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State Estimation of Main Rotor Flap and Lead-Lag Using Accelerometers and Laser Transducers on the RASCAL UH-60 Helicopter

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Modern rotorcraft flight control system designs which promise to yield high vehicle response bandwidth and good gust rejection can benefit from the use of rotor-state feedbacks [1,2]. The measurement of main rotor blade motions is also desirable to validate and improve rotorcraft simulation models, to identify high-order linear flight dynamics models, to provide rotor system health monitoring during flight test, and to provide for correlation with accustic meaurements from wind tunnel and flight tests. However, few attempts have been made to instrument a flight vehicle in this manner, and no previous system has had the robustness and accuracy required for these diverse applications.

A rotor blade motion measurement and estimation system has been developed by NASA and the U.S. Army for use on the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) helicopter. RASCAL is a UH-60 Blackhawk which is being modified at Ames Research Center in a phased development program for use in flight dynamics and controls, navigation, airspace management, and rotorcraft human factors research. The aircraft will feature a full-authority, digital, fly-by-wire research flight control system; a coupled ring laser gyro, differential GPS based navigation system; a stereoscopic color wide field of view helmet mounted display; programmable panel mounted displays; and advanced navigation sensors. The rotor blade motion system is currently installed for data acquisition only, but will be integrated with the research flight control system when it is installed later this year.

The blade motion measurement system was designed to be rugged and redundant. Two independent measurement systems, as described below, are employed; and all four blades are instrumented. As estimation of the tip path plane is of primary interest and requires measurements from only three blades, a failure on one blade of one or both systems is easily tolerated. Failures of both systems on two or more blades are required to totally degrade the estimation of the tip path plane. This level of redundancy will help to increase the productivity of flight test time on RASCAL and ensure safety of flight if the system is used in closed-loop flight control.

The redundant blade motion measurement system is shown in orange mounted on the UH-60 hub and rotor blades in figure 1. The system consists of three laser distance transducers mounted on each hub arm and four linear accelerometers mounted near the root of each blade. The laser transducers measure reflection distances to points on the blade root and pitch link from which blade flap, lead-lag, and feathering angles are calculated. The accelerometers are mounted in pairs, each member of the pair separated spanwise by approximately one foot as shown in figure 2. Each pair has its sensitive axes either parallel or perpendicular to the blade chord line to sense either blade lead-lag or flapping motions respectively.

Calculation of the flap, lead-lag, and pitch angles from the laser sensor outputs is achieved using a set of non-linear, coupled calibration equations determined from the blade/hub/pitch-link/sensor geometry and calibration test data. The surface represented by one of these calibration equations is plotted in figure 3 along with calibration data points obtained from hangar tests. The excellent fit of the data to the surface indicates that the calibration equation is adequate.

Assuming a rigid blade, the flap and lead-lag angles and angular accelerations are related to the linear accelerations according to equation 1, following the approach originally proposed by Ham, et. al [3]. The accelerometers must be low-pass filtered to prevent spillover of the flexible mode motions for this relationship to be valid. This equation can be inverted to directly calculate the angular motions from the accelerometer signals, or can be used as an observation equation in an estimator.

$$\begin{Bmatrix} a_{F_1} \\ a_{F_2} \\ a_{L_1} \\ a_{L_2} \end{Bmatrix} = \begin{bmatrix} r_{F_1}\Omega^2 & \left(r_{F_1} - e\right) & 0 & 0 \\ r_{F_2}\Omega^2 & \left(r_{F_2} - e\right) & 0 & 0 \\ 0 & 0 & r_{L_1}\Omega^2 & \left(r_{L_1} - e\right) \\ 0 & 0 & r_{L_2}\Omega^2 & \left(r_{L_2} - e\right) \end{bmatrix} \begin{Bmatrix} \beta \\ \ddot{\beta} \\ \varsigma \\ \ddot{\varsigma} \end{Bmatrix} \qquad (1)$$

