

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #1
due: End-of-day, Friday, September 19, 2014



The goal of this assignment is to document the physical characteristics and flight behavior of a balsa glider. Each of you has received your own test aircraft, a *Guillow Jetfire Glider*. Balsa wood is relatively strong, but it is soft and easily broken. It absorbs water and is even softer when wet. Don't put it in your overloaded backpack; it will break. Take care when you assemble the glider and do your flight experiments. Be prepared to glue your airplane back together (Duco Cement or Elmer's Glue should work).

You will work in teams of two to complete the assignment and to write your report (i.e., one report for each team, with the same grade assigned to each team member). The teams have been assembled with random selection. See the attached list to identify your teammate, and start early.

Assignment

- 1) Tell me everything that you know about the physical characteristics of the glider (either one, or the average). Examples of what you might measure or calculate are weight, length, wing span, area, dihedral angles, and aspect ratio of wing and tail, wing loading, horizontal and vertical tail height, area, and aspect ratio, moments of inertia, center of mass, and so on.

- 2) From experimentation, tell me everything that you know about the flight characteristics of the glider. This could include maximum range and time of flight for various launch conditions, average gliding speed, average glide path angle, rolling and yawing, effect of the glider's weight and wing position on these quantities, duration and radius of a loop, and so on. Sequences of digital photos can be useful for estimating these quantities.
- 3) The glide path may oscillate about the average gliding angle. Determine the period and approximate amplitude of the oscillation for various wing positions. What effect does varying the launch speed have on this oscillation?
- 4) Try a few non-standard configurations, such as:
 - a) Insert the wings upside down
 - b) Remove the vertical tail
 - c) Remove the horizontal tail
 - d) Tape paper ailerons to the wing to produce an "aileron roll"
 - e) Add weight to the fuselage
 - f) Cant the wingtips, either by cutting and gluing each tip, or adding cardboard "winglets"
 - g) Sweep the wings by cutting and gluing left and right wings

Does the glider fly in any of these cases? If so, how are the flight characteristics changed?

Organize your flight test into sections as defined above, and add brief introduction and conclusion sections. This assignment is a .docx file (HW 1-2014.docx). An easy way to organize your report is to enter your response directly below each part of the assignment.

Submit your assignment as a .doc file via Blackboard (<http://blackboard.princeton.edu/>) using the name **MAE_331_HW_1**.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #2
due: End-of-day, Friday, September 26, 2014

The *balsa glider* shown at right was the topic of Assignment #1. In this assignment, you will compute the motions of the glider using the point-mass dynamic equations and the aerodynamic and mass characteristics that you estimate for the glider. You will work in teams to complete the assignment and to write your report (i.e., one report for each team, with the same grade assigned to each team member). The teams have been assembled with random selection, and you have a new teammate for this assignment. See the list to identify your teammate, and start early.



- 1) Estimate and plot the variation of lift and drag coefficients, C_L and C_D , in the angle-of-attack range from -2 to 16 deg. Explain how you made your lift and drag estimates. What is the maximum lift-to-drag ratio (L/D) and corresponding angle of attack?
- 2) With no thrust, the point-mass longitudinal motions of the glider are governed by four differential equations:

$$\begin{aligned}\dot{V} &= -C_D \frac{1}{2} \rho V^2 S / m - g \sin \gamma \\ \dot{\gamma} &= \frac{1}{V} \left(C_L \frac{1}{2} \rho V^2 S / m - g \cos \gamma \right) \\ \dot{h} &= V \sin \gamma \\ \dot{r} &= V \cos \gamma\end{aligned}$$

where h and r are height (altitude) and ground range. The constant airspeed, V (m/s), and flight path angle, γ (rad), for equilibrium glide can be found by simultaneously solving the first two equations with $\dot{V} = 0$ and $\dot{\gamma} = 0$. Plot the equilibrium-glide values of V and γ for altitudes from 0 to 5,000 m, assuming that the L/D is maximized.

- 3) The goal is to calculate and plot flight paths for the glider using MATLAB's ode15s, ode23, or ode45. You may adapt the *Paper Airplane* code (Example 1.3-1 in *Flight Dynamics*) found at <http://www.princeton.edu/~stengel/PaperPlane.html> to solve this part of the problem. Comment on your findings, including the nature and time-scale of the response.
- a) Using your simulation program, calculate and plot V , γ , h , and r for an equilibrium glide path during 10 sec of flight, with $L/D = L/D_{max}$. Assume that the initial altitude is 10 m, and that the initial airspeed and flight path angle are the equilibrium values found in (2).
 - b) Repeat the calculation with the initial airspeed set to the equilibrium value but zero initial flight path angle.
 - c) Repeat the calculation with the equilibrium value of flight path angle but with airspeed 50% higher than equilibrium.
 - d) Beginning at the equilibrium glide altitude and flight path angle, increase the initial airspeed until the aircraft performs a loop.
 - e) Compare and plot an experimental flight path obtained in Assignment #1 with a calculated flight path using the same initial conditions.

General Guidelines

Explain what you did and discuss the significance of your findings, including comparisons with the results of Assignment #1. Organize your report in Sections a-e, and add brief introduction and conclusion sections. Give each figure a number and a title. Take care that the individual curves on each figure are well identified. An easy way to organize your report is to enter your response directly below each part of this assignment.

Submit your assignment as a .doc file via Blackboard (<http://blackboard.princeton.edu/>) using the name **MAE_331_HW-2**.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #3
due: End of Day, Friday, October 3, 2014

The goal of this assignment is to estimate the non-dimensional aerodynamic coefficients and control effects for the Cessna Citation Mustang 510 [1], using what you have learned in class, from the text book, and from any other sources that you may wish to use (see the course web page for some examples). As described in the Wikipedia page¹, the aircraft is a light executive jet.



Figure 1. Cessna Citation Mustang 510.

¹ http://en.wikipedia.org/wiki/Cessna_Citation_Mustang

You will work in teams of three to complete the assignment and to write your report (i.e., one report for each team, with the same grade assigned to each team member). The teams have been assembled with random selection, and you will have new teammates for this assignment. See the list to identify your teammates.

