Flight Control Design for Alleviation of Pilot Workload during Helicopter Shipboard Operations

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A flight control design methodology for alleviating pilot workload during helicopter shipboard operations was developed and tested in simulation. The methodology uses modern MIMO control theory to improve gust rejection properties when operating in a turbulent ship airwake. The spectral properties of the airwake are identified using simulations and incorporated into the control synthesis process. The controller design is constrained to represent a limited authority SAS. Model order reduction methods are used to simplify the control laws for practical implementation. The methodology was applied to design a modified SAS for the UH-60A operating over an LHA ship. The system was implemented in a high-fidelity simulation model and its performance was compared to that of the baseline SAS. Simulations were performed of the helicopter hovering in the turbulent airwake using a pilot model for two different wind-over-deck conditions. Results indicate that the modified SAS resulted in significantly lower control activity and angular motion of the aircraft.

Introduction

Shipboard launch and recovery operations continue to be one of the more challenging flight regimes for rotorcraft. Pilot workload issues can often be the limiting factor when defining allowable sea state and wind-over-deck (WOD) conditions for a particular helicopter and ship combination. A number of researchers have integrated models of ship airwake turbulence and ship motion effects into high fidelity simulation facilities and have demonstrated that the simulation provides a reasonable tool for handling qualities analysis and pilot training. The Dynamic Interface Modeling and Simulation System (DIMSS), developed under the JSHIP program, is a prime example. A number of other researchers have also implemented non-real-time simulation analyses of shipboard operations using pilot models to estimate workload. Only recently have researchers begun to investigate methods of alleviating pilot workload in this environment using advanced flight control design, including position hold systems over the ship deck and stability augmentation systems designed specifically to reject ship airwake turbulence.

Modern, multivariable control theory evolved dramatically in the 1980s and 1990’s. Robust control theory was developed to address control problems associated with poorly modeled systems or systems that are subject to large disturbances. In theory, $H_\infty$ synthesis method provides a systematic procedure for designing controllers for multivariable systems that provide good performance even when the system is subject to large perturbations either from model uncertainty or external disturbances and full-state measurement is not available. The effects of uncertainty and external disturbances are modeled in the same manner in this design procedure, and as such the methods may be well suited to disturbance rejection problems such as helicopter flight control in the ship airwake. Several researchers in the past have investigated the practical issues of using robust control theory for helicopter flight control design with the specific objective of meeting flying qualities requirements such as ADS-33. For example, Postlethwaite et al designed $H_\infty$ based controllers for the Lynx and successfully demonstrated handling qualities in piloted simulation. However, robust control theory has not found wide application in industry, partly due the high order and complexity of compensators produced in the synthesis process. The problem of applying multivariable control theory to develop simple, practical control laws has not been fully addressed.

This paper presents the development and analysis of a flight control design method for alleviating pilot workload associated with operating in the turbulent air over a ship deck. The objective is to apply modern, multivariable design methods to develop a relatively simple limited authority stability augmentation system (SAS), which provides improved gust rejection. *Currently with Advanced Rotorcraft Technology, Inc.

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characteristics in the shipboard environment. Such a system could be employed as a task-tailored flight control mode in existing operational aircraft. Similar design methods could also be applied in the development of future fly-by-wire flight control systems.

The flight control design is applied for a UH-60A Black Hawk helicopter operating off an LHA-class ship. A high-fidelity simulation model of this ship/rotorcraft combination was developed in previous work, in which the flow-field over the ship was calculated using advanced CFD methods and then integrated with the helicopter simulation using a gust penetration model. The helicopter flight dynamics model is based on the U.S. Army GENHEL simulation. In addition a simple ship motion and ground contact model have been added for this study.

This analysis focuses on a particular landing spot and WOD condition for the LHA that has been identified as a hazardous and high workload condition for approach and landing. An optimized controller is designed for this particular condition and its performance is compared to that of the existing baseline SAS. The baseline SAS is documented in Ref. The optimized SAS is tested for an off-design point (a less severe WOD deck condition). In previous studies a shipboard SAS was designed using a classical control law architecture, but it was found to provide only modest improvement with somewhat large compensator gains. A modern control design approach is used in this analysis, and model order reduction methods are used to reduce the complexity of the controller for practical implementation. The performance of the flight controllers is evaluated using simulation coupled with a pilot model.

**Helicopter / Ship Dynamic Interface Simulation**

The rotorcraft flight dynamics model used in this study is based on the U.S. Army/NASA Ames GENHEL model of the UH-60A Black Hawk. This is a well-established FORTRAN-based simulation code made available to Penn State by NASA Ames Rotorcraft Division. Numerous changes and upgrades have been made to the code resulting in a version called GENHEL-PSU. Some of the upgrades include: capability to generate high order linear models, network communication abilities that allow for interaction with other programs and computers, modification of the flight control system to incorporate user-defined controllers, and addition of a graphical user interface. The basic mathematical model of the aircraft aerodynamics and flight dynamics is largely unchanged. A notable exception is the addition of the shipboard interface modules, which accounts for the aircraft interaction with the ship airwake as well as ground contact with the moving ship deck.

