical starter onboard. In addition the RMAX helicopter is equipped with an onboard electrical generator and a rechargeable battery. General data of R-50 and RMAX helicopters are given in Table 1.

The RMAX helicopter has two main rotor blades with 1557 mm radius. It has a chord of 138 mm except between the sections r = 401mm to r = 744mm from the center of hub. This section is a cooling tab with the chord width 167 mm. The general description of the RMAX rotor blade is shown in Figure 12.

2. MEASUREMENT SYSTEM DESCRIPTION

2.1 Required Rotor Blade and Vehicle Measurements

As briefly described in the previous section certain data listed in Table 2 is needed to be measured. Some of these measurements are direct inputs to the load identification calculations whereas some of them are used for verification purposes. The data required in the non rotating system, already being measured by the existing R-50 instrumentation system, will be used in the RMAX helicopter and selected data will be used for the identification calculations. Measurements of bending and torsion moments distributions along the blade, the root moments and the blade root flap and lead-lag angles are needed as direct inputs to the load identification calculations for determining the blade displacements and shear forces. The calculated displacements will be compared with the displacements determined by the acceleration measurements.

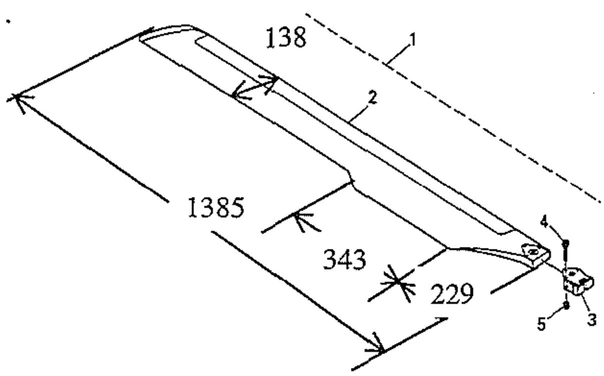


Figure 12. RMAX Rotor Blade General View.

Table 2. Measured Data for the Identification Methodology.

ROTATING SYSTEM	NONROTATING SYSTEM
Blade bending moments distributions	Collective pitch angle
Blade torsional moment distribution	Lateral cyclic pitch angle
Blade root moments	Longitudinal cyclic pitch angle
Blade flap and lead-lag angles	Rotor shaft power
Blade root pitch angle	Altitude
Pitch link rod loads	
Hub accelerations	Helicopter velocity
Rotor shaft loads	Helicopter attitude
Blade accelerations distribution	Rotor rotational speed

The currently developed load identification methodology is based on steady flight conditions (level, constant speed forward flight) and requires the assumption of non-accelerating hub in the analysis. The data obtained for the period of zero or close to zero hub acceleration will be used as input for the calculations.

General Description of the Measurement Sensors Configuration

The general layout of the sensors for the Load Identification Method consists of two major groups; sensors for the measurements on the rotating system and the sensors on the non-rotating system. For the rotating system the major difficulty is the limited space and the area for placing the sensors on the 5 ft radius rotor blade and data acquisition components on the hub of rotor system.

Based on the previous experience nine measurements for in-plane and out-of-plane bending moments and five measurements for torsional moment are needed along the rotor blade span. For five spanwise locations blade linear accelerations in flap, lead-lag and twist angular acceleration are required to be measured. Other measurements for at the blade root, rotor hub and pitch link rods as listed in Table 3.

Current selected sensor configuration requires six PVDF film sensors like DT1-028 K/L or LDT0-028K/L and four acceleration sensors at each blade spanwise station as shown in Figure 13. Two PVDF Film sensors will be used for measuring each curvature in flap (out of plane), lead-lag (in plane) bending and torsion (twist) at nine different blade spanwise locations (four for torsion). Placement of all these sensors on this rotor blade limited cross-section and planform is quite challenging.