General characteristics

- **Crew:** one or two pilots
- **Capacity:** 4 to 5 passengers
- **Length:** 40 feet 7 inches (12.37 m)
- **Wingspan:** 43 feet 2 inches (13.16 m)
- **Height:** 13 feet 5 inches (4.09 m)
- **Empty weight:** 5560 lb (2522 kg)
- **Loaded weight:** 8730 lb (3960 kg)
- **Useful load:** 3170 lb (1442 kg)
- **Max. takeoff weight:** 8645 lb (3930 kg)
- **Powerplant:** 2 × Pratt & Whitney Canada PW615F turbofan, 1460 lb (6.49 kN) each

Performance

- **Maximum speed:** Mach 0.63
- **Cruise speed:** 340 ktas (630 km/h)
- **Range:** 1167 nmi (at max. takeoff weight) (2161 km)
- **Service ceiling:** 41000 ft (12500 m)
- **Rate of climb:** 3010 fpm (917 mpm)
- **Thrust/weight:** 0.337 (at max. takeoff weight)
- **Takeoff distance:** 3,110 ft (948 m)
- **Landing distance:** 2,380 ft (729 m)

Assignment

- 1) Calculate the geometric parameters that are required to estimate the airplane's aerodynamic coefficients, including wing and tail areas and spans, airfoil chord sections, wetted area, aspect ratios, sweep angles, taper ratios, mean aerodynamic chords, centers of pressure, dihedral angles, fuselage length and diameter, and horizontal and vertical tail lengths.
- 2) Estimate and plot the aircraft's non-dimensional force coefficients in the Mach number range from 0 to 0.75:
 - a) Lift and drag coefficients, C_{L_α} , $C_{L_o} \triangleq 0$, C_{D_o} , ϵ (or e), for angle of attack in $-2^\circ < \alpha < 12^\circ$, for 0° flap setting, and for wheels retracted.
 - b) Side-force coefficient, C_{Y_β} , as a function of sideslip angle in $-2^\circ < \beta < 2^\circ$.
 - c) What is the maximum lift-to-drag ratio (L/D) and corresponding angle of attack at the normal cruising condition?

- 3) Estimate and plot the aircraft's non-dimensional moment coefficients in the Mach number range from 0 to 0.75:
 - a) Pitch moment coefficient, C_{m_α} with C_{m_0} required for flight at $(L/D)_{\max}$, as a function of angle of attack in $-2^\circ < \alpha < 12^\circ$, for 0° flap setting, and for wheels retracted. Present results for three center-of-mass locations: 20%, 25%, and 30% mean aerodynamic chord.
 - b) Roll- and yaw-moment coefficients, C_{l_β} and C_{n_β} , with C_{l_0} and C_{n_0} equal to zero, as functions of sideslip angle in $-2^\circ < \beta < 2^\circ$. Present results for three center-of-mass locations: 20%, 25%, and 30% mean aerodynamic chord.

In addition to the material on configuration aerodynamics found in Section 2.4 of *Flight Dynamics*, the lecture slides, and the virtual textbook (<http://www.princeton.edu/~stengel/AFDVirTex.html>), you may find web resources and the shelved and E-Library reserve books for MAE 331 helpful, including:

- [1] --, *Citation Mustang Specification and Description*, Cessna, Wichita, Mar. 2013. <http://www.cessna.com/~media/Files/citation/mustang/mustangsd.ashx>.
- [2] George, F., "Citation Mustang," *Business and Commercial Aviation*, Oct 2006, pp. 76-85. <http://d16bsf97ryvc45.cloudfront.net/Media/2012/10/mustang.pdf>.
- [3] McClellan, J., "Cessna Mustang Hits the Mark," *Flying*, Sept 2006. <http://www.flyingmag.com/pilot-reports/jets/cessna-mustang-hits-mark>.
- [4] Raymer, D., *Aircraft Design: A Conceptual Approach*, AIAA Press, 1989, 2006.
- [5] McCormick, B., *Aerodynamics, Aeronautics, and Flight Mechanics*, J. Wiley & Sons, 1994.
- [6] Schlichting, H., and Truckenbrodt, E., *Aerodynamics of the Airplane*, McGraw-Hill, 1978.
- [7] Torenbeek, E., *Synthesis of Subsonic Aircraft Design*, Academic Press, 1982.

Submit your assignment via Blackboard (<http://blackboard.princeton.edu/>) using the name **MAE_331_HW_3**.

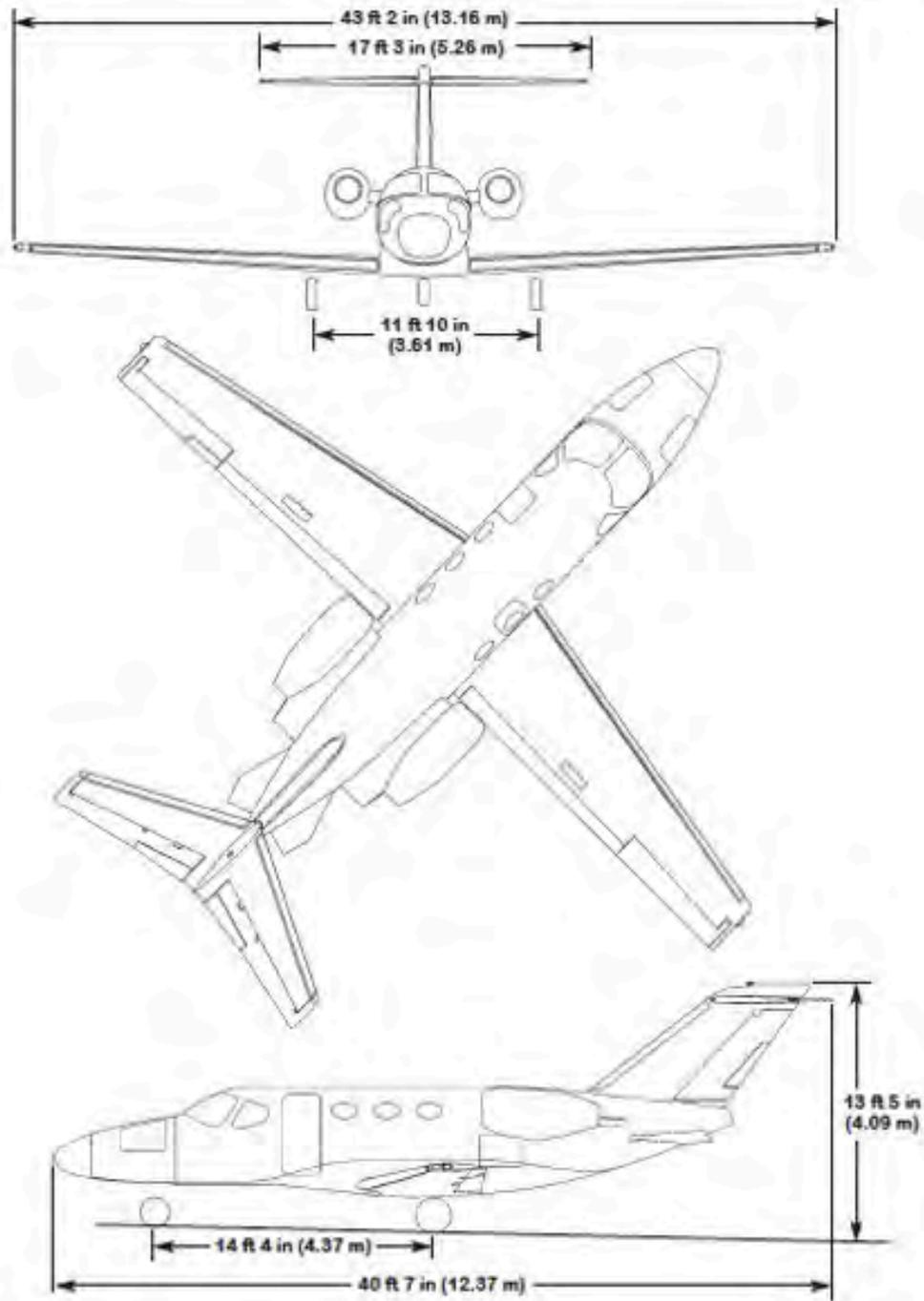


Figure 2. Three-view drawing of the Cessna Citation Mustang 510.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #4
due: End-of-Day, Wednesday, October 15, 2014

The goal of this assignment is to compute selected performance characteristics for the Cessna Citation Mustang (Fig. 1). You will work in teams of three to complete the assignment and to write your report (i.e., one report for each team, with the same grade assigned to each team member). The teams have been assembled with random selection, as identified by the list below.



