Data-Driven Modeling for Rotor State Feedback Simulation

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ABSTRACT

Advanced flight controls for rotorcraft may benefit from the use of rotor state feedback, as a means of improving vehicle dynamic response, augmenting stability margins, aiding handling qualities and mitigating disturbance to the aircraft. Efforts to provide rotor state estimates that surmount the reliability and installation issues associated with rotary transducers in the rotating frame show promise, but questions remain as to how best to model their dynamic response, particularly when part of a closed-loop flight control design. This paper addresses this modeling issue to provide a means of representing the rotor state estimation process for use in a flight simulation analysis aimed at investigating rotor state feedback control approaches.

INTRODUCTION

The U.S. Navy maintains an ongoing interest in providing enhanced flying qualities to rotary-wing pilots performing Dynamic Interface (DI) launch and recovery flight maneuvers from ship decks. Current sponsored research work has suggested that advanced flight control systems may provide these rotorcraft with a significantly improved ship airwake disturbance rejection capability, if the rotor system response to this environment is measured and mitigated using rotor state feedback1. Prior work has indicated that some of the challenging implementation issues associated with rotor-mounted instrumentation, required for the feedback process, may be lessened using accelerometer sensors mounted near the blade root structure2. Because these systems are flight-critical, significant risk is associated with testing them on actual manned aircraft in an operational setting that includes the very ship airwake effects to be reduced. As a result, the first step in Navy evaluation of this approach will be through the use of a detailed combined simulation of the aircraft, ship, airwake, and the rotor aeromechanical response in this environment. To support this process, detailed and accurate modeling is required on the effect of rotor state feedback on both the rotorcraft aeromechanics and the general vehicle handling characteristics when operating in a turbulent DI environment3.

Several challenges are associated with this modeling and simulation task, however. First, the time scales associated with a rotor state feedback system are significantly faster than those associated with traditional flight dynamics modes for fuselage response, and thus may require execution of simulation loops at higher speeds than may be present in an existing simulation environment. This issue is particularly acute for distributed processing simulations, as the required network bandwidth may jump an order of magnitude in speed if careful design practices are not followed. Second, proper modeling of the throughput of the rotor state estimation process is essential to ensure that loop robustness is maintained, and estimator processing lags do not undo the advantages associated with the original implementation of rotor state feedback itself. And third, simulation of potential failure modes, and their accommodation (such as from a faulty sensor) is necessary prior to the commitment to building flight hardware, as single-string failure scenarios would not be acceptable for either testing or production use of such a system.

ROTOR STATE MEASUREMENT BACKGROUND

Advances in helicopter flight control technology have shown significant benefits in being able to tailor aircraft response characteristics to both the piloting task at hand and the visible cues and disturbance environmental present4. Modern rotorcraft AFCS and SCAS controllers have been designed to avoid destabilizing rotor dynamic modes5-7, but may not always be able to reach their full potential for disturbance suppression due to fundamental gain limitations that ensue from the fact that the rotor dynamic response is typically estimated, rather than measured, for such systems. While the benefits of rotor state feedback on the performance of helicopter flight control systems has been known for some time and are still subject for investigation8,9, only one example of this application has ever been flight tested – on a CH-53 in the 1970s10.

A significant impediment to the adoption of rotor state feedback by the helicopter industry has been the difficulty in extracting robust and reliable rotor response measurements for this purpose. Almost all of the developments in rotor instrumentation have addressed experimental needs, thus almost guaranteeing that each sensor complement represents

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a unique, one-of-a-kind installation that is intricately wedded to the specific details of that particular rotorcraft type and model number. A recent example of the breadth of measurement instrumentation possible in a modern test application is the UH-60 Airloads aircraft\(^1\), which included many blade-mounted pressure transducers, strain gauges, and accelerometers, along with a specialized four-bar linkage system (dubbed the “crab arm,” see Figure 1) for measuring blade motion parameters, as part of its sensor suite. That aircraft, as well, utilized a sophisticated specialized rotating frame multiplexer that sent digital telemetry frames to the fixed fuselage recorders through a custom slipring assembly.