Table 3. Sensors Placed on the RMAX Rotor Blade

MEASUREMENT	TYPE	# OF SENSOR	# OF SIGNAL	OUTPUT TYPE
Blade Bending Moment	Strain	18	9	Analog
Blade Lead-lag Moment	Strain	18	9	Analog
Blade Torsional Moment	Strain	10	5	Analog
Blade Flap and lead-lag Angles	Accel	4	2	Analog
Root Lead-Lag Moment	Strain	2	1	Analog
Root Torsional Moment	Strain	2	1	Analog
Hub Acceleration	Accel	1	3	Digital
Blade Displacement	Accel	20	20	Analog
Pitch Link Rod Loads	Strain	2	2	Analog
Root Pitch Angle	Accel	2	2	Digital
Σ		79	54	

One triaxial acceleration sensor will be placed on the blade on the pitch axis of the blade for measuring three linear (X, Y and Z_1) accelerations. A second single axis accelerometer will be placed with an offset from the pitch axis as shown in Figure 13 to measure second Z_2 acceleration at this spanwise location. The difference between two measured Z accelerations at this blade station will give the sectional pitch acceleration.

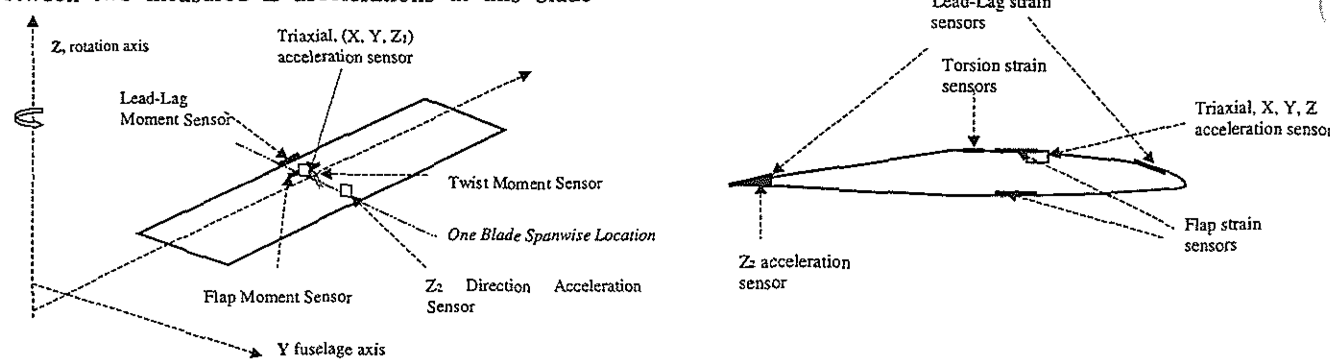


Figure 13. Sensor Placement on One Blade Spanwise Location.

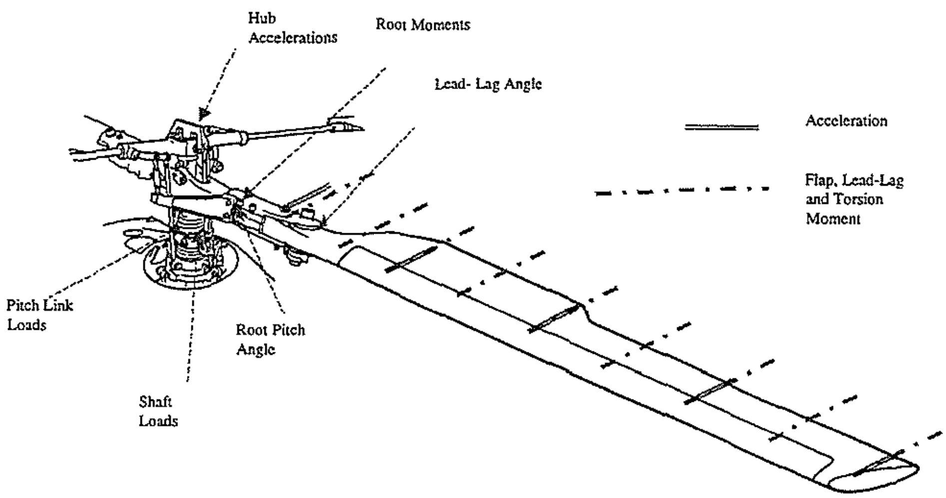


Figure 14. General Sensor Layout.

