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EXPERIMENTAL STUDIES IN SYSTEM IDENTIFICATION OF HELICOPTER ROTOR DYNAMICS

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EXPERIMENTAL STUDIES IN SYSTEM IDENTIFICATION OF HELICOPTER ROTOR DYNAMICS

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Abstract

Recent experiments investigating the system identification of helicopter rotor dynamics are described. The identification makes use of a two–pass procedure that estimates the rotor dynamic states prior to estimation of the dynamic equation parameters. Estimation of the rotor states is made possible through use of the predictive information contained in blade–mounted accelerometers, combined with a specialized processing scheme utilizing these signals. Descriptions of the experimental hardware and the system identification technique are given, as well as implementation issues for using the procedure on other similarly instrumented rotor blades. Finally, comparisons with other identification techniques using the same data are presented. It is demonstrated that the approach is an attractive one for measurement of a helicopter rotor's dynamic behavior.

1. Introduction

Recent efforts over the past few years has indicated the benefits of kinematic observers for use in state estimation for helicopter rotor systems [1,2]. The advantage of the technique stems from the fact that the state variables of the helicopter rotor can be accurately estimated without requiring any aerodynamic modeling of the rotor flow field. This result is a consequence of the additional predictive information provided to the estimation approach through incorporation of blade–mounted accelerometers. The ability to separate the state estimation task from a requirement for a predictive dynamic model has permitted the extension of the theory for rotor system parameter identification. Since the rotor states are estimated first, it becomes possible to incorporate the estimates into an equation error parameter estimation scheme. Such a formulation allows the use of a linear–in–the–parameters format, which enjoys both algorithmic simplicity and computational robustness over traditional Extended Kalman Filter approaches [3].

In support of this work, a series of experiments has been conducted at Princeton's Rotorcraft Dynamics Laboratory using a dynamically scaled model rotor [4]. The three–bladed, four–foot diameter rotor is capable of producing either individual blade pitch changes or higher harmonic control through a standard swashplate. The model blades are instrumented with miniature accelerometers such that both rigid and elastic blade response may be measured. The paper will present the design aspects of the rotor model, and describe the Rotorcraft Dynamics Laboratory facility and its data acquisition system. Results from the most recent set of experiments will be presented, and the parameter identification methodology used to reduce these data will be outlined and demonstrated. Finally, future research directions for the identification work will be described.

2. Description of the Rotorcraft Dynamics Laboratory

The Rotorcraft Dynamics Laboratory, located on Princeton's Forrestal Campus, was originally constructed in the mid–1950's for V/STOL flight dynamics research using Froude–scaled powered models [5]. The facility consists of a hydraulically–controlled powered carriage, running along a 230 meter (750–foot) long monorail track, with sufficient performance to follow or simulate motions of a model at the Froude time scale. The test section size of 9m×9m (30ft×30ft) can accommodate powered models up to 2.5m (8ft) in radius (span) and approximately 25kg (60 lbm). Models may be supported on the carriage using either limited motion linear and angular gimbals or by means of a six–component strain gauge sting mount, depending upon the nature of the data to be collected. (Figure 1)

Since the carriage control system operates in a closed–loop fashion, very precise control and programming of velocity profiles is possible, permitting the simulation of a wide variety of flight conditions. Such moving model testing offers advantages over conventional wind tunnel testing in the precise control of test velocity, low power requirements, and removal of any wall boundary–layer effects. Several past test programs have exploited this capability to investigate ground effect aerodynamics and transition maneuvers for different V/STOL vehicles as well as conventional rotorcraft. Current research efforts are directed at studying the structural dynamics, aerodynamics and flight mechanics of isolated rotors and generic helicopter configurations.

3. Data Acquisition and Processing Features

Recent replacement of the original vacuum tube–based telemetry system has allowed the expansion of the scope and type of experiments conducted to include high–frequency vibration measurements. A solid–state Aydin/Vector PDS–700 commutator and PAD–400 decommutator provide high–speed digital data transmission from the carriage, accepting up to 32 high–level single–ended analog inputs and 12 low–level differential strain gauge–type channels for a total of 44 possible signals. These signals are sampled at 44KHz

through band–selectable anti–aliasing filters and an internal 10–bit A/D converter, combined with synchronization words comprising one "frame" of data, and then converted to a phase–code modulated (PCM) serial data stream. This data signal is then routed to an American Laser Systems ALS–85 optical open–air transmitter/receiver pair, which provides the link from the moving carriage to the fixed decommutator. The decommutator converts the data back to 10–bit parallel digital data words, and provides appropriate clock and lock detection signals. A block diagram of this data system is shown in Figure 2.