More recently, researchers at Ames Research Center have developed an optical-based approach for measurement of blade flapping position\(^18\). This system combines lasers with specialized optical targets and mounting hardware to measure the blade flapping response on the UH-60 RASCAL research aircraft while in flight testing. While quite functional, it is solely intended for testing applications.

While successfully demonstrated using a Bensen Gyrocopter as a test bed (Figure 3), the Navy system produced biased modal displacement estimates if not properly calibrated prior to data collection operations. This biased estimation result is a consequence of the (initially) unknown bias present on all accelerometer sensors that can measure static (DC) accelerations, and thus improvements were desired to make this system more attractive for general rotor system testing. NASA sponsored a Phase I research program\(^17\) that allowed improvements to this system both in its ability to collect a wider range of sensor data, at a higher rate, as well as additional improvements in both bias removal and optical data transfer techniques. In particular, the optical telemetry system was converted from a continuous transmission process (requiring multiple transceivers in viewing range of the transmitter) to a burst-mode data dump scheme, the latter being activated when the transmitter is within the solid angle of the receiver’s optical field of view. Individualized printed circuit “nodes” were fabricated that included accelerometer sensors, an IR transceiver, and a Microchip dsPIC digital signal controller chip, coupled to a low-voltage serial interface network to “daisy chain” multiple units along the pressure side of an instrumented rotorblade (Figure 4). Blade modal displacement bias correction was to be handled using a blade-mounted magnetometer, which met with limited success. The goals of this system, which was only developed to a demonstration state in Phase I, were to provide a flexible instrumentation system for generic rotorcraft research applications (shown schematically in Figure 5).

![Figure 1: Specialized instrumentation for the UH-60 Airloads test program for measuring blade motion (from rotorcraft.arc.nasa.gov/tutorial/index.html)](Image)

**Accelerometer-based approaches**

Navy efforts to improve helicopter flight simulations models, through the acquisition of operational flight data from both fuselage and rotating-frame components, resulted in a prior SBIR-sponsored effort at CDF\(^2\) which produced key elements of a “generic” rotor instrumentation unit that was aircraft-agnostic. Design constraints for this system were that it must operate on a variety of rotor hub types (since the Navy operates several types of helicopters), and it should not assume that a slipring assembly was available to supply power or transfer electrical data signals back to the non-rotating aircraft system\(^2,12\). These design constraints led to the incorporation of flat-pack batteries for instrumentation power and an optical IR telemetry link for downlinking the measured sensor data. An additional novel feature of that design was the use of blade-mounted accelerometers for the measurement of combined blade displacement and modal acceleration (see Figure 2), such that the extraction of blade modal response may be realized through linear combinations of sensor outputs combined with a simple complementary filter scheme, called a “Kinematic Observer.” Processing of the downlinked sensor data was performed in the fixed-frame, and could provide estimates of blade in-plane, out-of-plane, and torsional modal response. This filtering scheme had its origins in research work conducted on Individual Blade Control applications, which by its very nature requires suitable measurement of blade responses to implement an appropriate feedback control command\(^13-16\).

![Figure 2: Accelerometer signal content for measuring flap modal response.](Image)
to support NASA rotorcraft experiments and \textit{not} operate as a sensor component within a flight control loop.

The current system design, to be represented with a simulation model for pre-test assessment and planning, consists of small circuit assemblies having two three-axis accelerometers and a dedicated digital signal controller chip capable of computing the necessary filtering operations to extract rotor state estimates. This system will need to be represented in the simulation to confirm that the rotor state estimates produced are sufficiently accurate and timely to provide beneficial feedback functions within a high-bandwidth flight control system. Two simulation models were developed to support this process: (1) a time-domain based model that couples with a detailed aeromechanics model for the rotor system; and (2) a frequency-domain equivalent transfer function model, suitable for use in control law design and stability assessment. The design of these simulation representations is described next.

**TIME DOMAIN SIMULATION MODEL**

Proper representation of a time-domain model for the accelerometer-based rotor state estimation scheme must address all of the external sensor inputs and the processing delays encountered from the moment the sensor data is sampled until it is presented to the control law for feedback use. These delays include: sampling and A/D converter latencies; processing operations; and data transfer latencies. These must also include any additional processing required to coordinate other blade sensor systems on other blades, and error/fault accommodation performed by the central data receiver in the fixed frame. To appreciate the origin of these various subcomponents within the rotor state estimator, some further explanation of the system design is necessary.