Capability has been added to the simulation to model a ship moving at constant speed and heading as well as the time-varying motion due to a particular sea state. A semi-analytical method that calculates the heave, roll, and pitch motion using closed-form expressions is applied as was done in the work by Hess. These closed-form expressions are based on the ship geometry, speed, and heading, as well as the sea state; each of these parameters can be controlled through the user interface in GENHEL-PSU. The GENHEL landing module was also modified to include ground contact with a moving deck. At this point the landing module has not been validated, but it appears to simulate reasonable ground contact behavior. In any case, deck contact was not a focus of this study.

Ship airwake data has been obtained by computational fluid dynamics (CFD) analysis using the PUMA2 solver. This time-varying data is preloaded into memory by a separate program called AirwakeData, which allows it to be accessed quickly for the simulation to operate in real-time. During the actual flight simulation run, GENHEL-PSU transmits information to AirwakeData including time, position and orientation of the helicopter and ship, and the position of the point of interest relative to the helicopter. AirwakeData then calculates the position of point of interest relative to the ship and interpolates in the x, y, and z directions and time to calculate the airwake components. This process is repeated multiple times for each timestep, once for each main rotor blade segment, the tail rotor, the fuselage, and the horizontal and vertical tails. It should be noted that the airwake components stored and calculated by AirwakeData are only the time-varying perturbations from a constant wind-over-deck condition; the constant portion of the wind is implemented in the steady-wind model in GENHEL. This is done so that a given WOD condition can be modeled using different combinations of ship motion and steady wind.

A low-cost rotorcraft flight simulation facility has been developed for visualization and performing real-time piloted simulations. The facility has three 42-inch HDTV flat-panel plasma displays for the out-the-window views, two 15-inch LCD monitors for instrument displays, and a set of commercially available rotary-wing flight controls. The simulator incorporates several different software packages running on different nodes; these include GENHEL-PSU, AirwakeData, and FlightGear, which is an open-source flight simulation program used to generate out-the-window graphics, drive instrument displays, and read in pilot control inputs. FlightGear supports the use of multiple displays to form a panoramic view;
an unlimited number of display channels are permitted, where each channel is a separate process running on a separate computer, communicating with the master node via network sockets. In addition, a multiplayer mode allows for the display of multiple vehicles; in this case, both the helicopter and ship (portrayed by representative 3D models) can be displayed simultaneously. The simulation software also includes an interface to MATLAB, which is used to provide a graphical user interface (GUI) and post-processing capabilities. The schematic in Figure 1 illustrates how data is transferred between these different programs. Figure 2 shows sample graphics of the helicopter operating over a moving LHA ship.

Due to lack of motion cueing and limitations in the vertical field-of-view, the quality of the graphics, and the feel characteristics of control inceptors, the facility is a relatively low-fidelity part-task simulator (this is not due to the flight dynamics model which has reasonably good fidelity). The simulator is quite useful for visualization and preliminary piloted evaluation of the model and control law designs, but the tasks performed in this study were too challenging to perform with human pilots given the limited cue environment. Thus, a simulated pilot model, developed in previous work, was used to control the aircraft in the final simulation results.

Fig. 1 Software Schematic of Simulation Facility

Fig. 2 Simulation of Ship / Helicopter Dynamic Interface
Flight Control Design and Optimization

The design objective is to reduce workload by improving gust rejection properties of the helicopter when operating in the ship airwake, i.e. to minimize the vehicle response to the airwake disturbances. The control system is designed for the UH-60A helicopter and optimized for operation in the airwake of an LHA for a very severe WOD condition. The first task in achieving the design objective is to characterize the spectral properties of the gust disturbances that occur in this flight condition. The spectral characteristics of the wake are then incorporated into an augmented plant model of the vehicle dynamics, and the gust response of the vehicle is minimized using modern control methods. The weighting functions in the performance objective are adjusted so that the controller is practical for a limited authority SAS system. In addition, model order reduction methods are applied to simplify the controller structure for practical implementation. Finally, the controller is implemented in simulation and evaluated using a pilot model for the design flight condition as well as an off-design point. Preliminary piloted tests were also used to provide qualitative evaluation, but at this point are inconclusive due to the limited cueing environment of the simulator.

Design Point

The UH-60A / LHA ship combination was chosen for this study due to the availability of the GENHEL model and CFD airwake data of the LHA. Furthermore, the model used in this study has previously been shown to have good qualitative agreement with flight test data for the same helicopter / ship combination. This analysis focuses specifically on operations over landing spot 8 on the LHA in 30 knot, 30° WOD conditions. Results from the JSHIP program have indicated that this WOD condition resulted in unacceptably high pilot workload. Thus, it can be considered a “worst-case” WOD conditions for this ship / aircraft combination. The design point used in extracting the gust disturbance model and evaluating the controller was for the helicopter hovering relative to the ship deck with a wheel height of 10 ft. This ship is moving at constant speed of 20 knots, with a steady wind of 16.15 knots, 68.3° off the port bow. This results in a 30 knot, 30° relative wind as shown in Fig. 3. The gust disturbances due to the airwake are then superimposed on this steady wind.