In order to provide for precise identification of the incoming parallel data words, the clock signals and 10–bit data are combined via a separate data buffer that adds the channel identifier as an additional six bits to form a 16–bit digital data word. The clock signals are also subdivided such that unused channels may be skipped, and switches are provided to further decimate the sampling rate by skipping selected frames of data. These digital data are then routed to an IBM PC/AT computer equipped with an ICS Computer Products HSD–16 digital I/O card having direct memory access (DMA) capability. The card enables the PC/AT host to achieve transfer rates up to 120,000 16–bit words per second, well beyond the 46,000 KHz requirement imposed by the decommutator. Because the DMA transfer is transparent to the central processor of the PC/AT, real–time graphic display of the telemetry data is possible in a variety of formats. This feature allows for data validity checks, direct comparison with theoretical values in real time, and on–line operator intervention to adjust experimental parameters to provide the highest quality data possible. Data is subsequently transferred from core memory to disk data files for cataloging and further post–test analysis. The PC/AT host has additional high–speed connections to both of Princeton's mainframe computers as well as the John Von Neumann Supercomputer Facility colocated on the Forrestal Campus.

4. Design Features of the Instrumented Model Rotor

The model used in the system identification studies in progress at the Rotorcraft Dynamics Laboratory was designed using as many off–the–shelf components as physically possible in order to reduce overall cost. The main model support structure uses many components now found in radio–controlled helicopter kits, which now exhibit a precision and sophistication unavailable less than a decade ago. In order to maintain the capability for both Individual–Blade–Control (IBC) and Higher Harmonic Control (HHC), a three–bladed rotor hub was chosen that incorporates a conventional swashplate assembly. The basic helicopter kit mechanics were modified with the installation of a hollow shaft and 20–channel slip ring assembly, a 1 hp permanent–magnet DC drive motor, rotor 1/rev pulse detector, individual blade pitch angle transducers, and modified high–bandwidth servos for swash plate positioning. The slip ring assembly allows rotating frame measurements such as pitch angles and blade mounted accelerometer signals. A picture of the model rotor mechanics can be seen in Figure 3.

Support electronics for the identification experiment include a combination of carriage–mounted card cages to provide both "pilot" inputs as well as IBC or HHC feedback signals to the swashplate actuators. The 1/rev pulse is fed into a phase–lock loop circuit to produce quadrature $\sin\psi$ and $\cos\psi$ signals, which in turn are used to drive individual blade pitch angles through conventional cyclic and collective commands as in [6].

The rotor blades on the model were built using a lightweight two–component urethane foam, poured into an aluminum mold of a 60cm (2ft) long blade having a NACA 0012 airfoil section. The mold was produced using an on–campus numerically controlled milling machine in order to assure aerodynamic similarity among the three rotor blades. The blades were designed to have an extremely soft structure in order to provide for dynamic scaling of rotor structural frequencies at relatively low rotation speeds. This requirement directly impacts the required servo bandwidth of the swashplate actuation system, making the attainment of individual blade control possible using less exotic servo hardware. For the initial hover tests reported here, a single blade was instrumented with two accelerometers sensing out–of–plane acceleration components. A sketch of the blade and sensor locations is given in Figure 4.

5. System Identification Experiments

System identification methodology has been applied to isolated helicopter rotor systems in the past to estimate state variables of the rotor (i.e., blade degrees of freedom and associated velocities) [7,8], estimate both rotor states and parameters [9,10], or estimate the input–output transfer characteristics directly [11]. Most of the state estimator approaches have used some simplifying assumptions in their dynamic models for the rotor that would make them unsuitable for use in a state variable feedback control system, due to a violation of the "separation principle" of modern control theory. The combined state and parameter attempts have convergence problems typical of Extended Kalman Filters and other nonlinear identification algorithms, which often show acute sensitivity to initial condition information. The direct transfer function estimation techniques, while very useful for HHC active vibration suppression schemes, are difficult to incorporate into rotor state feedback designs or relate to parametric models of the rotor dynamics.