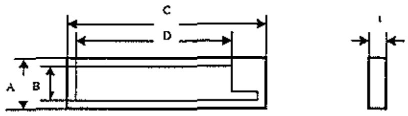
2.2 Strain Sensors

Strain Gauge Sensors

The resistance strain gauge is one of the most common sensors in force and moment measurements based on the measurement of the strain of the attached deformed object. Strain gauges are most suitable for static measurements and be produced in every size without decreasing the functionality. Due to their shapes they can be glued on any aerodynamic surface without significantly disturbing the flow pattern. Available off the shelf gauges are also widely used for dynamic measurements of up to 100 kHz. The voltage output signal is in the range of magnitudes of 10^{-3} V and before a further analysis or transfer of the signal can take place it must be amplified to values at least in the 10^0 V range.

Piezo Film, Polyvinylidene Flourine (PVDF) Sensors

Based on the previous study for the Instrumentation of the R-50 helicopter by Meyer [8] Piezo Film, Polyvinylidene Flourine, (PVDF) Sensors are also considered for strain (moment) measurements. A conductive layer applied to both sides of the piezo film provides a capacitative storing of the developed charge. A reverse force produces an output voltage of opposite polarity. However, this capacitance is only in the order of 10^{-9} Farad and any measurement device can cause a drift. This is why piezo films typically perform better in dynamic than static measurements. Silver ink electrodes are below and above the piezo film and a protective coating seals the sensor against pollution. Dimensions of the selected PVDF sensor is shown in Figure 15.



Measurement Specialties Inc. PVDF strain sensor: LDT1-028K/L w/rivets
A= 0.640 (16.26) B=0.484 (12.29) C= 1.63 (41.40) D= 1.19 (30.17)
t = 205 (μm)

Figure 15. Piezo Film Composition from Measurement Specialties (Dimensions: inch [mm]).

PVDF sensors require no source of power for the pure sensing a deformation, due to the dipole characteristics under force influence. The output signal is in the order of 10^{-3} Volts to 10^{-1} Volts depends on the piezo film configuration selected and the deflection occurred. Further amplification is needed depended on the voltage output level. Based on the assumption of low curvatures for the relatively rigid rotor blade, amplification of the PVDF signals are assumed.

2.3 Acceleration Sensors

In present study, rotor blade acceleration measurements will be obtained for validation purposes. Displacements calculated through the blade load identification methodology, where strain measurements are used as inputs will be compared with the displacements calculated from the accelerometer measurements. This approach will assure the validation of the methodology and cross checking of the measurement accuracy.

As explained in Reference [9] blade flapping motions can be also used for rotor state feedback in the design of advanced multicyclic controllers. High bandwidth, active controllers are aimed for gust alleviation, blade stress reduction and vibration suppression. In Reference [9] several major problems related with acceleration measurements on rotor blades have been addressed. These difficulties can be listed as:

- Proper placement of accelerometers on blade spanwise axis regarding blade mode shapes.
- At least four acceleration measurements are needed and additional locations are preferred.
- Maintaining accurate sensor calibration is essential for accuracy of the measurements especially if the signals are to be used as a source of rotor state feedback.
- For different purposes certain frequencies of blade response is needed to be eliminated therefore, proper filtering based on blade rotation frequency is needed.

Additional difficulties, primarily for the RMAX rotor blade is investigated. Major difficulty is the total number of accelerometer sensors to be placed on the rotor blade. The number of accelerometers at one blade spanwise location is four and total of 20 accelerometers along the blade are needed. The second difficulty is the cross-sectional size limitation of RMAX rotor blade. This rotor has a chord of 105 mm and thickness of 13 mm as shown in Figure 16. As the consequence of this size limitation of the rotor blade the size and the placement of accelerometers become difficult. Besides the weight of the accelerometers must be as small as possible.

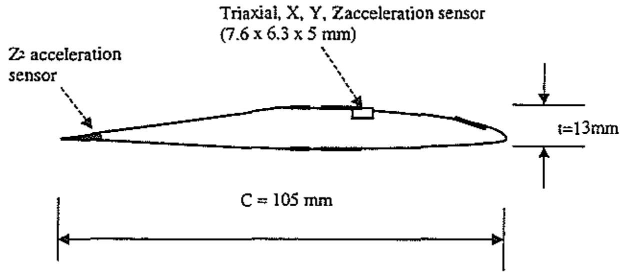


Figure 16. RMAX Rotor Blade Cross Section Dimensions.