The linear model used for flight control design, was extracted from a pure hover trim condition, while using the gust properties from the 30 knot / 30° WOD case. Although the linear dynamics of the aircraft in hover are slightly different from those in a 30 knot relative wind, it was felt that a controller designed around hover would have reasonable performance in the 30 knot case and have better performance over a wider range of low speed flight conditions.

Airwake Gust Disturbance Model

In order to more efficiently compensate for airwake disturbances, it is necessary to characterize the specific spectral properties of the airwake. In this analysis, we are primarily interest in the effect of airwake on the flying qualities of the helicopter, while higher-order flow features that may only be responsible for vibration and high frequency effects are of lesser interest. A method was developed in previous studies for extracting equivalent airwake disturbances from the simulation model. The equivalent disturbances are then modeled as a stochastic process. The airwake is represented as a disturbance vector of 3 velocity and 3 angular rate components, similar to the von Karman turbulence model. The current disturbance modeling process is similar to the process developed in Ref. 19. In that study, a disturbance model was developed by extracting the aircraft remnant rates due to atmospheric turbulence from flight test data. The remnant rates were then put into an inverse model of the aircraft to create equivalent control inputs that could then be fed into the aircraft actuators to simulate response to turbulence. The present disturbance modeling effort is different in that the equivalent disturbances are expressed in terms of body velocities and angular rates, and that the effort focuses specifically on modeling the gust velocities due to the turbulent wake of a ship’s superstructure.

The first step was to perform a series of simulations in which the helicopter hovers over the ship deck in the turbulent airwake. The hover cases were flown for 50 seconds and were performed over landing spot 8 on the LHA as described in the previous section and illustrated in Fig. 3. The test was repeated five times, and in each case the airwake data was initialized at a different starting point to add variability in the tests. The maneuvers were performed using a pilot model to hold station over the landing spot. The pilot model uses the Optimal Control Model (OCM) of the human pilot, and it is described in some detail in References 7 and 13. Aircraft rigid body states, state derivatives, and control inputs to the mixer (which includes pilot stick and SAS inputs) were recorded.
A 28-state linearized model of the open-loop dynamics of the helicopter were extracted for a trim condition in a 30 knot / 30° steady wind. This model includes rotor, inflow, and engine dynamics. For this analysis a simple 9 state model of the rigid body dynamics was derived from this high order model. The linearized model is of the form:

\[ \dot{x} = Ax + Bu + Gw \]  

where the aircraft state, control, and disturbances vectors are:

\[ x = [u \quad v \quad w \quad p \quad q \quad r \quad \phi \quad \theta \quad \psi]^T \]

\[ u = [\delta_{lat} \quad \delta_{long} \quad \delta_{roll} \quad \delta_{ped}]^T \]

\[ w = [u_g \quad v_g \quad w_g \quad p_g \quad q_g \quad r_g]^T \]

Note that the control vector consists of the equivalent pilot control inputs going into the UH-60 mixer, and the disturbance vector consists of the equivalent aerodynamic gusts. There is an important aspect to remember when deriving linear models for this type of analysis. The gust disturbances should only produce aerodynamic perturbations on the aircraft and should not affect inertial forces. This is important for two reasons:

1. The rigid body equations of motion include Coriolis terms and gyroscopic terms that should only be affected by changes in inertial velocities and angular rates. These terms are independent of the relative velocity of the surrounding air mass.
2. The equations of motion for the rotor flapping and lagging dynamics include inertial forces on the rotor blades that are affected only by inertial velocities and angular rates of the rotor hub. These forces are also independent of the motion of the surrounding air.

Item two is of particular importance due to the effect of pitch and roll angular rates on the rotor system. The effect of angular rate on rotor flapping due to aerodynamics is known to be fundamentally different than the effect due to gyroscopic coupling. Significant modifications were made to the GENHEL model in order generate perturbation based linear models in which the aerodynamic perturbations are partitioned from the inertial perturbations. The resulting terms in the \( G \) matrix (which include only aerodynamic forces) are substantially different from the equivalent terms in the \( A \) matrix (which include both aerodynamic and inertial forces).

After the hovering simulations were performed and the linear model was derived, a time history of the equivalent disturbance vector can be estimated using an inversion method. Note that \( G \) is a 9 x 6 matrix. Thus it is neither square nor invertible. There are fewer disturbances than aircraft states, so an exact solution of the equivalent disturbance vector does not exist. However, the best least squares approximation of the effect of the airwake on the aircraft can be derived using:

\[ w = G^+ (x - Ax - Bu) \]

where \( G^+ \) is the pseudo-inverse or left inverse of \( G \).