The experimental program underway at the Rotorcraft Dynamics Laboratory is an attempt to quantify the use of "kinematic observers" for estimating both rotor states and parameters using specially instrumented rotor blades in a two–step recursive process. The information represented in the accelerometer signal is used in place of a complicated model of the rotor blade dynamics to form the predictive portion of a linear Kalman Filter–like structure. Accompanying position measurements are compared with the

twice–integrated acceleration measurements to provide residual feedback to reduce the state estimation errors to zero. In this way, accurate rotor state estimates may be generated *prior* to any parameter identification task. Reconstruction of the blade modal accelerations is performed using knowledge of the kinematics of the accelerometer sensor location and the blade's modal properties. The rotor state estimates may also be used directly for feedback control purposes, and can be shown not to violate the "separation principle" that permits separate design of state feedback gains and state estimation filters. Details of the use of the technique for vibration reduction via state feedback are given in reference [1].

Because this technique does not require any assumptions concerning the rotor blade aerodynamic model, one may use the resulting state estimates for identification of various terms in the blade aeroelastic equations of motion. In fact, if a small perturbation model is proposed, the coefficient identification task becomes linear–in–the–parameters (when formulated in an equation error sense), and thus enjoys considerably improved convergence properties over more complex nonlinear estimation algorithms. The inherent disadvantage of the method lies in the fairly restrictive requirement of at least two blade mounted sensors installed (one of which must be an accelerometer) for every rotor mode desired to be estimated.

6. Estimation of Flapping States

Recent investigations of full–scale rotors equipped with blade–mounted accelerometers revealed a strong presence of higher–mode excitation in their signal content [2]. If the resulting state estimates using these sensors were corrupted with signals from unmodeled rotor modes, potentially dangerous instabilities could result from their use in rotor state feedback control schemes. In order to investigate possible effects of modal truncation in kinematic observer design, and to evaluate implementation issues of the observers on actual data, a series of simple hover experiments were conducted using the previously described model rotor hardware. A sample of one of the data sets can be seen in Figure 5, which includes the 1/rev signal, the two blade–mounted accelerometer signals, and the blade root pitch angle.

Because the two accelerometers are oriented with their sensitive axes in the out–of–plane direction, they will sense accelerations proportional to both vertical acceleration and modal deflection out–of–plane, as shown in Figure 6. The latter component is a result of centrifugal acceleration coupling into the sensor as its sensitive axis rotates with the bending of the blade. For the case of the first out–of–plane (flapping) mode of the model blade, this may be written as:

$$\begin{bmatrix} a_{.5R} \\ a_{.25R} \end{bmatrix} = \begin{bmatrix} .3542 & .700 \\ .1055 & .3083 \end{bmatrix} \begin{bmatrix} \ddot{\beta} \\ \beta \end{bmatrix} \qquad (1)$$

This invertible expression gives a direct expression for measured flap acceleration and position, that is combined into a kinematic observer for the flap position and velocity according to:

$$\frac{d}{dt}\begin{bmatrix} \hat{\beta} \\ \dot{\hat{\beta}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \hat{\beta} \\ \dot{\hat{\beta}} \end{bmatrix} + \begin{bmatrix} 0 \\ \ddot{\beta}_{meas} \end{bmatrix} + \begin{bmatrix} K_1 \\ K_2 \end{bmatrix}(\beta_{meas} - \hat{\beta}) \qquad (2)$$

Selection of the gains K_1 and K_2 control the tracking performance of the estimation error of the observer, and thus should be picked to give the observer as high a "bandwidth" as possible without being adversely affected by higher unmodeled modes corrupting the assumed measurement signals. As the gains are increased, the differences between the measured and estimated flapping angle are driven to ever smaller values, forcing the observer's output to become more sensitive to any measurement errors. These errors are primarily due to a truncation of the number of modes considered in the accelerometer's signal content, producing an effect known in the structural control community as "measurement spillover" [12].

Various means exist for alleviating this problem, among which include sensor placement to produce higher mode "canceling", pre–filtering of the accelerometer data prior to solving for the desired displacements and accelerations, or including an explicit filtering action on the acceleration data within the observer structure. As the first option was not available for this experiment, due to the physical constraints of the model rotor blade, only the latter two options will be explored in the discussions that follow.