**“External” Sensor Inputs**

Follow-on work, supported again from NASA at the Phase I SBIR level, replaced the magnetometer measurement with a once-per-rev optical blade position measurement, as a means of bias correction to the accelerometer-based Kinematic Observer blade modal displacement measurement scheme. Improvements in the processing capability on-blade have also permitted the computation of blade harmonic displacement quantities (such as tip path plane measurement, or steady and first harmonic flapping), and thereby decreased the requirement on downlinked data transfer speeds. As was the case before, the goal of that particular instrumentation development was
Figure 5: Schematic of accelerometer-based rotor-mounted instrumentation system, developed for the U.S. Navy by CDI.

Figure 6: UH-60 data from a roll-reversal maneuver at 120KT, showing effect of body motion on accelerometers.

Since this additional acceleration component does not relate to rotor state (other than via blade azimuth position), it can interfere with the blade state estimation if not directly accounted for in the processing of the sensor signals. Two methods may be incorporated for providing this corrective input – the first is to correct the blade sensor data (on the outboard component) with physical measurements of fuselage rotation rates measured in the fuselage frame (thus requiring an uplink of data to the rotor processors on those rotation rate quantities); the second is to measure the Coriolis acceleration effects directly, along with the combined Coriolis and blade response acceleration, and subtract the two. This latter method is under investigation in the current model rotor test program, as it is easier to
implement since it provides less ambiguities with regards to when various acceleration signals were measured and thus what the “age” of the measurements is prior to the subtraction process. The approach, then, is to make measurements near the hub of the effects of only body rates on accelerometers, and scale that measurement and subtract it from the measurements on the blade outboard of the articulation hinge. The implication is that the difference would contain acceleration content only from the motion of the blade relative to the articulation point and not from body-axis rotation rates. The rotor test stand has been modified to include a mounting location for an inboard accelerometer array, since little physical space exists on this model to accommodate acceleration measurements inboard of the combined flap/pitch hinge location. This mounting arrangement is shown in Figure 7.

![Figure 7: Underside view of the instrumented articulated rotor hub, showing the hub data acquisition PCB (wrapped in blue tape) with Hall-effect sensors for root flap and pitch angle measurements, plus mounting bracket with accelerometer sensor PCB attached (indicated with arrow).](image)

In order to validate this approach, additional data is being collected from the hub microcontroller on the actual blade positions (pitch and flap) using Hall-effect linear transducers with rare earth permanent magnets as the excitation source (also shown in Figure 7). The hub microcontroller system includes two serial ports, with one dedicated to communication links over the half-duplex databus with separate accelerometer sensor PCBs, and the second providing a full-duplex link to a host computer for data collection from the experiment. Since one of the key demonstrations from this test rig is the successful estimation of rotor state variables in the presence of body rotational effects, a shaft angle-of-attack ball-screw drive will be sinusoidally excited at a range of frequencies during the testing to validate the approach using the accelerometer instrumentation.

**Electronic System Delays**

Software for sequencing the collection of both accelerometer data and hub motion data from the Hall-effect transducers was substantially modified to support testing of various rotor state estimation schemes. This was necessary, as the experiment was designed to collect both accelerometer data and hub displacement sensor data for comparison with the acceleration-only rotor state estimates. Actual implementation of the rotor state estimation scheme will use accelerometer measurements internally in the filtering scheme, and only transmit processed information to the hub and the fixed frame systems. However, the experimental hardware here has been designed to also support high-speed collection of additional time series data to permit algorithm development using these samples off-line, prior to implementation of algorithms within the microcontrollers.

![Figure 8: Interconnected hub microcontroller board (round) hosting the data acquisition components for the hub Hall-effect sensors (rigid blade flap and pitch, for 3 blades), plus two three-axis accelerometer measurements on each accelerometer sensor board.](image)
these PCBs at a serial speed approaching 230Kbaud, in order
to get all channels sampled within the time interval of 1/64th
of the period for a nominal operating rpm of 300.