The three velocity components of the gust vector represent the average gust velocity over the body of the aircraft, while the three angular velocity components represent a linear variation of the gust field over the body of the aircraft. More complex non-linear variations of the gust field over the body of the aircraft are not captured, but previous studies have shown that re-playing the equivalent airwake disturbances into the model result in a very similar vehicle response as simulation with the full non-linear airwake model.

The final step of the overall modeling process is to derive transfer functions that, when stimulated with zero mean unity white noise, generate a disturbance time history with similar spectral properties as those observed in the simulation runs. A power spectral density (PSD) for each of the six disturbances was
calculated from the five simulation time histories. A transfer function, or spectral filter, was then calculated to match the PSD derived from the simulation using least squares curve fitting methods. The spectral filters were assumed to be third order, and have a similar form as those used in the classic von Karman turbulence model:

$$H(s) = \frac{4\sigma \sqrt{L}}{V} \left(1 + b_1 \frac{L}{V}s + b_2 \left(\frac{L}{V}s\right)^2\right)$$

$$1 + a_1 \frac{L}{V}s + a_2 \left(\frac{L}{V}s\right)^2 + a_3 \left(\frac{L}{V}s\right)^3 \tag{4}$$

The intensity factor, $\sigma$, the length scale, $L$, and the coefficients, $a_i$ and $b_i$, were selected to fit the PSD derived from simulation over the frequency range of 0.1 to 40 rad/sec. $V$ is the reference airspeed, which is 30 knots (50.64 ft/sec) in this case.

Fig. 4 and Fig. 5 show sample results for the lateral and pitch rate components of the equivalent gust vectors. The spectral filters are reasonable fits to the PSD’s derived from the simulation. The PSD for each of the six gust components exhibited a peak in the range of 1 to 4 rad/sec, which would be expected to have significant impact on handling qualities. The shape of these PSD’s is very different from those obtained from the standard von Karman model, which tend to roll off gradually as frequency increases. The airwake turbulence appears to have unique spectral properties compared to standard atmospheric turbulence models.

**MIMO Flight Control Design**

In a previous study, the SAS design was restricted to a very simple single-input / single-output (SISO) architecture using classical lead-lag compensation. The controller was then optimized using an advanced flight control optimization tool, CONDUIT. Although the results of that study were promising, it was clear that the performance improvements were limited, and the resulting loop gains were significantly higher than those of the baseline SAS. Even though the spectral properties of the airwake gusts were included in the control synthesis, the design tended to address the problem by just increasing the compensator gain rather than shaping the compensator to better reject the specific type of gust disturbance. Although the controller did not appear to cause excessive SAS actuator saturations, the high compensator gain could cause other problems when coupled with the higher order dynamics and phase delays that might occur when implemented on a real aircraft.

In this study, modern multi-input / multi-output (MIMO) design methods are applied to better optimize the controller to reject the specific type of disturbances experienced in the ship airwake. However, in order to develop a practical flight controller that could be implemented in an existing limited authority SAS, and to have a fair comparison with the baseline SAS system, the design optimization is subjected to some relatively strict constraints:

1. Output feedback parameters are limited to the angular rates of the vehicle (roll, pitch, and yaw rate).
2. There are no feed forward terms in the controller. Thus it is a pure SAS and not a Stability and Control Augmentation System (SCAS).
3. The controller is designed to produce similar response to pilot control inputs as the baseline SAS.
The controller is designed such that the compensator and loop transfer function gains are similar to that of the baseline SAS over most frequencies. In addition to these constraints, the controller order is reduced as much as possible, to the extent that each control channel can readily be expressed as a transfer function, and unnecessary cross-axis channels are eliminated.

The augmented plant model used in the control synthesis is illustrated in Fig. 6. The aircraft is represented by a 23 state model, linearized about hover trim:

$$\dot{x} = Ax + Bu + Gw$$

$$y = Cx$$

$$x^T = \begin{bmatrix} x^T & x_T^T \end{bmatrix}$$

$$x_T = \begin{bmatrix} u & v & w & p & q & r & \phi & \theta \end{bmatrix} \quad (5)$$

$$x_T = \begin{bmatrix} \beta_0 & \beta_0 & \beta_c & \beta_c & \beta_1 & \beta_1 & \ldots \\
\zeta_0 & \zeta_0 & \zeta_c & \zeta_c & \zeta_1 & \zeta_1 & \ldots \\
u_{\text{act}} & \delta_{\text{lat}} & \delta_{\text{long}} & \delta_{\text{pad}} \\
w_{\text{act}} & w_g & w_g & p_g & q_g & r_g \end{bmatrix}$$

$$y = \begin{bmatrix} \rho^0 \end{bmatrix}$$

The aircraft states include rigid body motion of the fuselage, rotor flapping and lagging degrees of freedom, and three inflow states. The rotor RPM dynamics are neglected in the control synthesis, but are included in the simulation runs in the final evaluation. The inputs include lateral, longitudinal, and directional control to the mixer in terms of equivalent inches of pilot stick input. The outputs are roll, pitch, and yaw rate in deg/sec. Heave axis control is not addressed in the study, and is not included in the baseline SAS. It should be noted that the compensator is placed in the feedback path like a traditional SAS, and the output is limited to rate feedback only. The actuator states are represented by standard second order models.