Figure 1. Cessna *Citation Mustang 510*.

- 1) Model the total thrust as a function of altitude from sea level to 14,000 m (see Lecture 6 slides).
- 2) What are the C_L , C_D , α , and C_T , true airspeed, indicated airspeed, power, load factor, thrust/weight ratio, wing loading, and dynamic pressure during cruising flight at $(L/D)_{\max}$ and an altitude of 12,000 m? Assume the aircraft mass is 3,000 kg.
- 3) What are the achievable maximum and minimum true airspeeds for steady, level flight at an altitude of 12,000 m? Remember that there is a limit on the available thrust, and there must be enough lift to equal weight.

- 4) Calculate the maximum cruise-climb range of the *Cessna Mustang* for an initial altitude of 11,000 m, an initial airplane mass of 3,600 kg, and a total fuel burn of 1,000 kg. Assume that the maximum sea-level thrust for each engine is 6.5 kN and that the specific fuel consumption is 12 (g/s)/kN.
- What are the C_L , C_D , α , and C_T during the cruise-climb?
 - What is the optimal dynamic pressure?
 - Assuming that the cruise-climb begins at an altitude of 11,000 m, what is the corresponding initial airspeed?
 - What is the range covered during this flight segment?
 - What is the final altitude?
- 5) Calculate the flight (altitude vs. equivalent airspeed) envelope, corner velocity, and maximum sea-level climb rate for the *Cessna Mustang* at the same mass and in "clean" condition (flaps and gear up). Assume that the lift coefficient is linear in angle of attack up to an effective stall angle of 15° (at which point, C_L becomes constant) and that the maximum allowable load factor is 2.5.

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AIRCRAFT FLIGHT DYNAMICS
Assignment #5
due: End of Day, Friday, October 24, 2014

The goal of this assignment is to use the MAE “HotSeat” cockpit simulator (Fig. 1, <http://www.hotseatsim.com/pilot-pro-4/>) to fly the Lockheed Martin *Prepar3d* simulation of the Cessna 172 airplane (Fig. 2). You will takeoff from Princeton Airport, fly over the campus and Lake Carnegie, and return to land at the Princeton Airport (Fig. 3). You will work in teams of three to complete the assignment. Each team member will complete the flight as pilot, with assistance from the team, and individually report his or her flight testing experience. Our teaching assistant, Aaron Lemmer, will explain how to use the simulator and give basic guidance about takeoff, navigation along your route, and landing. Please see Aaron to arrange a meeting time and to schedule use of the simulator.



Figure 1. "HotSeat" aircraft cockpit simulator.



Figure 2. Simulated Cessna 172 airplane.

Assignment

- 1) Fly the mission, as described above. Provide details of your flight, e.g., takeoff and landing airspeeds, altitude reached, maximum bank angle, fastest and slowest speeds, screen shots of the ground track, altitude vs. range plot, and time from takeoff to landing. You can record the entire flight and replay as often as possible to get additional information about your flight.
- 2) Each of you should document your work in a brief report that is organized with Abstract (one-paragraph overview), Introduction, Technical Content, Conclusion, and References. In your report, comment on the procedures that you used to conduct the test. Use graphics wherever appropriate.



Figure 3. Princeton Area, Google Earth.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #6
due: End of Day, Friday, November 7, 2014

This is the first of two assignments that will culminate in simulation of *Citation Mustang 510* (Fig. 1) maneuvers using *FLIGHT.m*, a nonlinear, six-degree-of-freedom simulation program. The goal of this assignment is to code the aerodynamic, thrust, and inertial properties of the airplane in *AeroModel.m*, based on results of Assignments #3 and #4, as well as new information. The equations of motion are described in the MATLAB function *EoM.m*, which in turn calls the function *AeroModel.m* for the inertial, aerodynamic, and thrust properties. *EoM.m* uses body-axis equations to solve for rotational and translational rates. Inertial-axis equations are used to compute translational position and the Euler angles that orient the body axes in the inertial frame.



Figure 1. Cessna Citation Mustang 510.

Prior versions of *AeroModel.m* apply to the generic business jet that is used throughout *Flight Dynamics*, <http://www.princeton.edu/~stengel/FDcodeB.html>. *@AeroModelMach.m* is suitable for high-subsonic-Mach-number, low-angle-of-attack simulation. *@AeroModelAlpha.m* uses aerodynamic data that is suitable for low-Mach-number, high-angle-of-attack simulation of the airplane. This assignment focuses on the low-speed characteristics of the *Mustang* extending up to high angles of attack; therefore, *@AeroModelAlpha.m* is the appropriate starting point for your work. The function calls *DataTable.m*, which contains tabulations of the angle-of-attack-dependent variables. You will modify *@AeroModelAlpha.m* and *DataTable.m* to model the *Mustang*. Appendices A and B list the current versions of these functions. You will work in teams

of three and four to complete the assignment and to write your report (i.e., one report for each team, with the same grade assigned to each team member). The teams are identified by the list below. Teams will be the same for this and the next assignment.

Assignment

For the assignment, assume that the stabilator [$u(7)$] effect is identical to the elevator [$u(1)$] effect (The *Mustang* has no stabilator, and so trim is actually provided by the elevator). This assures that the trimming routine (*fminsearch* of *TrimCost.m*) works properly. The landing gear is "up", and flap setting [$u(6)$] and asymmetric spoilers [$u(5)$] can be neglected.

- 1) Assume that the airplane's mass is fixed at 3,000 kg, as typical for an aircraft nearing its destination. Revise *AeroModel.m* mass and inertial properties accordingly.
- 2) Revise *AeroModel.m* geometric and thrust properties to reflect *Mustang* characteristics.
- 3) Revise *DataTable.m* to agree with *Mustang* low-speed aerodynamic characteristics for an angle-of-attack range of -10° to $+90^\circ$ and a sideslip-angle range of $\pm 6^\circ$. Previously, you examined the aerodynamics in a more limited range of aerodynamic angles; extend your aerodynamic estimates by scaling data found in [1], a report of wind-tunnel testing for a configuration that is similar to the generic business jet, and using approximations found in *Flight Dynamics*.
 - *DataTable.m* contains tabulations of the longitudinal coefficients C_L , C_D , and C_m with all control surfaces undeflected. The derivatives of linear control and angular rate effects also may vary with angle of attack (i.e., the control and angular rate effects are assumed to be linear but with multipliers that vary with angle of attack).
 - All lateral-directional aerodynamic coefficients are assumed to be linear in sideslip angle, angular rates, and control settings, although their multipliers also may change with angle of attack.
- 4) Write a brief plotting script to assure that *DataTable.m* represents the *Mustang's* aerodynamics properly.
 - It is suggested that you first write the script to plot the data in the original bizjet's *DataTable.m* as a verification step and then modify it to plot the corresponding *Mustang* data. Examples for the generic business jet data are shown in Fig. 2 to 5.
- 5) Assure that *AeroModel.m* and *DataTable.m* are compatible with *FLIGHT.m* so that simulations can be conducted in the next assignment.