The third major difficulty in acceleration measurement is the difference between the magnitude of measured accelerations at different axes and at different spanwise locations. Centrifugal accelerations on R-50 and RMAX rotor blades are very high due to their high angular speeds (870 and 830 rpm respectively) compared with normal size helicopters. The level of blade centrifugal acceleration exceeds 1200 g for RMAX and 1300 g for R50 at blade tip.

Several accelerometers are investigated and two sets of accelerometers are selected based on the blade cross-sectional and planform limitations. Selected accelerometers are ENDEVCO Model 22-23 Piezoelectric, 25A and 25B ISOTRON accelerometers made by ENDEVCO Inc. Model 23 is basically the combination of three Model 22 accelerometers placed in a special case for triaxial measurements. Model 23 Piezoelectric accelerometer is an extremely small, adhesive mounting piezoelectric triaxial accelerometer, designed for specifically for vibration measurement in three orthogonal axes on small objects.

Dimensions of Model 23 accelerometer is 0.3 x 0.250 x 0.2 inch (7.62 x 6.35 x 5.08 mm). It weights only 0.85 grams which effectively eliminates mass loading effects. All three low-noise cables exit from a single surface to allow mounting flexibility. The accelerometer is a self-generating device that requires no external power source for operation. Model 22 and 23 can measure accelerations 10 000g's as shock limit and 1300 g's continuos.

Proper signal conditioning can be made by either Endevco Airborne charge amplifiers Model 2680M1-M7 or Aydin Telemetry SC-808 two channel Signal Conditioner with constant current source and CA-801 two channel Accelerometer Conditioner with charge amplifier which can be placed on a platform attached to the RMAX rotor hub as described in the next sections.

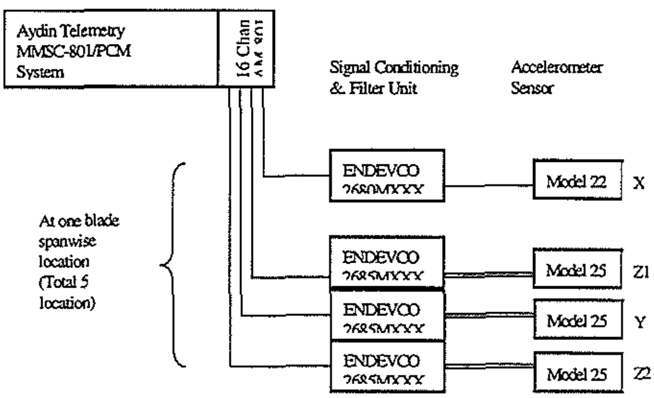


Figure 17. Accelerometers with ENDEVCO 2685MXX Signal Conditioners.

Several combinations of the above mentioned accelerometer sensors are considered in terms of functionality, placement and cost considerations. The set of acceleration consist of one Model 22 piezoelectric for X and three Model 25B ISOTRON single axis accelerometers combined in a triaxial mounting at one spanwise blade location. This configuration is shown schematically in Figure 17 with the use of Endevco 2685MXX airborne signal conditioning units. This configuration has the advantage of using fully compatible same family of acceleration sensors and signal conditioners.

The configuration with one Endevco Model 22 and three Model 25B accelerometers can be also used with Aydin Telemetery signal conditioning modules. For Model 22 piezoelectric accelerometer which does not require external power. Model 22 gives output with charge sensitivity of 0.40 pC/g and for the highest measurement of 1200 g it gives an output of 480 pC charge. Model 22 accelerometer can be used with Aydin Telemetry CA-801 two channel accelerometer conditioner with charge amplifier. CA-801 has $\pm$ 150 to $\pm$ 6000 pC/G full scale and eight programmable ranges. Each channel contains a 6-pole low pass Butterworth filter.

Model 25B Isotron accelerometers are extremely small, adhesive mounted piezoelectric accelerometer with integrated electronics, designed specifically for measuring vibration on very small objects. Model 'B' version offers a flexible, detachable coaxial cable which can be replaced by the user in the field. It has an output sensitivity of 4-5 mV/g and requires +18 to +24 Vdc +3.5 to +4.5 mA current supply. Model 25 B accelerometer scan be used with Aydin Telemetry AC-801 two channel signal conditioner with constant current source. The configuration is illustrated in Figure 18.