**Fig. 6 Augmented Plant Model**

In this design, performance is measured in terms of the angular rate of the aircraft, which ideally should be regulated close to 0, and the actuator control activity. The augmented plant can include frequency varying weighting functions on the performance variables which include the vectors $z_p$ and $z_a$. Since the control design is based purely on disturbance rejection, and does not address command following, no frequency weighting is required in the angular rate performance weights; i.e. $W_p$ is simply an identity matrix. The actuator weighting is designed to penalize high frequency activity (greater than 20 rad/sec) over low frequency (less than 2 rad/sec) by a factor of ten. The actuator weighting functions are:

$$W_a = \begin{bmatrix} 50 \frac{s+2}{s+20} & 25 \frac{s+2}{s+20} & 50 \frac{s+2}{s+20} \end{bmatrix} \quad (6)$$

The scaling factors on the actuator weighting were adjusted through trial and error so that the resulting loop shapes had reasonable agreement with the baseline SAS over most frequencies. This is discussed in more detail later in the paper.

Disturbances to the system include the airwake gust disturbances as well as sensor noise. The gust filters, $G_{\text{gust}}(s)$, include the spectral filters derived in the previous section. When $d_g$ is a 6 x 1 vector of unity white noise signals, the output of $G_{\text{gust}}(s)$ will produce gust disturbances representative of the ship airwake. Sensor noise is not considered a major factor in the design, but it must be included in the control synthesis for the problem to be well-posed. The noise weighting function was arbitrarily selected as a diagonal matrix to produce 0.5 deg/sec RMS noise in each gyro.

The augmented state, disturbance, and performance vectors are:

$$\tilde{x}^T = \begin{bmatrix} x_{\text{act}}^T & x_{\text{act}}^T & x_p^T & x_a^T \end{bmatrix}$$

$$z^T = \begin{bmatrix} z_p^T & z_a^T \end{bmatrix}$$

$$d^T = \begin{bmatrix} d_g^T & d_a^T \end{bmatrix}$$

where the state vector includes states associated with the aircraft dynamics, actuators, gust filters, and the angular rate and actuator performance weighting functions respectively. Now the augmented system can be defined in the classic form used in robust control theory:

$$\dot{\tilde{x}} = A\tilde{x} + B_1d + B_2u$$

$$z = C_1\tilde{x} + D_{11}d + D_{12}u$$

$$y = C_2\tilde{x} + D_{21}d + D_{22}u$$

(8)

In the closed loop system, control is related to output by $u = K(s)y$. Robust control theory seeks to find the compensator $K(s)$ that will result in optimal behavior of the closed loop MIMO transfer function from the disturbances to the performance, $T_{\text{sd}}(s)$. The
“optimal” behavior can be defined in terms of different function norms. In $H_2$ optimal control, one seeks to minimize the norm:

$$\|T_{ad}(s)\|_2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \text{tr}\left\{T_{ad}(j\omega)^* T_{ad}(j\omega)\right\}d\omega$$ (9)

which represents the area under the singular value curve of $T_{ad}(s)$. In $H_{\infty}$ control, one seeks to guarantee that the maximum singular value of the closed loop system is constrained:

$$\|T_{ad}(s)\|_{\infty} = \sup_{\omega} \sigma[T_{ad}(j\omega)] < \gamma$$ (10)

In either case, the compensator can be calculated using a pair of algebraic Riccati equations. In this study, we apply the formulation of Haddad and Bernstein. The generalized Riccati equations are applicable for $H_{\infty}$ synthesis, but reduce to the standard $H_2$ or LQG solution when $\gamma^2$ is set to 0. The control synthesis process is readily automated using available functions in the MATLAB control systems toolbox.

**Controller Order Reduction and Simplification**

The synthesis methods described above will produce a compensator in state-space form that has as many states as the augmented plant model. With 23 aircraft states, 6 actuator states, 18 states associated with the gust filters, and three states associated with the actuator weighting functions, this results in a 50th order compensator. Obviously, such a high order compensator would be difficult to implement on an actual aircraft flight control system. A number of model order reduction methods are available that produce sub-optimal controllers that have much lower order, and in many practical applications have nearly the same performance has the high order optimal control law. In general, model order reduction on the controller is much easier to apply than fixed-order control synthesis. The first reduction method is balanced model realization and reduction. A balanced realization and Grammian of the controller is calculated, and states corresponding to low terms in the Grammian are eliminated. The balred function in the MATLAB control system toolbox automates this form of model order reduction. For the $H_2$ control law, the controller could be reduced to 14th order with minimal loss in performance. Only modest reductions in order of the $H_\infty$ controller could be achieved without major degradation in performances (as discussed below), which is the main reason this controller was not selected in the final analysis.