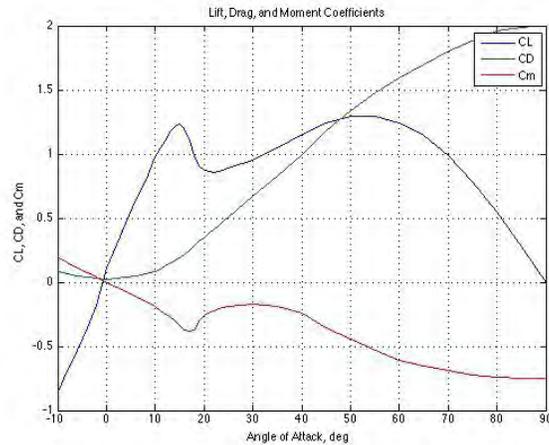


Figure 2. Lift, drag, and pitching moment coefficients of generic business jet vs. angle of attack.

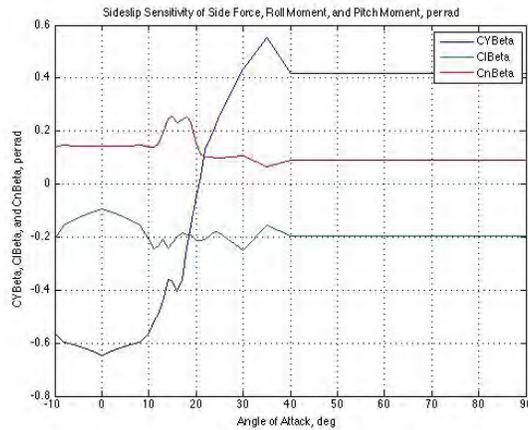


Figure 3. Side force, rolling, and yawing moment derivatives with respect to sideslip angle vs. angle of attack for generic business jet.

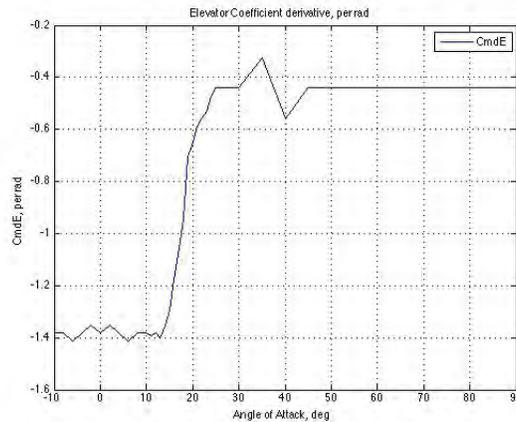


Figure 4. Pitching moment derivative with respect to elevator angle vs. angle of attack for generic business jet.

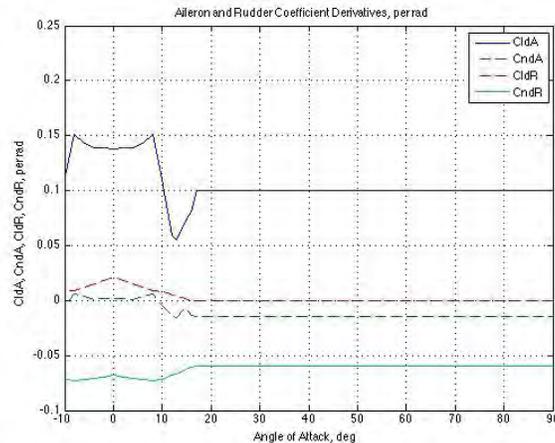


Figure 5. Rolling and yawing moment derivatives with respect to aileron and rudder angle vs. angle of attack for generic business jet.

Team Members

Donegan, Riley; Kelly, Brett; Macdonald, Karen
 Schiavone, Nicole; Ezratty, Samuel; Baase, James
 Narayan, Varun; Dyrda, David; Charpentier, Francois
 Jerpbak, Skye; Ciummo, Rosa; Hull, Forrest
 Valverde Lizano, Jonathan; Beck, David; Mehl, Jeremy
 McDonnell, Ryan; Li, Clement; Markowitz, Anthony
 Pease, Henry; Pardinas, Kevin; Krastev, Daniel
 Liang, Victor; Perrine, Glenn (Richie); Lee, Mike; Henke, Lena
 Shonibare, Oluwakemi; Lee, Kevin; Fleiss, Rebecca; Krasnovsky, Ilya