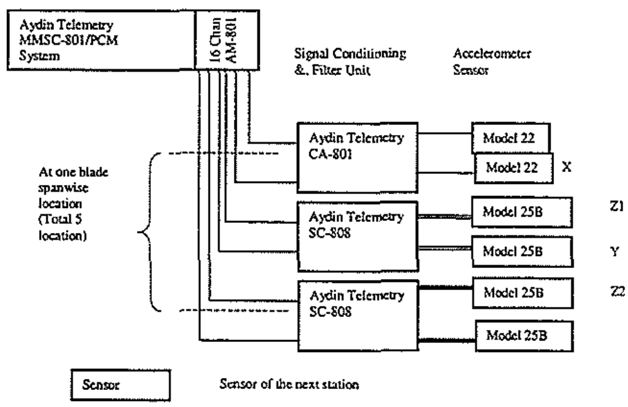


Figure 18. Accelerometer Combination with Aydin Telemetry Signal Conditioners.

2.4 Blade Root Angle Sensors

Due to the hub kinematics of the RMAX helicopter the bolt connection and the rubber block at the blade root acts like a damper at the lead-lag hinge. Blade lead-lag angle is measured by two tilt accelerometers, MMAS40G, from Motorola Inc., which is placed very close to the damper on each side of (A) in Figure 19. The lead-lag angle is obtained by the comparison of the two accelerometer signals obtained from (1) and (3). For the blade root flap moment is measured at the point indicated (4) in Figure 19. The root torsional moment has to be measured at a point just outboard of where the pitch link rod is connected to the blade, indicated (2) in Figure 19.

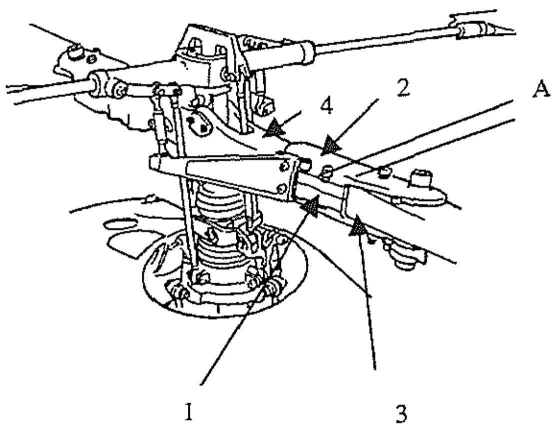


Figure 19. Blade Root Angle Sensor Layout.

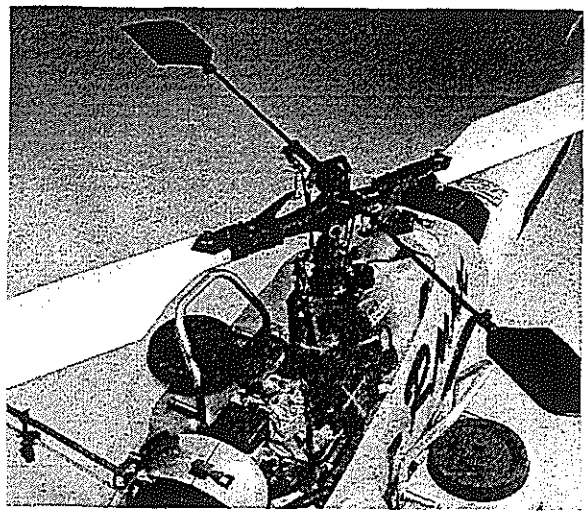


Figure 20. RMAX Hub Configuration.

2.5 Non-rotating System Measurements

All the measurements in the non-rotating system are developed for the helicopter automatic flight control system. The velocity is measured with the use of D-GPS, NovAtel RT-2 with maximum accuracy of 2 cm. The helicopter altitude will be given by an onboard gyro system. The rotor rotational speed is measured by the RPM sensor mounted at the base of the main shaft which uses a Hall effect sensor producing a pulse (0-5V) that is detected by a timing pin on a Motorola 68332. Similarly the rotor shaft power is determined by measuring the rotor torque and the rotational speed and is calculated by multiplying these two quantities. The blade control inputs, collective, lateral cyclic and the longitudinal cyclic pitch components are extracted from the on-board computer of the helicopter.