Operation of the software for extraction of these data is
as follows. The hub controller measures the time intervals
between edges of the 1/rev shaft pulse that is fed up from the
fixed frame of the rotor test stand. This value is divided by
64 and used as a period for a second clock that triggers
sampling of the on-chip A/D converter, with the first sample
taken synchronously with the detected edge of the 1/rev
pulse. At the same instant, a four-byte serial command to
sample data is sent out on a half-duplex databus that
connects two accelerometer printed circuit boards (PCBs).
One board is mounted inboard of the hinge articulation
point, and the second board is mounted on the moving blade.
Upon receipt of this sample command, each accelerometer
board also triggers its respective A/D converter, storing the
analog measurement samples in on-chip RAM. When
conversions have completed on the hub unit (which is
exceedingly fast), the sampled values are combined with the
current clock measurement from another on-chip timer, and
the “packet” of sampled data plus the timer count is sent out
the chip’s serial connection to the slipring assembly for
storage in the fixed frame. At the end of the transmission of
that packet, a second unique four-byte command is sent out
on the half-duplex databus from the hub controller to the
accelerometer boards, instructing the first to transmit its
stored analog samples back to the hub controller. The hub
releases the half-duplex bus, and the processor on the
inboard accelerometer board sends out its own packet of
information representing the sampled accelerometer signal
values. Each byte, when received at the hub controller, is
retransmitted onto the serial output connected to the slipring
assembly. The end of this packet includes a four-byte
sequence from the inboard accelerometer controller that
signals the hub controller to transmit a second data request
command (also a unique 4-byte transmission), which is
intercepted by the outboard accelerometer board. The
second, outboard board transmits its data on the databus, and
again each byte is retransmitted onto the serial line on the
slipring assembly. At that point, all processors had
transmitted their data, and are now “idle”, awaiting the next
64/rev trigger to fire, at which point the process is repeated.

Since data is sampled from the hub board plus two
separate boards containing two three-axis accelerometers
each, a significant amount of data must be transmitted at
each clock trigger. The hub unit samples 6 blade
displacements (flap and root pitch), the 1/rev toggle signal,
and the shaft pitch angle, and the hub packet includes a 16-
bit timer value, plus four preamble bytes and a trailing
checkbyte (23 bytes); the inboard accelerometer board
samples 3 3-axis accelerometers (6 analog channels), plus a
4-byte preamble and trailing checkbyte and four-byte end-
of-packet sequence (21 bytes); and the outboard
accelerometer board has the same size packet (21 bytes) –
resulting in a total per-sample stream of 65 bytes. For a
nominal rotation rate of 300 rpm (5Hz), at 64 samples per
revolution, this results in a bit rate of 200.8Kbps (when one
includes the start and stop bit associated with a serial byte
transfer). Thus, the boards all communicate with one
another, and over the slipring system, at a 256Kbps baud
rate. Timing of the data transfer is appreciated through
examination of the following screen capture from the mixed-
signal scope used in the development process. Figure 9
shows two traces collected when the data system is not
rotating, thus defaulting to a sample rate of approximately
140Hz. The upper trace shows the serial data transmissions
from the master hub controller down the slipring assembly
on the model, to the serial port on the computer collecting
these data; the lower trace is the data transmissions being
imposed upon the half-duplex databus connecting the two
accelerometer boards to the hub controller.

![Figure 9: Dual trace capture of serial data – top: data
downlink from hub to fixed frame; bottom: data
transferred on databus connecting hub and two
accelerometer boards.](image)

**Simulation Formulation**

Time domain simulation of the system for estimating
rotor state values was constructed in a two-step process, as it
was not (at this point) necessary or desirable for this
component to run in real-time. To both guide the
experimental program, and to provide a means of assessing
the processing algorithm, a simulation model of the test
hardware was set up using the CHARM Toolbox operating
within a MATLAB environment19. However, since this
software tool is also structured to support flight simulation,
the calculation of blade response and the spanwise
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attached to the blade surface. Thus, MATLAB support routines were constructed in concert with the CHARM Toolbox to output acceleration effects from each contribution, so that they may be combined appropriately to represent the sensor outputs of the blade- and shaft-mounted accelerometers on each printed circuit card as part of the simulation output.