7. Recursive Estimation of Flapping Equation Coefficients

Assuming that accurate estimates have been obtained of the rotor state variables, one may use this information to then estimate the coefficients of the governing aeroelastic equations of motion. For the case of the single out–of–plane flap mode considered, its linearized dynamics due to root pitch change are:

$$\ddot{\beta}(t) = -m_{\beta}(t)\beta(t) - m_{\dot{\beta}}(t)\dot{\beta}(t) + m_{\theta}(t)\theta(t) \qquad (3)$$

Since the flap acceleration and pitch angle are measured quantities, and the flap velocity and position are available from the observer, one may directly solve for the parameters m_{β}, $m_{\dot{\beta}}$, and m_{θ} given a sufficient number of data time points. Methods such as least–squares or Kalman–Filter approaches can be used to extract these parameters, using the output of the Kinematic Observer as dependent variables, and computing the coefficient values that best match the measured modal acceleration. This study used a recursive weighted least–squares technique employing UDU^T factorization of the error covariance matrix, in order to enhance numerical robustness of the solution [13].

As no direct flapping measurement was available on the model rotor tested, the results of the flapping equation parameter identification were used to validate various Kinematic Observer designs in terms of sensitivity to measurement spillover from higher modes. This was deemed a reasonable solution, as the flapping equation coefficients are well defined constants for hover [14]. Three different observer structures were used, with the first consisting of a direct application of equation (2) above. That is, the blade–mounted accelerometers are combined directly to produce measurements of flapping position and acceleration without any filtering action. Since flapping response is dominant at frequencies of 1/revolution and less, the values of $K_1 = 2.8$ and $K_2 = 4.0$ were used to set the speed of response of the observer to less than 2/revolution. The results of such processing can be seen in Figure 7a, where the flap velocity and position estimates from the Kinematic Observer can be seen to contain a large amount of extraneous noise, indicating the lack of proper filtering action from direct application of equation (2). Closer examination of that equation reveals a direct feed–through from the accelerometer to both the position and rate estimate at low frequencies, thus introducing spurious inputs that the observer will attempt to track.

The estimated states from Figure 7a were then used to estimate the three flapping equation coefficients plus an additional bias term. The time histories of the recursive parameter estimation can be seen in Figure 7b, where both the damping ($m_{\dot{\beta}}$) and spring (m_{β}) coefficient show fairly erratic behavior over the first few rotor revolutions, finally settling down to approach physically unreasonable negative values. Clearly this behavior suggests that the state estimates using direct accelerometer measurements are suspect.

In order to directly reduce the amount of high–frequency information passed from the accelerometers to the observer estimates, low–pass filters with break frequencies at approximately 2/rev were used on the accelerometers prior to application of equation (2). The results are documented in Figure 8a, showing a marked smoothing of the state estimates for flapping velocity and position. Further use of these estimates to predict the flapping equation coefficients produced very reasonable results, as shown in Figure 8b. The values of $m_{\beta} = 1.089$, $m_{\dot{\beta}} = 0.428$ and $m_{\theta} = 0.560$ correlate well with the known blade stiffness and Lock number, indicating that the state estimates from the Kinematic Observer are fairly reliable.

The last attempt to reduce measurement spillover was to increase the order of the Kinematic Observer, by modeling the flapping acceleration as a random–walk process. That is, the flap acceleration is represented by an integrator driven by white noise, with the accelerometer measurements accounted for directly as a combination of these three flap–mode state variables, as:

$$\frac{d}{dt}\begin{bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}\{w\}$$

$$\begin{bmatrix}a_1\\ a_2\end{bmatrix} = \begin{bmatrix}c_{11} & 0 & c_{13}\\ c_{31} & 0 & c_{33}\end{bmatrix}\begin{bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\end{bmatrix} + \begin{bmatrix}v_1\\ v_2\end{bmatrix}$$

Observer design for this model directly follows Kalman Filter theory, in that one calculates measurement residual feedback gains based upon assumed noise covariances for the process noise w and the measurement noises v_i. These were iterated to produce a steady–state observer with feedback gain matrix:

$$K = \begin{bmatrix}.8034 & 1.398\\ 1.292 & 3.902\\ 1.219 & 5.340\end{bmatrix}$$

producing poles at non–dimensional frequencies of –2.627 and –0.3095±1.224j. These form an effective bandwidth near the 2/rev of the second–order observer from the two previous cases. Results for this last set not only reveal noise seepage into the state estimates, as in Figure 9a, but also produce negative flap damping estimates when used to extract equation coefficients. This clearly indicates that some form of sensor pre–filtering is required if one is to use the state estimates from the observer for feedback control or system identification.