3. DATA COLLECTION AND TRANSMITTING SYSTEM

3.1 GENERAL DESCRIPTION OF THE DATA COLLECTING AND TRANSMITTING SYSTEM

As indicated by the initial study by Meyer [8] the biggest challenge of the instrumentation of the RMAX helicopter is defining a suitable signal transmission system from rotating to the non-rotating system. The main design constraints were the available space for the hardware, the amount of data and the cost of the data transmission system. The general view of the RMAX helicopter hub is illustrated in Figure 20.

Three different options; slip rings, telemetric transmission and rotary transformers are considered. Based on this initial study the telemetry system option is selected for transmitting data from airborne helicopter to the ground. Systems consist of data collecting, conditioning and encoding unit, data telemetry unit which are placed on the airborne helicopter. The second part of the system is on the ground, providing data receiving and acquisition of the transmitted data. The airborne components of the telemetry system are planned to be placed on a platform attached to the rotor hub as shown in Figure 21.

3.2 Data Transmitting and Acquisition System

The data transmitting and acquisition system selected is based on Aydin Telemetry Corp. instruments and schematic description of the system is shown in Figure 22. The system consists of Airborne Encoder System MMSC-800-SA and ST-805S Transmitter with antenna. A S-5200 PC-based Ground Telemetry System for data reception, recording, processing and display is proposed. The S-5200 System includes a portable PC computer with S-band receiver, PC 335 Bit Synchronizer and PC 440 Frame Synchronizer/Decommulator under the control of ATAS software package.

An ADAS software for setup of the Airborne Encoder is also resident in the S-5200 system. The portability allows the unit to be taken out to the helicopter for setup and testing prior to the flight testing. A schematic description of the Aydin Telemetry Corp. data telemetry and acquisition system is shown in Figure 22.

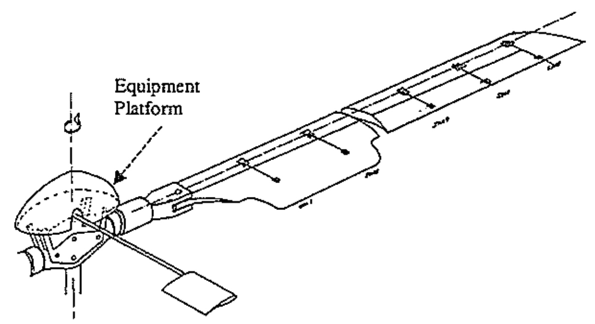


Figure 21. RMAX Rotor Hub Equipment Platform Attachment.

The MMSC-800 is an integrated analog and digital conditioner and PCM encoder. A complete family of modules provides signal conditioning for all types of sensors. EEPROM programmable gain/offset and sample rates provide user programmability of measurement characteristics and output data formatting. As shown in Figure 23, MMSC-800 has five major sections/modules where digital and analog signal conditioning modules are selected based on the specific application needs. The sum total of the digital and analog modules must not exceed 31 per system stack. Each digital and analog module is 0.25 inch (6.35 mm) thick.

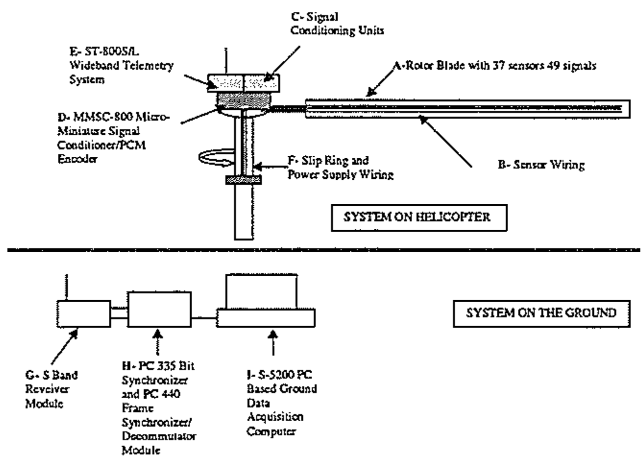


Figure 22. The RMAX Helicopter Instrumentation With Aydin Telemetry Corp. Instruments.

Two different configurations for MMSC-800 system are considered. Configuration 1, shown schmatically in Figure 24, is organized for the use of piezoelectric film strain sensors. For this configuration 13 CA-801 two channel conditioner and charge amplifiers are needed to support Model 22 piezoelectric accelerometers and film sensors.