After balanced model reduction is performed, the control laws can be further simplified using approximate pole-zero cancellations. Transfer function realizations of the various channels in the compensators can be generated in MATLAB. Pole-zero cancellation can then be performed manually or using the minreal function in MATLAB. This step does not necessarily reduce the order of the overall controller, but it can allow each channel to be expressed as a relatively low order transfer function, as is normally seen in classical control. Furthermore, if some the cross-axis channels in the controller appear to have relatively low gain compared to the on-axis channels they can often be eliminated with little loss in performance. As a result, this analysis can produce a kind of “modified SAS” that is represented by a relatively small number of basic transfer functions. Such a system was developed and described below.

**Linear Analysis of Control Designs**

Three different controllers were first evaluated using linear analysis and compared to the baseline SAS. The controllers include the full-order $H_2$ controller, the full order $H_\infty$ controller, and a reduced-order modified SAS. In the case of the $H_\infty$ controller, a maximum singular value $\gamma=20$ was selected, as this was approximately the smallest value of $\gamma$ that produced a feasible controller. As discussed above, the order on controller could not be significantly reduced, and thus it would not be selected unless it proved dramatic performance improvements over the reduced order SAS.

A modified SAS design was derived from the $H_2$ controller and is summarized in Table 1. The channels coupling the yaw axis to the pitch and roll axes were found to have relatively low gain so they were eliminated to simplify the controller. This was found to have minimal impact on performance. On the other hand, roll-to-pitch and pitch-to-roll channels were found to improve performance significantly and thus were included in the final design.

<table>
<thead>
<tr>
<th>On-Axis Compensators</th>
<th>Roll Rate to Lateral Control</th>
<th>Pitch Rate to Longitudinal Control</th>
<th>Yaw Rate to Directional Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.09(s + 0.464)x^2 + 2.10s + 9.67{x^2 + 12.5s + 151}$</td>
<td>$s + 13.0{x + 0.036}x^2 + 1.31sx + 10.5s^2 + 13.2s + 202$</td>
<td>$1.25{x^2 + 1.51s + 4.5}$</td>
<td></td>
</tr>
<tr>
<td>$s + 5.45{x^2 + 0.977s + 9.13}$</td>
<td>$s + 13.0{x + 0.042}x^2 + 1.56sx + 14.2s^2 + 13.2s + 202$</td>
<td>$(s + 12.00)x^2 + 7.17s^2 + 25.8s + 330$</td>
<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Off-Axis Compensators</th>
<th>Roll Rate to Longitudinal Control</th>
<th>Pitch Rate to Lateral Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.30(s + 0.461)x - 0.357{x^2 + 0.893s + 7.57}x^2 + 5.31s + 154.1$</td>
<td>$s + 13.0{x + 0.079s + 0.0015}x^2 + 1.31sx + 10.5s^2 + 13.2s + 202$</td>
<td>$0.319(s + 48.4)x - 0.378{x^2 + 0.237s + 1.06}x^2 - 4.55s + 41.0$</td>
</tr>
<tr>
<td>$(s + 13.0)x^2 + 0.050c + 0.0052x^2 + 1.56s + 14.2s^2 + 13.2s + 202$</td>
<td>$(s + 13.0)x^2 + 0.050c + 0.0052x^2 + 1.56s + 14.2s^2 + 13.2s + 202$</td>
<td>$(s + 13.0)x^2 + 0.050c + 0.0052x^2 + 1.56s + 14.2s^2 + 13.2s + 202$</td>
</tr>
</tbody>
</table>

**Table 1 – Modified SAS Compensators**
The primary measures of performance used to evaluate the controllers were the gust rejection properties. These were evaluated using singular value plots, which are the MIMO equivalent to magnitude frequency response plots. The gust disturbance is a vector (it consists of six different components), so analysis of the vehicle response to a single gust component does not really capture the effect of all simultaneous disturbances that might occur in flight. Singular value analysis essentially looks at the response of the closed loop system to the worst possible combination of disturbances at a given frequency. Consider the input to the gust filters in Fig. 6, the vector $d_g$. Suppose $d_g$ represents a set of sinusoidal signals, where each signal in the set has the same frequency $\omega$. Each signal in $d_g$ can have a different phase and amplitude, but the total norm is constrained such that $\|d_g\|_2 \leq 1$. The maximum singular value for a given output variable represents the maximum possible amplitude of that output variable for a disturbance input $d_g$ that meets the criteria described above.

