Air Vehicle Modelling and Simulation Assignment

1 Aims

The aim of the assignment is the development and critical assessment of a non-linear simulation of a twin-engined commuter aircraft. To successfully complete this assignment students will need to demonstrate:

- Accurate and well structured model construction with comprehensive description;
- Robust model testing and validation;
- Calculation of correct trim conditions and associated linear models;
- Analysis of the longitudinal dynamics using frequency techniques.

2 Data Provision and Assumptions

The aerodynamic, control and power plant data is in the form of a sub-model `j31_avms_10.mdl`. The model and associated m-files can be downloaded from the BlackBoard website.

Note that a dynamic engine model is not needed nor an undercarriage model as no landing simulations are required. Model validation should be performed using data gathered during the Flight Experiment Methods Module. Copies of the response data can be found on BlackBoard in the form of `.csv` files[1]. A `.pdf` file is also provided that contains the relevant seating/loading information. Algorithms to determine typical trim data are provided in Appendix A.

Students are reminded that implementation will require $\dot{w}$ and that feeding back the signal *will* require some care especially during the linearisation process.

3 Assignment Requirements

3.1 Major Tasks (Objectives)

1. Produce, verify and document a sub-model[2] that solves the equations of motion for a symmetric rigid airframe where the centre of gravity (CG) and body axes centre (BAC) are *not* co-located and the mass properties are given about the (BAC).

2. Construct a generic 6 dof (Euler Angle) simulation using the provided sub-model and those available from the Aerospace Blockset.

3. Generate an initialisation file (use `InitialiseJ31.m` as a template).

4. Test and verify the model (check that it runs without error).

5. Trim aircraft at a chosen flight condition and check the accuracy of the trim solution by running the model in Simulink® for a short period of time (1 minute). A modified model will be required for the trim process to ensure that the appropriate outputs are fixed and 'freedom' is given to the correct states.

[1] The AoA data given in the SPPO time response is based on the wing root and must be reduced by 2° to give the fuselage incidence (α_b)

[2] It is expected that students will make use of the *embedded M-file* facility provided in Simulink® .

6. Validate the model by comparing the *trim data* and *dynamic response data* with that for the actual aircraft in all axes[3][4]. Be careful with the effects of sample rate dictating the time step for the simulation[5].

7. Generate a linear model at the chosen flight condition[6].

8. Decouple into longitudinal and lateral/directional models.

9. Validate the linear models by comparing the response with that of the full non-linear model.

10. Predict the longitudinal handling qualities of the aircraft using the frequency domain[7].

3.2 Report

The assessment report should consist of the following elements:

1. A brief but pertinent description of the air vehicle and the scope of the assignment.

2. A data flow diagram of the simulation model and any masked sub-models you have produced.[8].

3. A data dictionary - an alphabetical description of all *additional* variables and constants used within the simulation[9].

4. A simple test specification and accompanying results for the equations of motion module.

5. A discussion of the methods used to trim the full non-linear model followed by a statement of the trim solution along with examples of the dynamic response and evidence of its validation[9]. Students are expected to provide reasons for any mismatch observed.

6. A complete set of transfer functions for the decoupled linear models in their simplest form[10]. Provide evidence of validation against the full non-linear model for both the longitudinal and lateral/directional axes.

7. Predictions for the frequency response in pitch of the aircraft at your chosen flight condition.

8. Discussion of the results and limitations of the simulation.

9. A quantitative summary of the findings concerning the accuracy of the simulation and the estimated frequency response characteristics of the aircraft. *This should be written as a stand-alone section than can be understood without reference to the rest of the report. It will therefore require a short section detailing the work undertaken.*

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[3] You should aim to run the model with same input as that used to on the aircraft.

[4] You should use the 'Consolidated Flight Test Data' provided in Appendix A as this has been processed statistically to remove the scatter associated with flight test.

[5] You may need to consider interpolating the input time histories to provide values at a higher data rate.

[6] Students may find it advantageous to eliminate the 'navigational' states (P_N, P_E and P_D.

[7] Use a Bode plot of the pitch attitude to elevator transfer function to determine the limiting frequencies and the phase rate or delay as defined in Appendix B. Great care MUST be employed when using the MATLAB® command `bode` as it rarely produces the correct phase plot without some 'coaxing' or post-process adjustment. It will be necessary to add some additional dynamics to ensure that the Bode plot 'rolls-off' beyond 180°. It is suggested that the mechanical 'slop' and backlash may be modelled by a unit lag with a time constant of 0.01s.

[8] You can consider the sub-model and GUIs provided as "black boxes" that require no explanation.

[9] It is expected that an attempt will be made to validate the static(trim) characteristics as well as the dynamic response.

[10] Remove any common factors and effects of rounding errors.

The main emphasis will be on high quality model design and verification combined with a comprehensive and robust analysis of the resultant models and simulation responses. The report needs to provide convincing evidence that the simulation is a valid implementation of the supplied mathematical model as well as providing justification, or otherwise, for its adoption as representation of the Jetstream J31 aircraft.

4 Timescales

Set date = 21 Jan 2017 Submission date = 04 Mar 2017
It is envisaged that this assignment should take approximately 60 hours of continuous effort for the average student. Try and plan the amount of time spent on each part of the assignment and keep to it. There is no objection to students working together to develop a common simulation environment provided the written report is an individual effort.

MM Lone and JF Whidborne
21 January 2017

References

[1] C.Wolowizc and R. Yancey. Longitudinal aerodynamic characteristics of light, twin-engine, propeller driven airplanes. Technical Report NASA TN D-6800, National Aeronautics and Space Administration, June 1972.

