An Equivalent Model for
UAV Automated Aerial Refueling Research

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Nomenclature

AR = aspect ratio
BL = buttock line
FS = fuselage station
LE = leading edge
MAC = mean aerodynamic chord
TE = trailing edge
ω = frequency
ζ = damping ratio

I. Abstract

FUTURE combat UAVs will need in-flight refueling to realize their full potential. Refueling brings the benefits of increased range, extended time on station, and rapid deployment. In addition, it allows UAVs to strike from long distances without the need for forward staging bases. However, a significant challenge exists in the precise navigation and control needed to allow UAV receivers to perform refueling in a manner similar to manned aircraft. Boeing and Northrop Grumman are under contract to the Air Force Research Laboratory to develop and flight demonstrate an automatic aerial refueling system for combat unmanned air vehicles. To protect proprietary data associated with their respective competing designs, an equivalent model as shown in Figure 1 was needed. This model would be representative in performance and maneuvering characteristics of a tailless UAV. It was developed from a specification created by a panel of experts at the AFRL with inputs from both contractors.

Figure 1. The Equivalent Model

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This paper discusses the development of the equivalent model specification and the vehicle that evolved based on this specification. The use of the equivalent model will yield a robust refueling design applicable to a range of future unmanned vehicles. It has enabled the cooperative development of a system by competing companies and is a crucial step in the final realization of UAV in-flight refueling.

II. Vehicle Configuration and Initial Agreement

A baseline configuration was sought that would serve to connect the equivalent model to a realistic aircraft configuration. The Innovative Control Effectors 101 or ICE 101 configuration was selected as this baseline. ICE was developed by Lockheed under contract to the Air Force Research Laboratory. It was subject of extensive wind tunnel testing. A full nonlinear aerodynamic simulation model had been developed from this wind tunnel data. In addition several control system design studies had been conducted with this model. The ICE 101 configuration and aerodynamic data had been cleared for release to the public. Recently ICE was used in wind tunnel investigations to determine the effects of the KC-135 tanker wake on an unmanned receiver. The ICE configuration is shown in Figure 2. Changes to the ICE aerodynamics would be needed to better model UAV characteristics key to gust sensitivity. Control surface effectiveness and interactions were simplified since control allocation was not the focus of the effort.

An initial agreement establishing the foundation for the Equivalent (EQ) model was established with Boeing, Northrop Grumman, and the Air Force Research Laboratory. This agreement stated that the model would be non-proprietary. The ICE configuration would be modified to yield an aspect ratio of 3.7 to represent the value of future unmanned aerial vehicles. Wing loading would be adjusted to 50 pounds per square foot to model properly pitch axis gust sensitivity; however, wing area would be held constant. Control power would be adjusted to 1) meet pitch, roll, and yaw acceleration requirements by scaling of the specific ICE control surfaces; and, 2) provide predictable, linear, inner-loop responses. Control surface effectiveness and interactions would be simplified since control allocation was not the focus of this effort.

The resulting equivalent model configuration is shown in Table 1. To obtain the required aspect ratio, wing span was increased from 37 feet 6 inches to 54 feet 8 inches. Body length decreased from 43 feet 2 inches to 29 feet 7 inches. The leading edge sweep was reduced from 65 degrees to slightly less than 43 degrees.

New lift, drag, and moment characteristics were estimated by engineers at Boeing with a vortex-lattice technique for the new equivalent model shape. These estimates were used to adjust ICE aerodynamic tables for lift, drag, and moment. New dynamic derivatives were estimated for the new shape. Control surfaces were scaled to yield the specified vehicle responses. ICE control surface lift, drag, and moment tables were then modified to reflect this scaling.