Appendix A. AeroModelAlpha.m for Generic Business Jet

```
function [CD,CL,CY,C1,Cm,Cn,Thrust] = AeroModelAlpha(x,u,Mach,alphar,betar,V)
% FLIGHT Aerodynamic Coefficients of the Aircraft, Thrust Model,
% and Geometric and Inertial Properties

% October 28, 2014
% =====
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% Business Jet -- High-Angle-of-Attack, Mach-Independent Model
% Landing Gear: Up (GEAR = 0)
% Flap Setting, u(6): 0 deg
% Symmetric Spoiler: Closed (SPOIL = 0)

global m Ixx Iyy Izz Ixz S b c GEAR CONHIS SPOIL SMI

% Typical Mass and Inertial Properties
m = 4536; % Mass, kg
Ixx = 35926.5; % Roll Moment of Inertia, kg-m^2
Iyy = 33940.7; % Pitch Moment of Inertia, kg-m^2
Izz = 67085.5; % Yaw Moment of Inertia, kg-m^2
Ixz = 3418.17; % Nose-high(low) Product of Inertia, kg-m^2

% Geometric Properties
c = 2.14; % Mean Aerodynamic Chord, m
b = 10.4; % Wing Span, m
S = 21.5; % Reference Area, m^2
taperw = 0.507; % Wing Taper Ratio
lvt = 4.72; % Vert Tail Length, m
```

```

% Aerodynamic Data Tables for Business Jet Aircraft
[AlphaTable,CLTable,CDTable,CmTable,CmdETable,CYBetaTable,ClBetaTable, ...
  CnBetaTable,ClDatable,Cndatable,ClDRtable,Cndrtable] = DataTable;
alphadeg = 57.29578 * alphas;

% Thrust Properties
StaticThrust = 26243.2; % Static Thrust @ Sea Level, N
% Current Thrust
[airDens,airPres,temp,soundSpeed] = Atmos(-x(6));
Thrust = u(4) * StaticThrust * (airDens / 1.225)^0.7 ...
        * (1 - exp((-x(6) - 17000) / 2000));
        % Thrust at Altitude, N

% Current Longitudinal Characteristics
% =====

% Lift Coefficient
CLStatic = interp1(AlphaTable,CLTable,alphadeg);
          % Static Lift Coefficient

CLqr = 4.231 * c / (2 * V);
      % Pitch-Rate Effect, per rad/s

CLdSr = 1.08;
      % Stabilator Effect, per rad

CLdEr = 0.5774;
      % Elevator Effect, per rad

CL = CLStatic + CLqr*x(8) + CLdSr*u(7) + CLdEr*u(1);
    % Total Lift Coefficient

% Drag Coefficient
CDStatic = interp1(AlphaTable,CDTable,alphadeg);
          % Static Drag Coefficient

CD = CDStatic;
    % Total Drag Coefficient

% Pitching Moment Coefficient
CmStatic = interp1(AlphaTable,CmTable,alphadeg);
          % Static Pitching Moment Coefficient
CmdEr = interp1(AlphaTable,CmdETable,alphadeg);
       % Elevator Effect, per rad

Cmqr = -18.8 * c / (2 * V);
      % Pitch-Rate + Alpha-Rate Effect, per rad/s

CmdSr = -2.291;
      % Stabilator Effect, per rad

Cm = CmStatic - CL*SMI + Cmqr*x(8) + CmdSr*u(7) + CmdEr*u(1);
    % Total Pitching Moment Coefficient

% Current Lateral-Directional Characteristics
% =====

% Side-Force Coefficient
CYBr = interp1(AlphaTable,CYBetaTable,alphadeg);
      % Side-Force Slope, per rad

CYdAr = -0.00699;
      % Aileron Effect, per rad

CYdRr = 0.1574;
      % Rudder Effect, per rad

CYdASr = 0.0264;
      % Asymmetric Spoiler Effect, per rad

CY = (CYBr*betar + CYdRr*u(3)) + (CYdAr*u(2) + CYdASr*u(5));
    % Total Side-Force Coefficient

% Yawing Moment Coefficient
CnBr = interp1(AlphaTable,CnBetaTable,alphadeg);
      % Directional Stability, per rad

Cnpr = CL * (1 + 3 * taperw)/(12 * (1 + taperw)) * (b / (2 * V));
      % Roll-Rate Effect, per rad/s

```

```

Cnrr = (-2 * (lvt / b) * CnBr - 0.1 * CL^2) * (b / (2 * V));
      % Yaw-Rate Effect, per rad/s

CndAr = interp1(AlphaTable,CndATable,alphadeg);
      % Aileron Effect, per rad

CndRr = interp1(AlphaTable,CndRTable,alphadeg);
      % Rudder Effect, per rad

CndASr = -0.0088;          % Asymmetric Spoiler Effect, per rad

Cn = (CnBr*betar + CndRr*u(3)) + Cnrr * x(9) + Cnpr * x(7) ...
     + (CndAr*u(2) + CndASr*u(5));
     % Total Yawing-Moment Coefficient

% Rolling Moment Coefficient
ClBr = interp1(AlphaTable,ClBetaTable,alphadeg);
     % Dihedral Effect, per rad

CLar = 5.6575;
Clpr = -CLar * (1 + 3 * taperw)/(12 * (1 + taperw)) * (b / (2 * V));
     % Roll-Rate Effect, per rad/s

Clrr = CL * (1 + 3 * taperw)/(12 * (1 + taperw)) * (b / (2 * V));
     % Yaw-Rate Effect, per rad/s

CldAr = interp1(AlphaTable,CldATable,alphadeg);
     % Aileron Effect, per rad

CldRr = interp1(AlphaTable,CldRTable,alphadeg);
     % Rudder Effect, per rad

CldASr = -0.01496;       % Asymmetric Spoiler Effect, per rad

Cl = (ClBr*betar + CldRr*u(3)) + Clrr * x(9) + Clpr * x(7) ...
     + (CldAr*u(2) + CldASr*u(5));
     % Total Rolling-Moment Coefficient

```

Appendix B. DataTable.m for Generic Business Jet

```

function [AlphaTable,CLTable,CDTable,CmTable,CmdETable,CYBetaTable,ClBetaTable, ...
        CnBetaTable,CldATable,CndATable,CldRTable,CndRTable] = DataTable
% High-Alpha, Mach-Independent Aerodynamic Data for Business Jet

% October 30, 2014
% =====
% Copyright 2014 by ROBERT F. STENGEL. All rights reserved.

% Data Tables for High-Angle-of-Attack Business Jet Model
AlphaTable = [-10 -8 -6 -4 -2 0 2 4 6 8 10 11 12 13 14 15 16 17 18 19 20 ...
              21 22 23 24 25 30 35 40 45 50 55 60 65 70 75 80 85 90];
CLTable = [-0.8681 -0.6870 -0.5348 -0.3536 -0.1797 0.1101 0.2899 0.4638 ...
           0.6449 0.7971 0.9783 1.0507 1.1014 1.1739 1.2174 1.2319 ...
           1.1957 1.101 0.9873 0.9114 0.8734 0.8608 0.8544 0.8608 ...
           0.8734 0.8861 0.9494 1.0506 1.1495 1.2407 1.2916 1.2946 ...
           1.2450 1.1414 0.9860 0.7844 0.5452 0.2795 0.0000];
CDTable = [0.0870 0.0689 0.0508 0.0363 0.0268 0.0254 0.0268 0.0363 ...
           0.0508 0.0689 0.0870 0.1051 0.1233 0.1450 0.1668 0.1885 ...
           0.2175 0.2520 0.2840 0.3160 0.3480 0.3800 0.4120 0.4440 ...
           0.4760 0.5080 0.6680 0.8280 1.0000 1.1800 1.3400 1.4800 ...
           1.5900 1.7000 1.8000 1.8800 1.9600 1.9900 2.0000];
CmTable = [0.1900 0.1520 0.1140 0.0760 0.0380 0.0000 -0.0380 -0.0760 ...
           -0.1140 -0.1520 -0.1900 -0.2200 -0.2500 -0.2700 -0.3000 -0.3350 ...
           -0.3700 -0.3800 -0.3700 -0.3000 -0.2600 -0.2400 -0.2200 -0.2100 ...
           -0.2000 -0.1900 -0.1700 -0.1900 -0.2455 -0.3535 -0.4396 -0.5327 ...
           -0.6061 -0.6515 -0.6898 -0.7196 -0.7400 -0.7502 -0.7500];
CmdETable = [-1.3824 -1.3824 -1.4118 -1.3824 -1.3529 -1.3824 -1.3529 -1.3824 ...
             -1.4118 -1.3824 -1.3824 -1.3941 -1.3824 -1.4000 -1.3529 -1.2941 ...
             -1.1765 -1.0588 -0.9412 -0.7059 -0.6471 -0.5882 -0.5588 -0.5294 ...
             -0.4706 -0.4412 -0.4412 -0.3235 -0.5588 -0.4412 -0.4412 -0.4412 ...
             -0.4412 -0.4412 -0.4412 -0.4412 -0.4412 -0.4412 -0.4412];
CYBetaTable = [-0.5636 -0.5968 -0.6061 -0.6190 -0.6282 -0.6467 -0.6282 -0.6190 ...
               -0.6061 -0.5968 -0.5636 -0.5174 -0.4897 -0.4435 -0.3603 -0.3696 ...