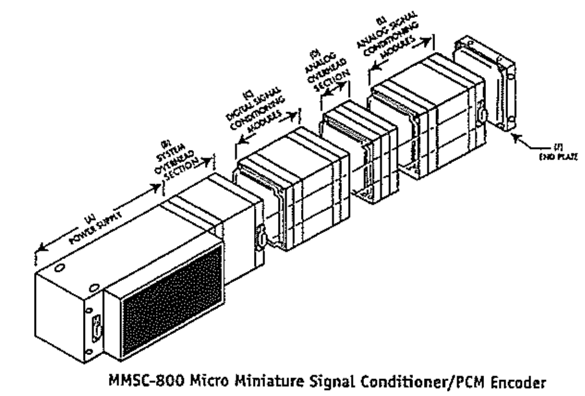


Figure 23 MMSC-800 Micro Miniature Signal Conditioner /PCM Encoder Modules.

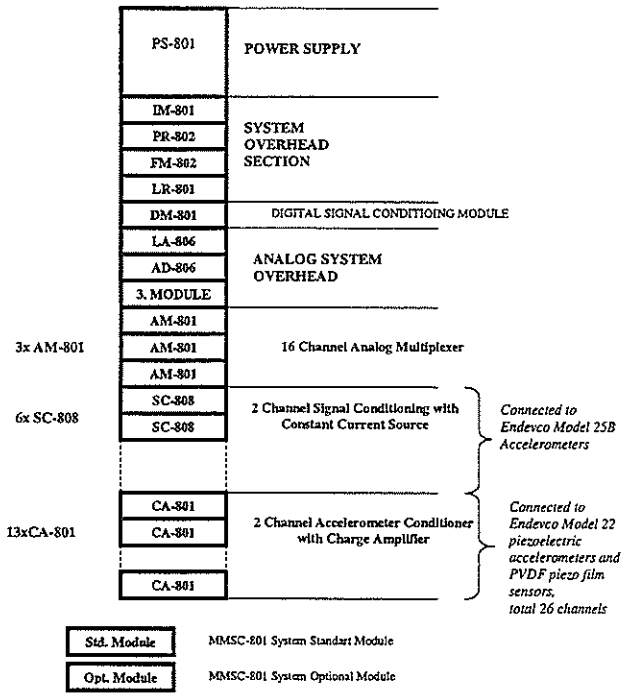


Figure 24. MMSC-800 Standard and Optional Modules – Configuration 1.

Configuration 2, shown schematically in Figure 25, is organized for strain gauge sensor application where 6 SC-806 four channel bridge conditioners are used for signal conditioning and power supply for the strain gauges placed on the rotor blade.

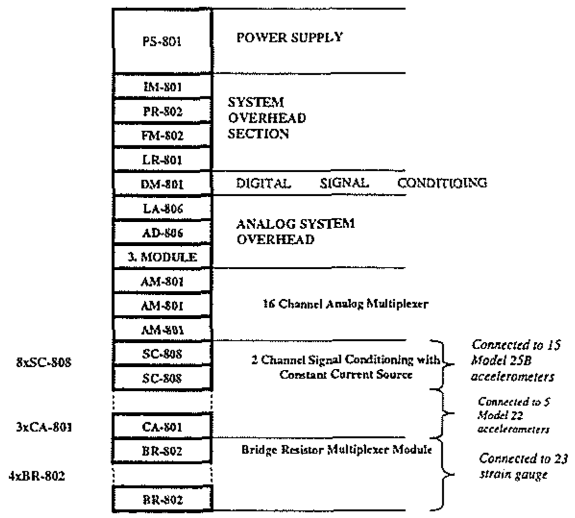


Figure 25. MMSC-800 Standard and Optional Modules - Configuration 2.

SUMMARY

A number of high payoff technologies are becoming available to make intelligent UAVs and enhanced manned systems possible. To get the synergistic advantage of these technologies requires the integration of information technologies from computer science with advances in controls engineering and vehicle technologies. It also requires the integration of design, analysis and tests which can be greatly enhanced through the use of virtual prototyping. This paper has identified a first step in this process which is to fully instrument a low cost VTOL UAV, the Yamaha RMAX, so that a baseline testbed can be established.

ACKNOWLEDGEMENTS

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