ICE had a variety of control surfaces with a high degree of interaction. It was designed for the investigation into the use of such new control effectors. To reduce the interaction between aircraft control axes, only trailing edge surfaces were chosen for use on the equivalent model. In addition only one surface was used for each axis with the exception of the clamshells which were needed for yaw control as well as speed brake control.
### Table 1. Configuration Changes for the Equivalent Model

With a maximum wing loading designated and the wind area fixed, the vehicle’s maximum gross weight increased to slightly more than 40,000 pounds. Published information lists takeoff gross weight of the X-45C at 36,500 pounds and for the X-47B at more than 45,000 pounds. Thus, this was considered a reasonable selection for the equivalent model. This weight included a fuel load of 17,500 pounds and a total weapons load of 4,000 pounds based on the proposed vehicle’s use at the time of the specification creation. Three fuel states were deemed adequate for evaluating the vehicle’s response variations to fuel quantity changes during the refueling mission. These consisted of a full fuel load, a fifty percent fuel load, and a minimum fuel load of ten percent of maximum. All of these fuel conditions assumed a full weapons load. Inertial properties for these loadings were estimated employing a non-dimensional radius of gyration calculation using the Roskam method.

![Control Surface Scaling and Allocation](image)

**Figure 3. Control Surface Scaling and Allocation**

Basic aircraft acceleration responses were specified for pitch, roll, and yaw. These established the rotational accelerations to be obtained by the independent deflection of associated control surfaces. To reduce control surface interaction, only trailing edge devices were selected for use. In addition each control axis was assigned an independent control surface. In the pitch axis the pitch flaps will provide control. The elevons will be used for roll control. However, the clamshells provide a dual use function. Symmetric deflection of surfaces on the top and bottom of one wing provided yaw control while simultaneous deflection of top and bottom surfaces on both wings allowed a speed brake function to be realized.
III. The Specification Development Process

The process started with the development of a specification outline. This outline, agreed to by all parties, contained the items required to yield a vehicle with representative performance and maneuvering characteristics of a tailless UAV for use in automated refueling research. It addressed the flight envelope, bare airframe acceleration responses, vehicle mode responses, target closed loop dynamics, stability margins, mass properties, equipment locations, inner loop control system structure, engine dynamics, and speed brake configuration. However, it lacked the specific numbers for an actual air vehicle.

Northrop Grumman and Boeing independently provided the Air Force Research Laboratory (AFRL) with data for proprietary equivalent vehicle specifications using this outline. The degree to which this proprietary specification represented their respective vehicles was not disclosed. The AFRL Automated Aerial Refueling program manager created a special design team to develop a similar vehicle with similar capabilities to the extent needed to enable the creation of an independent AFRL proprietary specification.

The process involved combining these three proprietary specifications through an undisclosed method to yield a non-proprietary specification that would result in a simulation model representative of all the vehicles. In this way, knowing only one of the proprietary inputs and the resulting EQ specification, it was not possible to glean proprietary information about the other two input specifications.

IV. The EQ Specification

A refueling flight envelope was established for the equivalent vehicle which consisted of an altitude range from 20,000 to 30,000 feet, an airspeed range from 225 knots calibrated to 0.8 Mach number, an angle-of-attack range of positive ten to negative five degrees, and a side slip angle range of plus or minus five degrees. The unaugmented vehicle is to be neutrally stable in both pitch and yaw and stable in roll.

In the pitch axis the full deflection of the pitch flaps is to yield a rotational acceleration of 5.52 radians per second per second. In addition, linear deceleration using both clamshell surfaces as speed brakes was set at 12.35 feet per second per second. ICE control surfaces were resized to provide these accelerations responses. The pitch flaps, elevons, and clamshells were increased in both chord and span to become the equivalent model pitch flaps, ailerons, and clamshells. The large size of the clamshells was driven by the desire to have a 0.4 g deceleration capability. The clamshells were used primarily for yaw control. However symmetric deflection of both provided a speed brake capability. Use of modulated speed brakes for velocity control in refueling was allowed only if adequate control could not be achieved with engine control. The initial version of the specification had the speed brake command path and engine control path with separate inputs. In the latest version these two paths have been combined to form an inner loop speed control system with one axial command input.

Desired closed loop mode response was listed in the specification. To enable good control and station keeping a well behaved vehicle was required with the inner control loops closed. Using the Military Flying Qualities and Flight Control Systems Specifications as guides, target frequency and damping ratios were selected. The short period frequency was selected at 4.5 radians per second with a 0.8 damping ratio while the dutch roll was 1.5 radians per second with a 0.8 damping ratio. Stability margins of 6 decibels and 45 degrees were required. These margins had to be maintained with the guidance loops closed. The control loops would be broken at the pitch, roll, and yaw command points in determining the stability margins.