An additional check was made on the equation parameters obtained using the second approach above. A transfer function between the root pitch input and the mid–span accelerometer was estimated by ratioing the averaged cross power spectrum of the pitch and accelerometer with the pitch input power spectrum. As can be seen by the comparison with the theoretical model frequency response in Figure 11, a single simple blade flapping equation is not sufficient to account for the model's response, confirming the presence of additional modal information content in the accelerometer's signal. Further exploration of this result will be conducted in the tests to follow.

9. Conclusions and Future Work

Experimental results indicate that Kinematic Observers are a promising tool for rotorcraft system identification, provided that sufficient care is taken to properly condition their input signals over the frequency band of the desired modal information. The ability to separately predict rotor modal state variables and dynamic equation parameters suggests its use in hypothesis testing on various aeroelastic models for rotor behavior. Future experiments will extend these results to include additional blade modes and a range of rotor operating conditions.

10. Acknowledgements

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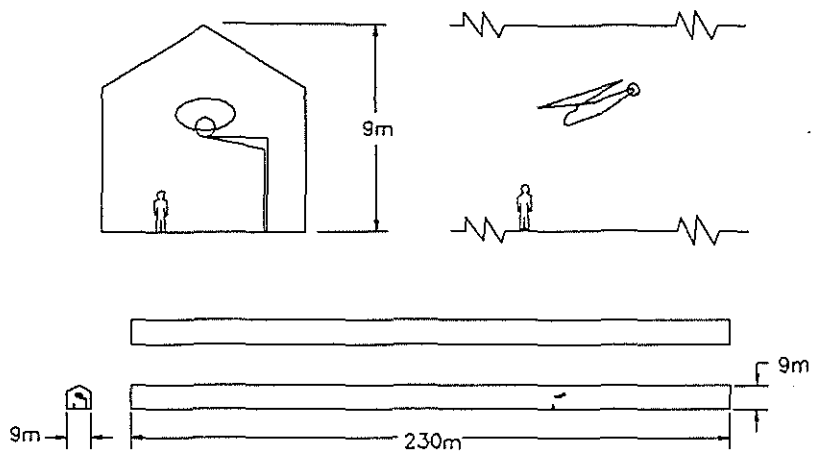


Fig. 1. The Princeton Rotorcraft Dynamics Laboratory ("Longtrack")