An optimal filter for estimation of blade flap and lead-lag motions using the laser and accelerometer measurements has been developed. The state and observation equations for the final filter design are shown in equations 2 and 3. Using a set of judiciously selected process and measurement noise covariance matrices, a constant-gain filter was determined from solution of the associated steady-state Ricatti equation. An extensive study was conducted to determine the benefits of various filter designs. The results of this study, including details on the determination of the nose covariances, will be described in the full length paper.

$$\frac{d}{dt}\begin{Bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\\ \varsigma\\ \dot{\varsigma}\\ \ddot{\varsigma}\end{Bmatrix}=\begin{bmatrix}0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&0&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\\0&0&0&0&0&0\end{bmatrix}\begin{Bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\\ \varsigma\\ \dot{\varsigma}\\ \ddot{\varsigma}\end{Bmatrix}+\begin{Bmatrix}0\\0\\w_F\\0\\0\\w_L\end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix}a_{F_1}\\a_{F_2}\\a_{L_1}\\a_{L_2}\\L_\beta\\L_\varsigma\end{Bmatrix}=\begin{bmatrix}r_{F_1}\Omega^2 & 0 & \left(r_{F_1}-e\right) & 0 & 0 & 0\\ r_{F_2}\Omega^2 & 0 & \left(r_{F_2}-e\right) & 0 & 0 & 0\\ 0&0&0& r_{L_1}\Omega^2 & 0 & \left(r_{L_1}-e\right)\\ 0&0&0& r_{L_2}\Omega^2 & 0 & \left(r_{L_2}-e\right)\\ 1&0&0&0&0&0\\ 0&0&0&1&0&0\end{bmatrix}\begin{Bmatrix}\beta\\ \dot{\beta}\\ \ddot{\beta}\\ \varsigma\\ \dot{\varsigma}\\ \ddot{\varsigma}\end{Bmatrix}+\begin{Bmatrix}v_1\\v_2\\v_3\\v_4\\v_5\\v_6\end{Bmatrix} \tag{3}$$

Flight test data was collected with the rotor blade motion measurement system on the RASCAL in January, 1995 and used to evaluate the performance of the optimal filter. Sample results are shown in figure 3, where the filter estimated flap angle is compared with that calculated from the laser flap sensor. Most of the 50ms time delay in the filtered signal is due to the low-pass prefiltering of the measurements to prevent modal spillover. This can be reduced for real-time applications by using a lower order filter, as the amount of attenuation provided by the six pole Butterworth filter used here is not necessary.

The accelerometer signals used in the estimation in figure 3 have been corrected for a 30% scale factor error. This error became evident when the signals were first compared. However, it may have gone unnoticed if two independent measurement systems had not been employed. The excellent agreement between the laser and filter signals indicates that the measurement model is adequate and that the filter is performing well.

Further application of the optimal filter to the flight test data will be illustrated in the full length paper. It is anticipated that correction of calibration errors will allow a consistent set of estimates to be produced. Sample results from the use of the estimated rotor motion states in rotorcraft simulation model validation and system identification will also be presented.

The results in this paper are new, and have not been presented before in any public forum. The results are unique in that high quality flight test data from a dual redundant rotor blade motion measurement system are presented and compared. The quality of the results and the applicability to various flight dynamics problems provides encouragement that this work will be of utility to the rotorcraft flight mechanics community.

References:

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2. Takahashi, M.D., "Design and Comparison of Pitch-Roll H∞ Control Laws With and Without Rotor-State Feedback for a Hovering Helicopter," NASA TM 108793 (USAATCOM TR 93-A-013), January, 1994.

2.Ham, N.D., et. al., "The Measurement and Control of Helicopter Blade Modal Response Using Blade-Mounted Accelerometers," 13th European Rotorcraft Forum, Paper No. 6-10, Arles, France, September, 1987.