[2] C.Wolowizc and R. Yancey. Lateral-directional aerodynamic characteristics of light, twin-engine, propeller driven airplanes. Technical Report NASA TN D-6946, National Aeronautics and Space Administration, October 1972.

[3] M. Laban. *On-line Aircraft Aerodynamic Model Identification*. PhD thesis, Proefschrift Technische Universiteit Delft, 1994.

A Consolidated Flight Test Data

It is possible to estimate the characteristics of the actual aircraft by combining data from numerous flight tests.

A.1 Clean Aircraft

A.1.1 Body Angle of Attack

Now:

$$C_L = [0.331 \pm 0.008] + [0.105 \pm 0.002]\,\alpha_b \qquad (\alpha_b \text{ in degrees})$$

where:

$$C_L = \frac{2\,(mg_0 - T\sin\alpha_b)}{\rho_0 V_e^2 S_w}$$

A.1.2 Elevator Angle to Trim

Now:

$$\eta = aC_L^2 + bC_L + 2.19 \pm 0.83 \qquad (\eta \text{ in degrees})$$

where:

$$\begin{aligned} a &= -1.75h + 2.12 \\ b &= +29.61h - 15.47 \end{aligned}$$

A.1.3 Inherent Sideslip

The sideslip required in wings-level ($\phi = 0°$) trimmed flight can be estimated from the results of a set of steady heading sideslips (SHSS). Data from the tests yielded the following relationship between bank angle (ϕ) and lateral velocity (v):

$$\phi = -0.5 + cv \qquad (\phi \text{ in degrees}, v \text{ in KEAS})$$

where:

$$c = 0.002V_e - 0.070 \qquad (V_e \text{ in kts})$$

Thus the inherent sideslip (KEAS) is given by:

$$v = \frac{0.5}{c}$$

A.1.4 Aileron Angle to Trim

Data from SHSS tests produced the following empirical relationship between mean aileron deflection (ξ) and lateral velocity (v):

$$\xi = d - 0.10v \qquad (\xi \text{ in degrees}, v \text{ in KEAS})$$

where:

$$d = 3.0 - 0.015V_e \qquad (V_e \text{ in kts})$$

The aileron angle required for trim can be obtained by combining this relationship with that for the inherent sideslip.

A.1.5 Rudder Angle to Trim

Data from SHSS tests produced the following empirical relationship between rudder deflection (ζ) and lateral velocity (v):

$$\zeta = -1.8 + ev \qquad (\zeta \text{ in degrees}, v \text{ in KEAS})$$

where:

$$e = 0.5 - 0.001V_e \qquad (V_e \text{ in kts})$$

The rudder angle required for trim can be obtained by combining this relationship with that for the inherent sideslip.

A.2 Effect of Landing Gear

A.2.1 Body Angle of Attack

The deployment of the landing gear into the propwash has an effect on the lift characteristics of the wing, thus:

$$C_L = [0.43 \pm 0.03] + [0.097 \pm 0.005]\,\alpha_b \qquad (\alpha_b \text{ in degrees})$$

A.2.2 Elevator Angle to Trim

With the landing gear lowered the elevator angle to trim is slightly more 'nose-down', that is:

$$\eta_{\mathsf{gear}} = \eta_{\mathsf{clean}} + 0.5^\circ$$

A.3 Effect of Flap

A.3.1 Body Angle of Attack

The deployment of flap improves the lift performance of the wing, thus:

$$C_L = a_0 + a_1\alpha_b$$

where:

flap angle	10°	20°	35°
a_0	0.47±0.02	0.63±0.03	0.98±0.03
a_1	0.110±0.005	0.114±0.008	0.117±0.009

Table 1: Effect of Flap on Lift Coefficient - flight test results

A.3.2 Elevator Angle to Trim

The deployment of flap, based on the limited testing conducted so far, appears to add a trailing edge down bias to the trimmed elevator angle, thus:

$$\eta_{\mathsf{flap}} = \eta_{\mathsf{clean}} + \Delta\eta_f$$

where:

$$\Delta\eta_f = f + gC_L \qquad (\delta\eta \text{ in degrees})$$

flap angle	10°	20°	35°
f	0.9	2.2	4.3
g	0.5	0.3	0.2

Table 2: Effect of Flap on Elevator - flight test results

B Assessing Handling Qualities in the Frequency Domain

Documents such as ADS-33E-PRF and MIL-HDBK-1797 suggest that the handling qualities of an aircraft can be predicted by analysing its 'open-loop' frequency response. Three parameters are used in this prediction:

1. Phase Limited Bandwidth ($\omega_{\mathrm{BW}_{\mathrm{phase}}}$) - the lowest frequency (rad/s) at which a phase (lag) of -135° (ϕ = -135°) is encountered.

2. Gain Limited Bandwidth ($\omega_{\mathrm{BW}_{\mathrm{gain}}}$) - the frequency (rad/s) lower than but closest to ω_{180} where the gain is 6dB higher than that obtained at ω_{180}[11].

3. Phase Rate or Delay (τ_p) - the value of the phase roll-off at ω_{180} in seconds. This may be estimated using the following:

$$\tau_p = \frac{10}{\omega_{185} - \omega_{175}} \cdot \frac{\pi}{180}$$

C Jetstream J31 Aerodynamic Model

The aerodynamic model provided builds on that presented in the Flight Dynamic Principles assignment. It uses the methodology described by Wolowicz and Yancey[1][2] and Laban[3] to estimate the 'steady' effect of the propeller slipstream on the wing, nacelle and tailplane. As whirl effects are omitted there is no in-built asymmetry to the fin/rudder aerodynamics.

[11] The frequency ω_{180} is the lowest frequency at which a phase (lag) of -180° is encountered.