```

```

-0.4065 -0.3603 -0.2402 -0.1571 -0.0462 0.0277 0.1293 0.1755 ...
0.2125 0.2587 0.4342 0.5543 0.4158 0.4158 0.4158 0.4158 ...
0.4158 0.4158 0.4158 0.4158 0.4158 0.4158 0.4158 0.4158 ...
ClBetaTable= [-0.2079 -0.1543 -0.1340 -0.1201 -0.1062 -0.0924 -0.1062 -0.1201 ...
-0.1340 -0.1543 -0.2079 -0.2448 -0.2310 -0.2079 -0.2402 -0.2217 ...
-0.1986 -0.1848 -0.1940 -0.1940 -0.2125 -0.2125 -0.2079 -0.1940 ...
-0.1802 -0.1848 -0.2495 -0.1571 -0.1971 -0.1971 -0.1971 -0.1971 ...
-0.1971 -0.1971 -0.1971 -0.1971 -0.1971 -0.1971 -0.1971];
CnBetaTable= [0.1386 0.1478 0.1432 0.1432 0.1432 0.1432 0.1432 0.1432 ...
0.1432 0.1478 0.1386 0.1386 0.1524 0.1940 0.2448 0.2541 ...
0.2356 0.2402 0.2541 0.2356 0.1524 0.1109 0.1016 0.1016 ...
0.0970 0.0970 0.1062 0.0647 0.0893 0.0893 0.0893 0.0893 ...
0.0893 0.0893 0.0893 0.0893 0.0893 0.0893 0.0893];
CldATable = [0.1108 0.1509 0.1432 0.1394 0.1385 0.1375 0.1385 0.1394 ...
0.1432 0.1509 0.1108 0.0821 0.0592 0.0554 0.0668 0.0745 ...
0.0802 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 ...
0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 ...
0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000];
CndATable = [-0.0048 0.0063 0.0038 0.0010 0.0014 0.0019 0.0014 0.0010 ...
0.0038 0.0063 -0.0048 -0.0095 -0.0141 -0.0159 -0.0090 -0.0069 ...
-0.0134 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 ...
-0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 ...
-0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150 -0.0150];
CldRTable = [0.0079 0.0092 0.0122 0.0153 0.0183 0.0214 0.0183 0.0153 ...
0.0122 0.0092 0.0079 0.0065 0.0052 0.0039 0.0026 0.0013 ...
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000];
CndRTable = [-0.0716 -0.0733 -0.0720 -0.0707 -0.0693 -0.0680 -0.0693 -0.0707 ...
-0.0720 -0.0733 -0.0716 -0.0698 -0.0681 -0.0664 -0.0646 -0.0629 ...
-0.0611 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 ...
-0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 ...
-0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600];

```

Reference

- 1) Soderman, P. T., and Aiken, T. N., *Full-Scale Wind-Tunnel Tests of a Small Unpowered Jet Aircraft with a T-Tail*, NASA TN D-6573, Nov. 1971.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #7
due: End of Day, Wednesday, November 19, 2014

This is the second of two assignments that culminate in simulation of *Citation Mustang 510* (Fig. 1) maneuvers using *FLIGHT.m*, a nonlinear, six-degree-of-freedom simulation program. The goal of this assignment is to assess the aircraft's response at various flight conditions using the *AeroModel.m* and *DataTable.m* files created in the last assignment (These files may be modified with new material). Think of the assignment as a simulated flight test. Team members will be the same as for Assignment #6.



Figure 1. Cessna Citation Mustang 510.

We want to simulate the *Mustang's* trim settings, response to initial conditions and control inputs, steady turning, and ability to perform a few extreme maneuvers that are not within the airplane's normal flight envelope. All of these are "open-loop" movements, that is, there is no pilot or autopilot feedback to correct control settings.

Assignment

As before, the assignment assumes that the stabilator [$u(7)$] effect is identical to the elevator [$u(1)$] effect (The *Mustang* has no stabilator, and so trim is provided by the elevator). This assures that the trimming routine works properly. The landing gear is "up", and flap setting [$u(6)$] and asymmetric spoilers [$u(5)$] can be neglected. Assume that the airplane's mass is fixed at 3,000 kg, as typical for an aircraft nearing its destination. Use *FLIGHT.m* to compute and plot all results, modifying the code inputs as needed.

- 1) Calculate the trimmed values of throttle setting, stabilator (i.e., elevator), and pitch angle (i.e., angle of attack) for two flight conditions:
 - a) $V = 150$ KIAS and $h = 5,000$ ft
 - b) $M = 0.44$ and $h = 30,000$ ft

- 2) **At Flight Condition (b)**, compute, plot, and comment on response to the following initial conditions (e.g., what can you deduce about the modes of motion?):
 - a) $p(0) = 1$ deg/s for $0 < t < 20$ s
 - b) $q(0) = 1$ deg/s for $0 < t < 20$ s
 - c) $r(0) = 1$ deg/s for $0 < t < 20$ s
 - d) $\Delta V(0) = 5$ m/s for $0 < t < 100$ s

- 3) **At Flight Condition (b)**, compute, plot, and comment on response to the following "doublet" control inputs (e.g., what can you deduce about the modes of motion?). The control history is defined by the vector, $tuHis$, and the matrix, $deluHis$, in *FLIGHT.m*.
 - a) $\delta A(0) = 1$ deg for 0.1 sec, -1 deg for 0.1 sec, 0 thereafter, for $0 < t < 20$ s
 - b) $\Delta \delta E(0) = 1$ deg for 0.1 sec, -1 deg for 0.1 sec, 0 thereafter, for $0 < t < 20$ s
 - c) $\delta R(0) = 1$ deg for 0.1 sec, -1 deg for 0.1 sec, 0 thereafter, for $0 < t < 20$ s
 - d) $\Delta \delta T(0) = 10\%$ for 2 sec, -10% for 2 sec, 0 thereafter, **for $0 < t < 100$ s**

- 4) Beginning at Flight Condition (a), where the roll angle is zero, specify $tuHis$ and $deluHis$ to produce a steady banked turn at fixed airspeed and altitude. The roll angle, ϕ , should be held constant at 10 deg from $t = 10$ sec to 30 sec.

- 5) Beginning at Flight Condition (a), see if it is possible to fly on the "back side of the thrust curve" by calculating the trimmed conditions at decreasing airspeed, in increments of 5 KIAS. At first, the required thrust will decrease; you have reached the back side when the required thrust begins to increase. However, you may reach a stalled angle of attack first. Report your findings.