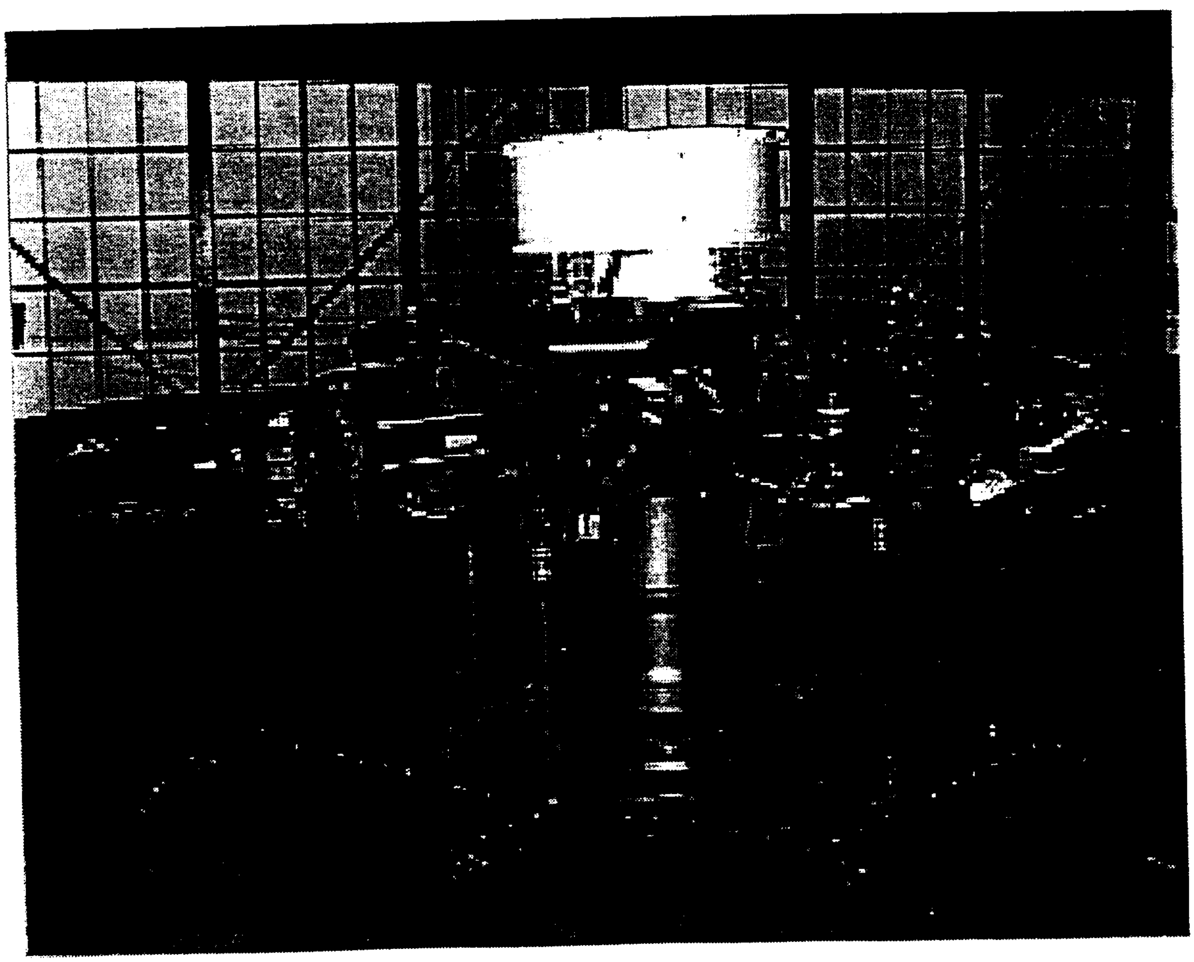

Figure 1. RASCAL Rotor State Measurement hardware.