With the ultimate goal of representing the estimation of the rotor state (fundamentally the tip-path-plane motion) as an equivalent transfer function, some means of excitation of the simulation environment was necessary to generate a time response to support that calculation. This same excitation should be representative of what is possible on the model rotor test rig in order to guide the experimental program, and to validate the approach for the transfer function determination. A sine wave sweep, or “chirp” input, was input to the lateral cyclic pitch in a hover condition for the simulated model rotor, and the equations for the rotor response, and the wake propagation, were integrated forward in time. MATLAB support routines updated the simulation in time, and added additional “outputs” representing each accelerometer sensor on each of the two PCBs – one attached to the blade, and the other rotating with the blade but inboard of the blade articulation point. Approximately 30 seconds of simulation time was used to compute the blade and sensor response to the chirp input, with the maximum excitation frequency set to approximately 10Hz, or 2/rev.

Verification of the blade response is shown in the time history plot of the excitation chirp signal, the blade flapping response, and one of the accelerometer traces (measuring in the flap direction) on the outboard PCB (Figure 10).

Taking the transfer function of this input to the tip path plane response of Figure 11, showing the somewhat light damping present in the model rotor due to its low Locke number of 3.69. A transfer function estimate, using this simulation data, from the flap response to the accelerometer (Figure 12) also reveals the anticipated “zero” associated with the frequency when the flap inertia response is exactly balanced by the contribution from centrifugal acceleration. Thus, the oscillatory excitation in pitch has been used to generate a flap response, which in turn will be treated as a fictitious “input” to the determination of the state estimation transfer function below.

Processing Approach

With the simulation results in hand, application of various signal processing schemes could be undertaken and evaluated. Since representative time histories were available from all sensors on the model, this same set of responses could be used to assess the robustness of the algorithm, and
the equivalent time delay associated with the generation of
an estimate of the rotor state variable.

As mentioned above, the underlying procedure for
operating on the accelerometer measurements is through the
use of a Kinematic Observer, which reconstructs modal
acceleration and displacement measurements from (at least)
a pair of acceleration measurements to then drive a
complementary filter that generates, in this case, flap rate
and flap position estimates. If the rotor system is in
unaccelerated flight, then the signal content of the
accelerometer signals is only from blade modal acceleration
(including local Coriolis effects from modal velocities), and
the component of local centrifugal acceleration oriented in
the sensor’s sensitive axis. If the rotorcraft is in accelerated
flight, however, then both the hub acceleration, and the
Coriolis acceleration from fuselage angular rates will be
seen in the sensor as well. In order to provide a test case for
handling the accelerated flight condition, an imposed pitch
rate was simulated for the model rotor, having a 30deg/s rate
toggle each second of the simulated test run. Figure 13
shows a similar time history to Figure 10, except with the
addition of the imposed pitch rate, the flapping response
and the sensor signal can be seen to be dominated by the Coriolis
acceleration from the imposed pitch rate.

![Figure 13](image1)

**Figure 13:** Time history of simulated model response for
combined “chirp” plus sawtooth shaft pitch input.

As described above, the model rotor configuration under
test has two dual-accelerometer boards for sensors, with the
most inboard one mounted to the shaft (Figure 7), and the
outboard one mounted on the blade, and thus capable of
sensing blade motion about the articulation hinges. They are
located at radial positions 1.1", 1.9", 6.85" and 7.75" from
the shaft centerline, with the flap hinge at 1.3” out from the
same datum. If we now represent the signal content of these
four accelerometers (called A, B, C, and D) in terms of hub
acceleration, body Coriolis acceleration, flap modal
acceleration, and centrifugal acceleration through flap angle,
we get the following matrix relationship:

\[
\begin{bmatrix}
A \\
B \\
C \\
D
\end{bmatrix} =
\begin{bmatrix}
1 & 1.1 & 0 & 0 \\
1 & 1.9 & 0 & 0 \\
1 & 6.85 & 5.55 & 6.85 \\
1 & 7.75 & 6.45 & 7.75
\end{bmatrix}
\begin{bmatrix}
a_{HUB} \\
a_{Coriolis} \\
\hat{\beta} \\
\Omega^2 \hat{\beta}
\end{bmatrix}
\]