- 6) Beginning at Flight Condition (b), specify $tuHis$ and $deluHis$ to produce a 360-deg roll at fixed airspeed within 10 sec, returning the roll angle to a steady value of zero at the end of the period. Simulate 60 sec of flight. How much altitude is lost in the maneuver? How could you assure that beginning and ending altitudes are the same?

- 7) Beginning at both flight conditions, provide an overview of the flight paths that occur when the constant elevator angle becomes more negative (trailing edge up) in increments of -1 deg. At what point does the aircraft stall? Can you demonstrate a "pitch-up" and "deep stall" (See Supplemental Material for Lecture 5 and *Flight Dynamics*, pages 93, 95, 502, 750, and 762)?

- 8) Beginning with trimmed flight at $V = 150$ KIAS and $h = 10,000$ ft, can you put the airplane into a flat spin using control deflections (See *Flight Dynamics*, pages 767-771)? If so, when you zero control settings, does the airplane automatically recover? Describe your efforts.

MAE 331
AIRCRAFT FLIGHT DYNAMICS
Assignment #8
due: End-of-Day, December 5, 2014

The goal of this assignment is to examine the linearized dynamics of the Cessna Citation Mustang 510 (Fig. 1) using the MATLAB script, *SURVEY.m* [<http://www.princeton.edu/~stengel/FDcodeC.html>] to perform the analysis. *SURVEY.m* accepts the linear, time-invariant stability and control-effect matrices, **Fmodel** and **Gmodel**, from *FLIGHT.m* as inputs, and it performs a variety of analyses with them. It first provides the option of reducing these matrices into smaller models using the function *LonLatDir.m*. The function produces a single model at each call for either longitudinal or lateral-directional motions, in body or stability/hybrid axes, and with four or six elements in the state vector. The remaining *SURVEY.m* functions operate on either the original 12-dimensional model or on a reduced-order model produced by *LonLatDir.m*. The program calculates transient response, static response, controllability and observability matrices, natural frequencies, damping ratios, and real roots. It forms single-input/single-output transfer functions selected by the user and produces their Bode, Nyquist, and Nichols plots.



Figure 1. Cessna Citation Mustang 510.

You can modify the *SURVEY.m* code to complete the assignment. For example, you can introduce ‘for loops’ to automatically cycle through a set of initial conditions, you can add a call to *rlocus* or iterate through a set of parameter values to generate a root locus plot, you could replace *bode.m* with *asympt.m* (from MATLAB Central) to generate Bode plots with asymptotes, and so on. Be sure to include your code as an appendix in your assignment.

Fourth-order longitudinal and lateral-directional stability-axis models will be investigated at four conditions:

- a) Typical cruising condition: TAS = 340 kt, h = 35,000 ft
- b) Fast flight near cruising altitude: M = 0.44, h = 30,000 ft
- c) Slow flight at low altitude: IAS = 150 kt, h = 5,000 ft
- d) Pre-landing approach, with flaps and gear up: IAS = 110 kt, h = 1,000 ft

Assignment

- 1) Compute and comment on the eigenvalues, eigenvectors, and corresponding damping ratios and natural frequencies of $\mathbf{F}_{L_{\text{lon}}}$ and $\mathbf{F}_{L_{\text{D}}}$ for the four cases noted above.
- 2) Plot the first 40 sec of longitudinal response to unit initial conditions (m/s, deg, and deg/s) in ΔV and Δq for Cases *b* and *c*. How do the results compare with each other and with results of HW #7?
- 3) For Cases *b* and *c*, plot the first 40 sec of response to:
 - a) One-deg step rudder input for both cases (lateral-directional only)
 - b) One-deg step aileron input for both cases (lateral-directional only)
- 4) Compute and describe the following transfer functions for Case *d*:
 - a) $\Delta\alpha(s)/\Delta\delta E(s)$, $\Delta q(s)/\Delta\delta E(s)$, $\Delta V(s)/\Delta\delta T(s)$, $\Delta\gamma(s)/\Delta\delta T(s)$
 - b) $\Delta p(s)/\Delta\delta R(s)$, $\Delta r(s)/\Delta\delta R(s)$, $\Delta\beta(s)/\Delta\delta R(s)$
 - c) $\Delta p(s)/\Delta\delta A(s)$, $\Delta r(s)/\Delta\delta A(s)$, $\Delta\beta(s)/\Delta\delta A(s)$
- 5) Present the Bode plots corresponding to the $\Delta\alpha(s)/\Delta\delta E(s)$, $\Delta V(s)/\Delta\delta T(s)$, $\Delta\beta(s)/\Delta\delta R(s)$, and $\Delta p(s)/\Delta\delta A(s)$ transfer functions for Case *d*. Indicate the zero and pole frequencies on each plot, as well as the slopes of the amplitude-ratio asymptotes (dB/dec) between the singularities. You may use *asympt.m* to generate the Bode plots with asymptotes.
- 6) A simple model for pilot control dynamics is $H(s)_{\text{pilot}} = K_p \left[\frac{(1/T_p)}{(s+1/T_p)} \right]$, with the time constant, $T_p = 0.25$ s. We want to evaluate the effect of pilot dynamics on feedback control for longitudinal and lateral-directional cruising flight at Case *c*. This can be done either by modifying *SURVEY.m* or exporting matrices to an external script. Plot the root locus for positive and negative root locus gain, K_p , in the following:
 - a) $H(s)_{\text{aircraft}} = K_p \Delta q(s)/\Delta\delta E(s)$
 - b) $H(s)_{\text{pilot-aircraft}} = H(s)_{\text{pilot}} \Delta q(s)/\Delta\delta E(s)$
 - c) $H(s)_{\text{aircraft}} = K_p \Delta p(s)/\Delta\delta A(s)$
 - d) $H(s)_{\text{pilot-aircraft}} = H(s)_{\text{pilot}} \Delta p(s)/\Delta\delta A(s)$

Document your work in report format, organized with Abstract (one-paragraph overview), Introduction, Technical Content, Conclusion, and References.

MAE 331
AIRCRAFT FLIGHT DYNAMICS

TERM PAPER ASSIGNMENT
Due: January 13, 2015

The purpose of your term paper is to analyze and report on the flight dynamics of a specific aircraft type. Using the methods that you have learned in the course, plus additional information gleaned from the literature, you will determine the flight envelope and dynamic characteristics of the airplane. The assignment is to compose a written report on your findings. Your written engineering report is due on the "Dean's Date."

You should work in teams of three/four to complete the assignment. Choose your teammates and *let Aaron and me know who they are via e-mail by December 10th*. Team members will receive the same grade for the report. Each of you should take the lead on certain tasks, and be sure that you are satisfied with each other's work on completion. After the course is over, your term paper will be available to the class via *Blackboard* unless you ask that it not be.

A list of possible aircraft types is attached; the aircraft that your team chooses need not be on the list. The Cessna 172, 510 and any closely similar types are excluded. Each team should analyze a different aircraft type. First-come, first-serve in the selection of aircraft types. *Let Aaron and me know your aircraft selections via e-mail no later than December 10th*. Your selections will be confirmed at the final class.