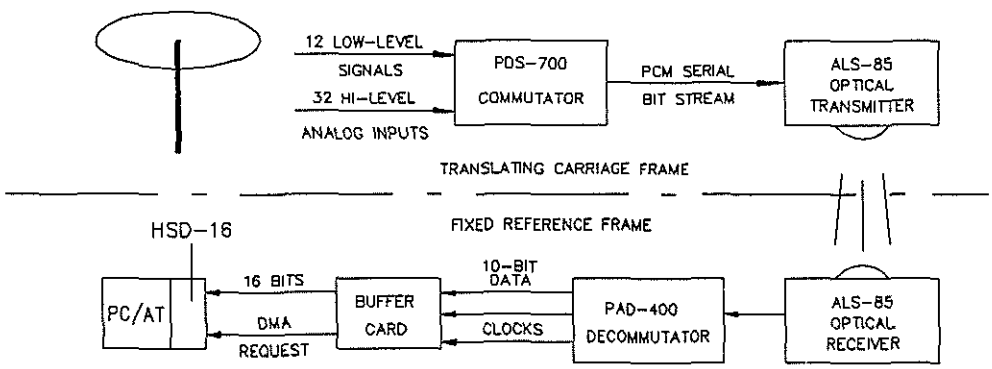


Fig. 2. High Speed Data System Block Diagram

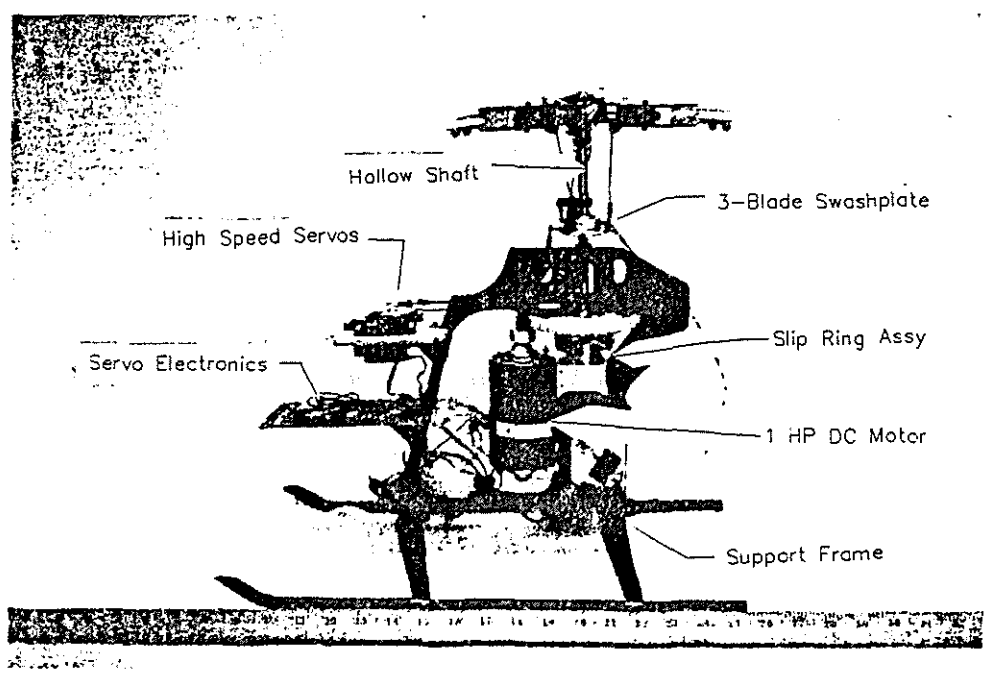
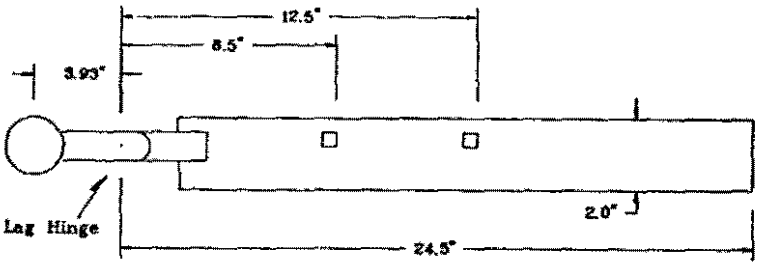