Figures 7 to 9 show the maximum singular value plots for roll rate, pitch rate, and yaw rate of the closed loop aircraft due to the airwake disturbances. Plots are shown for the baseline SAS, as well as the three different controllers evaluated. These plots essentially show the sensitivity of the closed aircraft to the disturbances as well as the frequency range where the aircraft is most sensitive. Note that the amplitude represents the response to the worst possible combination of disturbances, which is unlikely to actually occur in flight, but it is nonetheless a good measure of the gust rejection properties of the closed loop aircraft.

Not surprisingly, for the baseline SAS there are large peaks in the angular rate response in the frequency range of 1-4 rad/sec. The PSD plots for the equivalent gust disturbances (as shown in Fig. 4 and Fig. 5) all had peak amplitude in this frequency range. The modified controllers all significantly reduce this peak and generally flatten out the singular value curves, which should result in a milder gust response on the closed-loop aircraft. This is partly due to the fact that the spectral properties of the airwake are accounted for in the control synthesis process. It is clear that the $H_\infty$ controller is the most effective at reducing the vehicle response to the gusts, but the $H_2$ controller is also quite effective, reducing peak gust response by 50% or more. Furthermore, the modified SAS compensators achieve nearly the same performance as the full-order $H_2$ controller. Since the order of the $H_\infty$ controller could not be substantially reduced, it was not considered a practical solution. The complexity of the $H_\infty$ controller outweighed its performance advantages over the modified SAS system. Thus, the modified SAS derived from the $H_2$ controller was selected and the $H_\infty$ controller was not considered in any of the following analysis.
The design philosophy was to improve the gust rejection properties of the aircraft in the ship airwake, while not adversely affecting the handling characteristics or closed-loop stability of the aircraft. Thus, the following objectives were included in the design iteration:

1. Ensure the modified SAS compensators do not have excessively high gain relative to the baseline SAS.
2. Ensure the loop T.F. properties are similar to those of the baseline SAS over most frequencies.
3. Ensure the closed loop T.F. response to pilot inputs are similar to those of the baseline SAS over most frequencies.

These objectives were achieved by adjusting the scale of the actuator weighing functions in Equation 6 during the design iterations and checking the bode diagrams of the compensators, the on-axis loop transfer functions, and the on-axis closed loop transfer functions for each axis. Examples of these bode diagrams are shown in Figures 10-12 for the pitch axis. Each figure plots the frequency responses of the baseline SAS, the full-order $H_2$ controller, and the modified SAS. The results show that the modified SAS closely matches the $H_2$ controller, and thus the order reduction and compensator simplification did not have a major impact.

Figure 10 shows the frequency response of the compensators. It can be seen that at low frequencies the modified SAS gain closely matches that of the baseline SAS. The modified SAS produces a gain increase and some phase lead at around 3 rad/sec, which is around the frequency that the airwake disturbances are most severe. The gain rolls off as frequency increases. Figure 11 shows that the loop gain above 3 rad/sec is also increased due to the modified compensator, and that there is some reduction in phase for frequencies above 5 rad/sec. This increased the gain crossover frequency and reduced the stability margins of the system (this occurred to some extent in all three axes). However, these effects were considered an acceptable by-product of the improved gust rejection properties. Figure 12 shows the frequency response to pilot control inputs of the closed-loop aircraft. There are some changes in the response between 3-7 rad/sec, but overall the modified SAS retained similar closed-loop characteristics as the baseline SAS.
Simulation Results

The modified SAS was implemented in the full non-linear simulation facility and its performance was compared to that of the baseline SAS. The simulation tests involved hovering the helicopter over the landing spot for 50 seconds in the turbulent airwake, as illustrated in Fig. 3. Unfortunately, it was determined that the simulator facility did not have sufficient fidelity to collect these data using human pilots. The task of stationkeeping over the ship deck in the turbulent airwake was too difficult with the available cues. Instead, a pilot model, based on the Optimal Control Model (OCM) of the human pilot was used to perform the hovering tasks. The pilot model acts as an outer loop controller to regulate velocity and position of the aircraft, and the control inputs produced by the model provide an estimate of workload. The OCM pilot model used in this study has been well documented in previous papers.7,8,13

Figures 13 and 14 show sample time histories of the pilot control inputs and the angular rate response of the aircraft when the helicopter is hovering for 50 seconds over landing spot 8 in 30° / 30 knot WOD conditions. The results for the baseline and modified SAS were generated using exactly the same airwake data, and in each case the pilot model was able to hold the helicopter position and altitude within five feet of the desired location. Thus, the helicopter is experiencing essentially the same disturbances in both cases. The results indicate that both the pilot control activity and the rate response of the helicopter are reduced with the modified SAS. The level of reduction is different for the different control axes, for example control activity is more significantly reduced in roll and pitch, while in the directional axis control activity is not reduced but the angular rate response is decreased.