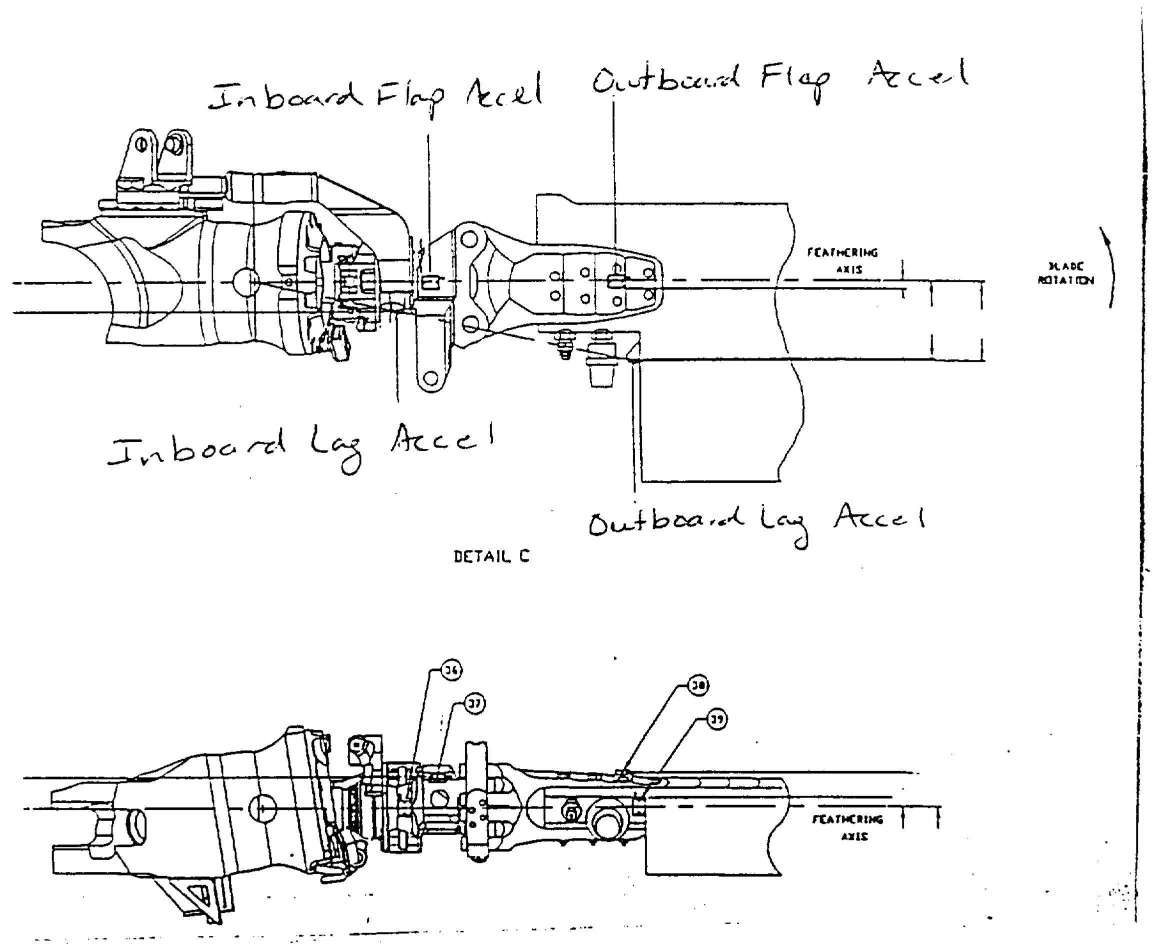

Figure 2. Flap and Lead-Lag Accelerometer Locations