Fig. 3. Model Rotor General Arrangement



Model Blade Accelerometer Locations

Fig. 4. Model Rotor Blade Geometry

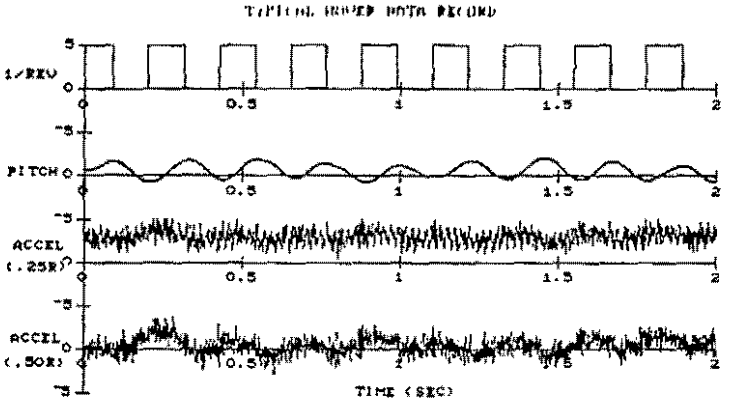


Fig. 5. Typical Hover Data Record

Kinematic Observer Sensor Requirements

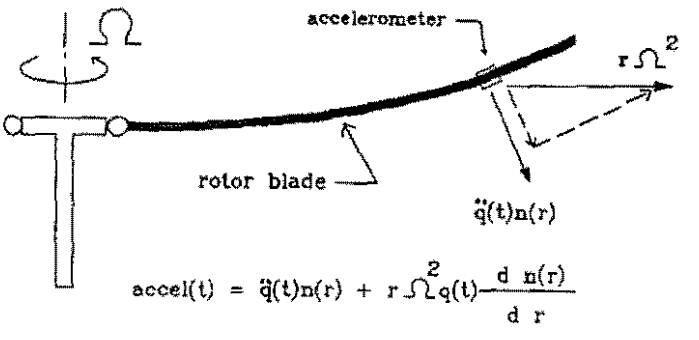


Fig. 6. Blade–Mounted Accelerometer Schematic

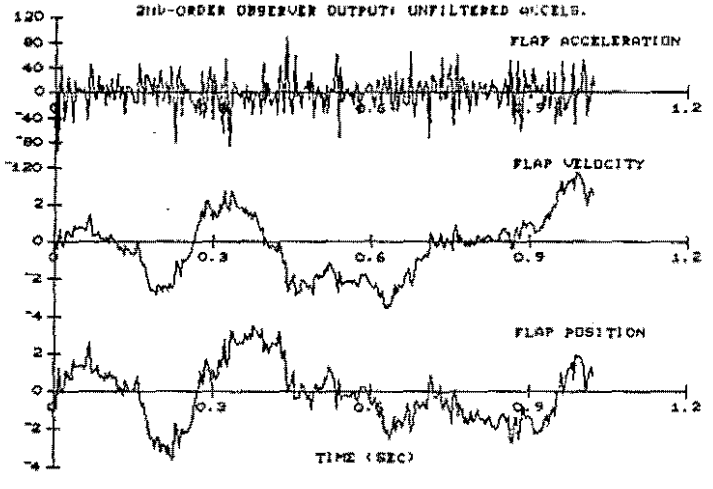


Fig. 7a. Kinematic Observer Output, Unfiltered Inputs

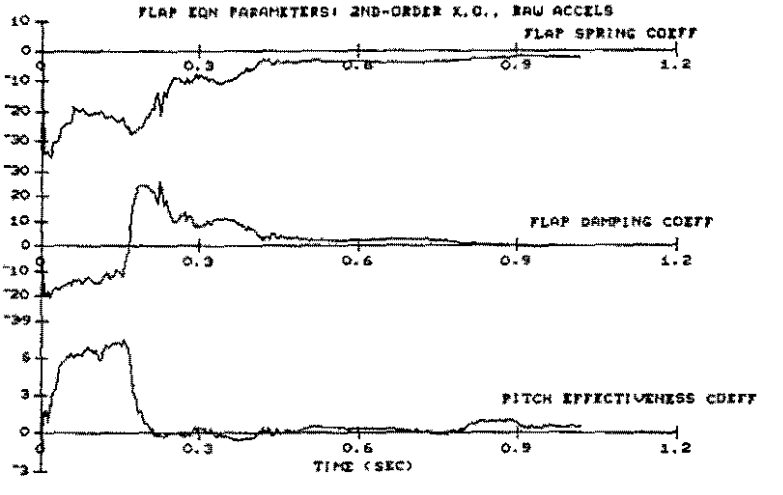


Fig. 7b. Parameter Estimates Using Observer Outputs