The hovering experiment was repeated five times, and in each case the airwake data was initialized at a different starting point to add variability to the runs. The time histories were collected and analyzed in the frequency domain using the software package CIFER®.22 CIFER® was used to calculate autospectra for the pilot control inputs as well as the angular rate response of the aircraft. These results are illustrated in Figures 15 and 16. In these figures the magnitude of the autospectra are plotted on a linear scale rather than in dB. This essentially represents the RMS value of the control input or angular rate versus frequency. The plots show that the magnitude of the control activity and the angular rate response of the aircraft are both significantly reduced (by as much as 50%) in the frequency range of 1 to 7 rad/sec. This would be expected to significantly reduce pilot workload. In some cases, the magnitude of the pilot inputs and angular rates at low frequencies are actually slightly higher for the modified SAS. However, the results in reference 2 indicated that high frequency control activity had a more detrimental effect on handling qualities and pilot ratings than low frequency control inputs.
The previous tests illustrated the performance of the modified SAS at its design point – the 30° / 30 knot WOD condition. A second test was conducted to test its performance in an off-design condition. In this test, the steady winds were set to produce a 30 knot wind directly over the bow of the ship (0° / 30 kts WOD), and another set of turbulent airwake data corresponding to this condition were used. Flight tests and simulations have indicated that the 0° WOD condition is much less severe than the 30° WOD condition. Figures 17 and 18 show the autospectra of the pilot control inputs and the angular rate response of the aircraft for this condition. As expected, the overall control activity and vehicle response are smaller in this more benign WOD condition. However, the modified SAS still shows some improvement over the baseline SAS.

A major concern in the design effort was whether the modified SAS design would produce excessive SAS actuator saturations relative to the baseline system. The SAS authority was limited to ±10%. In fact, no SAS saturations were observed for either the modified or baseline SAS for any of the hovering simulations performed by the pilot model. The average RMS deflection of the SAS actuators were calculated for the 30° WOD case for both SAS systems and are compared in Table 2. The results indicate that the modified SAS produced actuator deflections 36% to 80% larger than the baseline SAS, but on average the system is not close to saturating.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Baseline SAS</th>
<th>Modified SAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>0.82%</td>
<td>1.48%</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.83%</td>
<td>2.59%</td>
</tr>
<tr>
<td>Yaw</td>
<td>1.82%</td>
<td>2.47%</td>
</tr>
</tbody>
</table>

Table 2 – RMS SAS Deflection, 30° WOD Case

Preliminary piloted simulation tests were also conducted using both the baseline and modified SAS designs. As discussed above, limitations in the available cues made the tasks very difficult (using either SAS), and thus the tests were inconclusive, no qualitative assessment about the benefits of the modified SAS could be made. Preliminary evaluation of the pilot input time histories appear to show a reduction in control activity with the modified SAS. However, it was not possible to hold position within a tolerance of 10 feet, so it is possible the aircraft was drifting into more benign or more severe portions of the airwake during the tests thereby contaminating the data.

**Conclusions**

The objective of this study was to apply modern flight control design methods to develop a limited authority SAS that reduces pilot workload associated with operating a helicopter in the turbulent airwake over a ship deck. The methods were applied towards SAS design for a UH-60 operating on an LHA ship. The design effort focused on characterizing the spectral properties of the airwake disturbances, designing the controllers to reject these disturbances, and then simplifying the controller for practical implementation. The design process produced a “modified SAS” that was then tested in simulation using a pilot model, and its performance was compared to the existing baseline SAS. The results indicated a significant reduction in pilot control activity and in angular motion of the aircraft. Some specific conclusions of this study are as follows:

1. Identification of the spectral properties of the ship airwake indicates that these disturbances are fundamentally different than standard atmospheric turbulence. Peak amplitudes in the range of 1-4 rad/sec indicate that they will have a major impact on handling qualities.
2. Modern MIMO design methods are a powerful tool for incorporating a large number of dynamics in the control synthesis. Unfortunately, they often result in very high order compensators. Application of model order reduction methods is critical to make such control synthesis methods practical.
3. A logical solution for the airwake gust rejection problem is to increase compensator gain and phase lead in the frequency range of the disturbance. This is exactly the solution identified by the MIMO design process.
4. It appears feasible to achieve significant improvements in gust rejection with only modest increases in SAS actuator activity.

The next step in this work is clearly to evaluate the performance of the control methodology in a piloted simulation environment, in which handling qualities ratings can be obtained. This will require a high fidelity simulation facility which is beyond the scope of the current work. In addition there are some improvements that could be made to the design method in the near term:

1. Include feed forward shaping to obtain better response to pilot command (i.e. implement a SCAS).
2. Preliminary piloted simulation indicated that a great deal of workload exists in the collective axis, which was not addressed in the present study.
3. It is desired to incorporate the synthesis process with the CONDUIT design framework. The weighting parameters could be optimized to ensure flying qualities specifications are met.
Fig. 15 Autospectra of Pilot Inputs, 30° WOD

Fig. 16 Autospectra of Angular Rates, 30° WOD

Fig. 17 Autospectra of Pilot Inputs, 0° WOD

Fig. 18 Autospectra of Angular Rates, 0° WOD
References