If the above matrix is inverted and applied to the sensor
signals from the simulation, the flap modal acceleration and
centrifugal acceleration component are exactly
reconstructed. This is not too surprising, since the
simulation only includes flap response in the blade modal
representation, and hence there is no “spillover” of higher
frequency information from higher unmodeled modes into
these reconstructed values. However, if errors are present in
the representation of the sensor locations in the solution of
these linear equations, these will be propagated into the
reconstruction of the flap mode acceleration and centrifugal
acceleration as well. An example of this error could come
from a misrepresentation of the precise location of a sensor,
or of the effective flap hinge. To illustrate this effect, the
matrix equation above was solved with an offset of 0.1” in
the representation of the outermost accelerometer location,
and the resulting reconstruction of flap displacement is
compared to the actual value in the simulation data in Figure
14. What was originally a perfect correlation has now
developed a small skew in slope and a spread in the cross-
plot, illustrating the error associated with that reconstructed
signal.

![Figure 14](image2)

**Figure 14:** Correlation curve for reconstructed and
actual flap displacement with 2% position error on
sensor.

If this same simulated data is now used to reconstruct
modal acceleration and modal contribution to centrifugal
acceleration, but the Coriolis and hub accelerations from
accelerated “flight” are neglected, the correlation worsens,
as shown in Figure 15. This suggests that the estimation
error will be less sensitive to misrepresentations of sensor
location than to accelerated flight effects, even when the fuselage angular rates are significantly below rotor rotation speed.

Figure 15: Correlation curve for reconstructed and actual flap displacement, neglecting the Coriolis acceleration effects from fuselage angular rates.

**Rotor State Estimation**

Formulation for blade flap and flap rate estimation using a Kinematic Observer, following previous work, is a simple matter of picking feedback gains to obtain desired observer tracking performance. The continuous-time format for estimating the flap position and flap rate, given the extracted flap acceleration and flap position values from the solution of the prior matrix equation is:

\[
\frac{d}{dt} \begin{bmatrix} \dot{\beta} \\ \dot{\beta} \Omega^2 \end{bmatrix} = \begin{bmatrix} 0 & \Omega \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \beta \Omega^2 \\ \beta \Omega \end{bmatrix} + \begin{bmatrix} 0 \\ \Omega \end{bmatrix} \begin{bmatrix} \ddot{\beta} \\ \ddot{\beta} \Omega^2 \end{bmatrix} + \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} \begin{bmatrix} \beta_{\text{recon}} \\ \Omega^2 - \beta \Omega^2 \end{bmatrix}
\]

If both values of K1 and K2 are set to rotor rotation speed, the filter is critically damped and has the same relative bandwidth of the flapping response itself. Use of this structure in the computation of the estimated flap position and rate can be shown as correlation curves in Figures 16 and 17, where it may be seen that after a small tracking transient at initial startup (Figure 18), the estimation performance is quite good. Again, this performance is with perfect knowledge of the accelerometer sensor locations, with no sensor bias assumed in the measurements. The close phasing of the estimated and simulated flapping measurements suggests that the transfer function between the two will primarily be characterized (for these semi-ideal conditions) as just a pure time delay associated with the actual sampled data transmission and processing of these signals, which for the worst-case on this model, would be the 1/64th of the rotor period.

Figure 16: Correlation curve for flap response estimate from Kinematic Observer, including fuselage angular rate effects.

Figure 17: Correlation curve for estimated flap rate from Kinematic Observer, including fuselage angular rate effects.

Figure 18: Detail of transient flap estimate tracking of simulate flap response.
CONCLUDING REMARKS

The simulation work here has provided valuable insight to aid the planning of an experiment on a model rotor for demonstration of hardware to estimate blade tip path plane angle (or, flap position and rate), using on-blade accelerometer measurements. Limited error analysis has shown that neglecting fuselage angular rate effects in the sensor model can significantly degrade the estimators performance, while small errors in the representation of sensor locations appear to be tolerable to the technique. Tracking performance of the estimation algorithm is shown to be fast enough to approximate the overall transfer function between actual and estimate rotor flap angle as a pure time delay associated with the transfer of data and the processing of those measurements within the subframe between sensor samples.

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