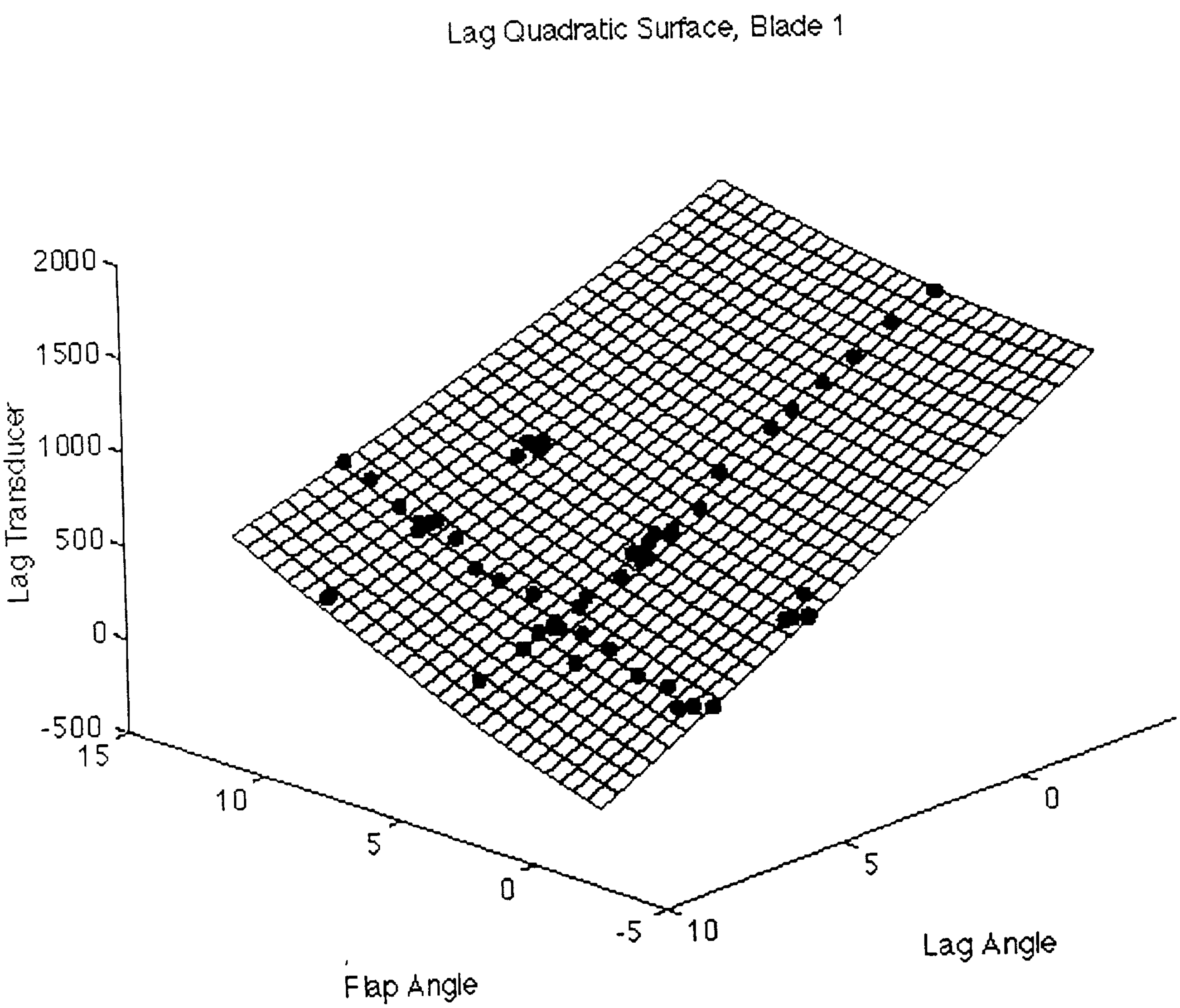

Figure 3. Typical Lead-Lag Sensor Calibration Surface