Development of an engine model presented its own set of problems. The Boeing X-45C and the Northrop Grumman X-47B were similar airframes. The X-45C was to use the F404 engine while the X-47B was to use the F100 engine. The F404 is a smaller engine with faster response but lower maximum thrust levels when compared with the F100. An afterburner capability is not provided for either vehicle. Both engines will suffer a significant thrust loss due to installation in this type of vehicle. After consultations with ASC and NAVAIR, a simple second order model was selected. A thrust rate limit will be applied to capture large amplitude throttle response characteristics as may be required for the breakaway maneuver. Maximum thrust, minimum thrust, and the thrust rate limits will be specified for the refueling flight condition. Steady state thrust will vary linearly with commanded thrust over the specified maximum to idle thrust range. For the second order model, a damping ratio of 0.9 and a frequency of 2.4 radians per second were selected. Maximum thrust was set at 5,600 pounds, with idle thrust at 600 pounds. Thrust rates of positive 1,450 pounds per second and negative 1,880 pounds per second were selected. Engine thrust will generate a force acting through the air vehicle CG. No pitching moment due to thrust changes will be modeled. No rotational inertia or gyroscopic effects will be modeled.
V. The EQ Model

Based on the initial agreements and through the specification process, a new vehicle evolved to be known as the equivalent or “EQ” model. It is shown in Figure 4. The upper body engine inlet replaced the original ICE cockpit. This inlet was lower than the cockpit resulting in a reduced body height in front of the center of gravity. The change improved the directional stability of the vehicle to yield the neutral condition needed. Fuel burn was assumed to be out of tanks equally spaced on each side of the center of gravity so that it did not move significantly from a full fuel load to a 10 percent fuel load. Equipment location on the vehicle is shown in Figure 5. The normal accelerometer was initially located at a position 7.7 feet in front of the CG to prevent a non-minimum phase response. Later analysis by Boeing and confirmed by AFRL, showed a condition due to the slope of the pitch flap moment curve near zero that resulted in the instantaneous center of rotation being in front of this accelerometer location. The accelerometer has been moved to a position 9.35 feet in front of the CG to preclude such a condition.

Figure 4. The Equivalent Model Simulation Representation

Figure 5. EQ Geometry and Equipment Locations

Note:
Top of Vehicle WL = 36.0 in
Vehicle Centerline WL = 0.0 in
Bottom of Vehicle WL = -12.0 in
Thrust Angle = 0.0 deg

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A common control system architecture was specified for each control axis. It consisted of a proportional plus integral command path with multiple feedbacks and independent gains in each path and on the command error path. This structure is illustrated by the pitch axis block diagram shown in Figure 6. Second order filters are included in all feedback paths to provide a representative element for sensor dynamics, anti-alias filters, and aeroservoelastic filters. These filters provide realistic phase lags for the control system. Initially the filters were to be independently specified. However, for simplicity the worst case filter requirements were applied to all feedbacks in all axes. In the initial issue of the specification, these filters were set to a damping ratio of 0.7 and a frequency of 20 radians per second. After problems were encountered meeting the phase margin requirements, the frequency was increased to 25 radians per second. Surface actuators are represented by second order filters, with rate limits and position limits. These are summarized in Table 2.

![Figure 6. Pitch Axis Inner Loop Control System Diagram](image)

In the pitch axis, normal acceleration is the command input. Sensed normal acceleration is fed back and summed with the input to create an acceleration error signal that is sent along proportional and integral paths with independent gains. Pitch rate feedback is used in the integral path while a blended pitch rate and angle of attack is fed back to the proportional path to create the pitch flap actuator command. A bank angle command system is used for the roll axis. Bank angle is subtracted from the command to create an error that is used in an integral plus proportional path with feedbacks similar to the pitch axis. Roll rate is summed with the error signal in the integral path while a blend of roll rate, yaw rate and side slip is summed and fed back in the proportional path. Cross feeds to and from the directional axis is provided. The resulting roll command is applied to the elevon actuators to cause differential deflections. In the yaw axis, a beta command system is implemented with beta, beta dot, roll rate, and yaw rate feedbacks. The method of design to arrive at specific gains for each axis was not specified. However, the gains were to be developed for operation at the nominal refueling flight condition and could be fixed or scheduled to meet performance and stability requirements.