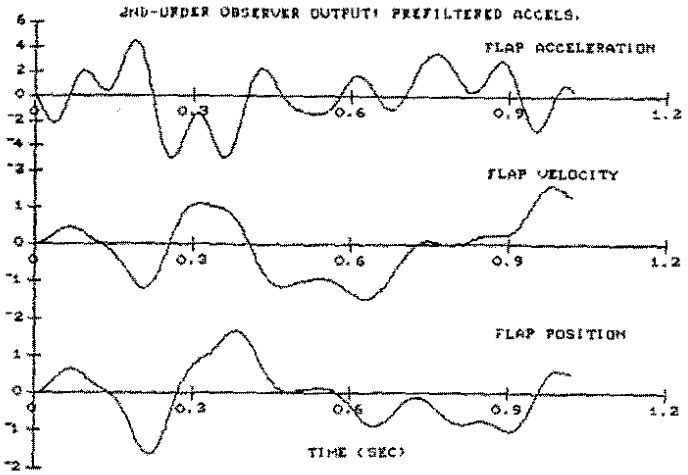


Fig. 8a. Kinematic Observer Output, Low–Pass Filtered Inputs

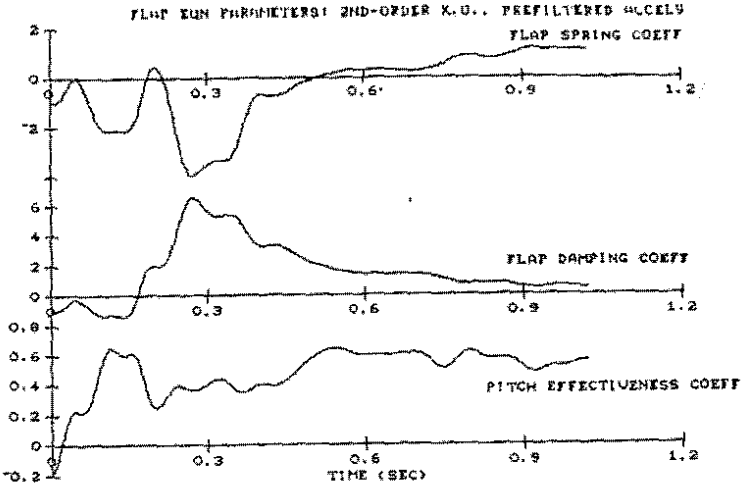


Fig. 8b. Parameter Estimates Using Observer Outputs

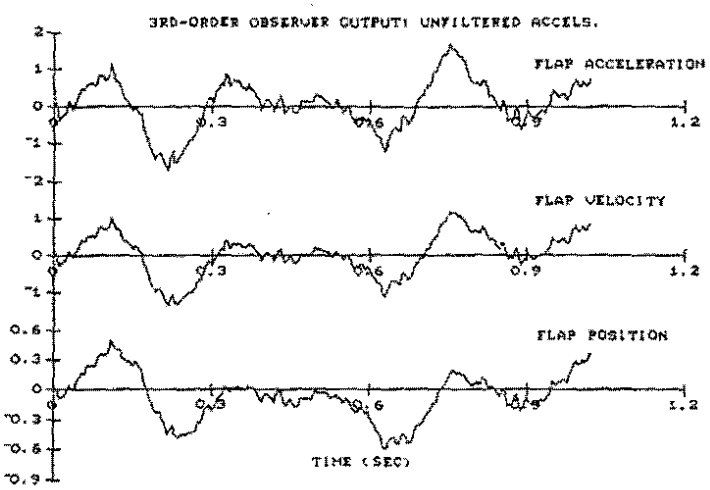


Fig. 9a. Augmented Kinematic Observer Output, Unfiltered Inputs

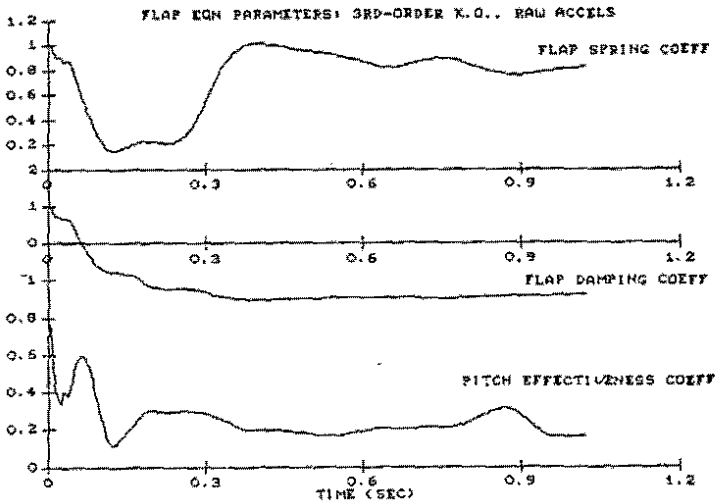


Fig. 9b. Parameter Estimates Using Observer Outputs

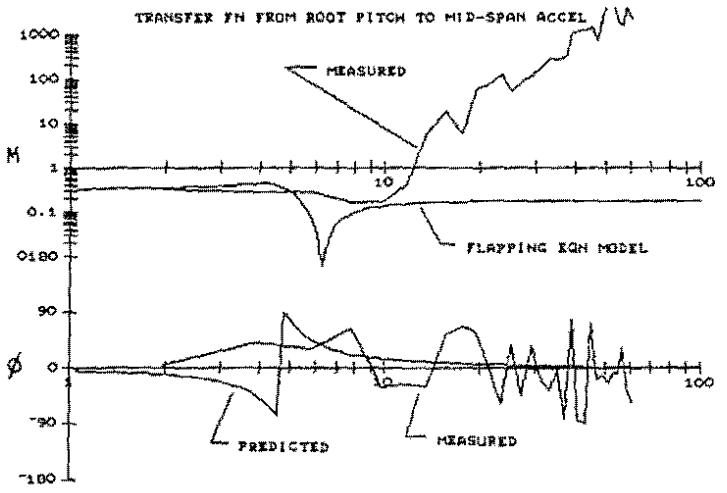


Fig. 10. Measured and Predicted (Single Mode) Frequency Response from Root Pitch to Mid–Span Accelerometer