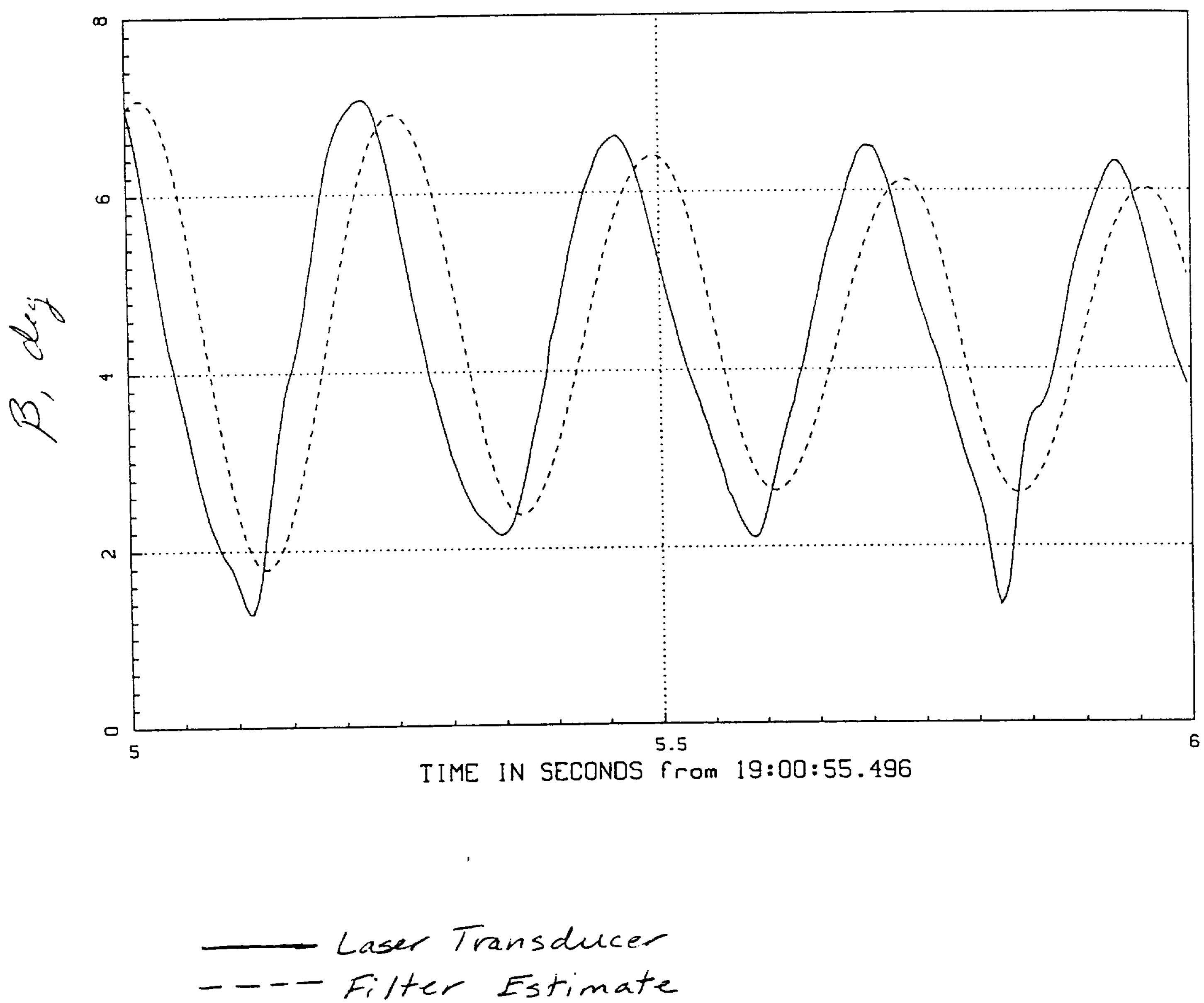

Figure 4. Laser Measured and Filter Estimated Flap Angle