Once the sizes of the control surfaces were established by the required rotational and linear accelerations, scaling of the ICE aerodynamics coefficients was accomplished. This scaling method is illustrated in Figure 7 for the pitch flap. The same method was used for each of the equivalent model control surfaces. ICE pitch control surface coefficients were scaled using the new equivalent model reference area, mean aerodynamic chord, new control surface area, and distance from surface centroid to the CG. In roll and yaw, the control surface coefficients were scaled with the new reference area, wing span, surface area, and the distance from the xz plane to the control surface centroid.
### Table 2. Surface Actuator Characteristics

<table>
<thead>
<tr>
<th>Actuator</th>
<th>( \omega )</th>
<th>( \zeta )</th>
<th>Max Defl.</th>
<th>Min Defl.</th>
<th>No Load Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch Axis</td>
<td>50 rad/sec</td>
<td>0.8</td>
<td>30 deg</td>
<td>-30 deg</td>
<td>90 deg/sec</td>
</tr>
<tr>
<td>Roll Axis</td>
<td>50 rad/sec</td>
<td>0.8</td>
<td>45 deg</td>
<td>-45 deg</td>
<td>90 deg/sec</td>
</tr>
<tr>
<td>Directional Axis</td>
<td>50 rad/sec</td>
<td>0.8</td>
<td>45 deg</td>
<td>-45 deg</td>
<td>90 deg/sec</td>
</tr>
<tr>
<td>Speed brake</td>
<td>50 rad/sec</td>
<td>0.8</td>
<td>60 deg*</td>
<td>0 deg</td>
<td>90 deg/sec</td>
</tr>
</tbody>
</table>

* Clamshell open - upper surface up 60 deg and lower surface down 60 deg

\[
C_{a,PF,ICE} = C_{a,PF,NEQ} \left( \frac{S_{ICE}}{S_{EQ}} \right) \left( \frac{S_{PF,ICE}}{S_{PF,NEQ}} \right)
\]

\[
C_{l,PF,ICE} = 0
\]

\[
C_{n,PF,ICE} = C_{n,PF,NEQ} \left( \frac{S_{ICE}}{S_{EQ}} \right) \left( \frac{S_{PF,ICE}}{S_{PF,NEQ}} \right)
\]

\[
C_{l,PF,NEQ} = 0
\]

\[
C_{n,PF,NEQ} = C_{n,PF,ICE} \left( \frac{S_{ICE}}{S_{EQ}} \right) \left( \frac{S_{PF,ICE}}{S_{PF,NEQ}} \right)
\]

\[
C_{l,PF,NEQ} = 0
\]

\[
S_{ICE} \rightarrow \text{Reference Area of ICE Model}
\]

\[
S_{EQ} \rightarrow \text{Reference Area of Equivalent Model}
\]

\[
c_{ICE} \rightarrow \text{Mean Aerodynamic Chord of ICE Model}
\]

\[
c_{EQ} \rightarrow \text{Mean Aerodynamic Chord of Equivalent Model}
\]

\[
S_{PF,ICE} \rightarrow \text{Surface Area of Pitch Flap on ICE Model}
\]

\[
S_{PF,NEQ} \rightarrow \text{Surface Area of Pitch Flap on Equivalent Model}
\]

\[
l_{x,PF,ICE} \rightarrow \text{Distance From CG for Neutral Stability to the Centroid of Pitch Flap on ICE Model}
\]

\[
l_{x,PF,NEQ} \rightarrow \text{Distance From CG for Neutral Stability to the Centroid of Pitch Flap on Equivalent Model}
\]

**Figure 7. Pitch Flap Coefficient Scaling**

### VI. Conclusion

The cooperative development of the equivalent model specification enabled the creation of a simulation model applicable to a range of unmanned aerial vehicles during air to air refueling. This is allowing simulation research and development to be conducted for automated aerial refueling of unmanned aerial vehicles. The equivalent model is currently being used to evaluate control methods for maneuvering UAVs in close proximity to a tanker during refueling operations. In addition algorithms for rendezvous and formation re joins are being investigated in man-in-the-loop simulations. It will allow the development of refinements of operational concepts, trajectory control algorithms, and control laws while considering the influences of data link dropouts and time delays during UAV refueling operations.

### References


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