Overall Objectives

- General description of the aircraft, mission, and history.
- Mathematical, flight-dynamic model of the aircraft, including aerodynamic, inertial, and thrust properties.
- Overview of trim conditions for steady, level flight (including thrust and elevator settings), performance limits, open-loop stability, transient response, frequency response, and flying qualities.
- Do not plan to use the cockpit simulator for this assignment.

Report Format

Sections of your report and the percentage of the grade assigned to each:

Section	Content	Weight
Abstract	Concise Description of Work	5%
	Table of Contents	
1. Introduction	General Description, Mission, History	5%
2. Technical Discussion		
	2.1 Mass, Inertia Model	7.5%
	2.2 Aero, Thrust Models	7.5%
	2.3 Flight Envelope (h-V, V-n, maximum turn and altitude rates)	10%
	2.4 Trim Conditions at 2 Operating Points (landing approach, cruise)	5%
	2.5 F & G, Steady-State Response of Linearized 4th-order Longitudinal and Lateral-Directional Systems at Both Points for Both Controls	5%
	2.6 Stability: E-Values at Both Points; Damping ratios, natural frequencies, periods, and time constants, as appropriate	5%
3. Longitudinal Motions		
	3.1 Initial-Condition Response at 1 Operating Point	5%
	3.2 Transfer Functions, Bode Plots at Same Point for Both Controls	5%
	3.3 Flying Qualities Assessment at Same Point	5%
4. Lateral-Directional Motions		
	4.1 Initial-Condition Response at 1 Operating Point	5%
	4.2 Transfer Functions, Bode Plots at Same Point for Both Controls	5%
	4.3 Flying Qualities Assessment at Same Point	5%
5. Conclusion	Summary, Results, Significance	5%
Refs	Format, Number, Sources	5%
	<i>Additional Grading Factors</i>	
Report Presentation	Grammar, Style, Nomenclature	5%
	Figures, Equations	5%
Extras	<i>e.g., appendices, additional flight conditions, analyses, graphics</i>	10%
	Maximum Possible Score	110%

Please adhere to this format. The literary content should be essentially the same as that contained in a typical term paper; however, remember that this is an engineering report, not a philosophical essay. Talk to the point, avoid extraneous information, and leave no loose ends. Cite all equations, figures, tables, and references in the text using accepted engineering style (<http://www.protrainco.com/writing->

[editing/technical_writing.htm](#)). Be sure to discuss the significance of results contained in all figures and tables; your discussion is at least as important as your numerical results. Scale and annotate all graphs so that the information that they contain is easily discernible. A typical paper length might be 25 to 40 pages. Submit your report via *Blackboard* as a Word file or *pdf*.

The *FLIGHT.m* script, <http://www.princeton.edu/~stengel/FDcodeB.html>, and *SURVEY.m* script, <http://www.princeton.edu/~stengel/FDcodeC.html>, will be helpful in doing your mathematical modeling and analysis. If you use *AeroModel.m* as a template for your aerodynamic, thrust, and inertial models, *FLIGHT.m* can compute trim conditions, flight paths, and linear, time-invariant F and G matrices. *SURVEY.m* takes F and G matrices as inputs and generates LTI transient response, equilibrium response, eigenvalues, Bode plots, Nyquist plots, and Nichols Charts. It also transforms F and G matrices between various coordinate systems.

Most of the airplanes on the attached list are likely to have stable longitudinal, Dutch roll, and roll modes over their flight envelopes; in many cases, the spiral mode may be slightly unstable. Be sure that you can find a 3-view drawing and some physical information on the airplane type before choosing it. Contemporary fighter, attack, reconnaissance, trans-/supersonic cruise, and some experimental aircraft may be unstable without closed-loop flight control. Designing feedback control laws is an interesting and important task, but that is not a goal of this assignment. If you encounter instability, first, make sure that you are confident in the result, then report your findings and comment on their consequences. Moving the assumed center of mass forward will generally provide stability.

Technical Sources

In addition to the course texts, there are numerous technical references listed and linked on the course home page, <http://www.princeton.edu/~stengel/MAE331.html>, and on the course *Blackboard* site. Survey information on specific aircraft can be found in *Wikipedia*, *Jane's All the World's Aircraft*, *AIAA Case Studies*, *Aviation Week*, and *Flight International*, <http://www.airliners.net/aircraft-data/>, as well as several URLs linked to the course home page. Selected aircraft are the subjects of books and case studies that can be found in the Engineering Library. All NACA and NASA technical reports are on the web (<http://ntrs.nasa.gov/search.jsp>). Additional references can be found via Princeton University Library e-Journals (http://sfx.princeton.edu:9003/sfx_pul/az) and Data Bases and Reference Tools (http://lib-terminal.princeton.edu/databases/by_subject.asp?subjectkey=27).

MAE 331
AIRCRAFT FLIGHT DYNAMICS
EXAMPLES OF AIRCRAFT TYPES FOR TERM PAPER

*Aircraft Types Analyzed by 2012 MAE
331 Students*

Airbus A380
Beech Baron
Boeing 747
Boeing 757
Boeing 767
Boeing 767
Boeing 787
Cessna Citation X
Douglas A4D
Douglas DC-3
Douglas DC-8
Grumman F-14
Grumman TBM Avenger
Lockheed C-130
Lockheed-Martin F-35
Lockheed SR-71
Mitsubishi Zero
Republic P-47

*Aircraft Types Analyzed by 2010 MAE
331 Students*

Airbus A380
Beechcraft Baron 58
Bell X-1
Boeing 747
Boeing 777
Boeing B-29
Douglas DC-3
General Dynamics F-111
Lockheed Martin F-22
Lockheed SR--71
Messerschmitt Me 109
Northrop B-2
Northrop Grumman RQ-4A
Sukhoi Su-27
Sukhoi Su-47
Supermarine Spitfire

Propeller-driven General Aviation/Aerobatic

Beech T-34 Mentor
Cirrus SR20/22
Mooney Bravo
Mudry CAP 10
Pilatus PC-12, PC-21
Pipistrel Panthera, Virus 912,
Sinus
North American Navion
Raytheon Bonanza, T-6,
2000 Starship
Rutan Long-Eze
Socata Tampico, TBM 700

Large Business Jet

Dassault Falcon 50, 900
Gulfstream 550, 650
Learjet 85

Small Jet Transport

Airbus A320NEO
Boeing 737 Max
Canadair Regional Jet
Embraer 145, 195
Sukhoi Superjet 100

Mid-Size Turboprop

ATR 72
Bombardier Q400
Beechcraft C-12
Grumman C-2 Greyhound
Piaggio P-180

Large Jet Transport

Airbus A300, A340, A380
Boeing 747, 767, 777, 787, C-17
Boeing/NASA Blended Wing-
Body
Lockheed C-5, C-17
Antonov An-225

Historic

Douglas DC-3
Fokker Dr-1, D-VII
Gee Bee Model R
Sopwith Camel
Ryan Spirit of Saint Louis

World War II-Era Fighter/Trainer

Bell P-39, P-63
De Havilland Mosquito
Douglas AD-1
Grumman Avenger
Mitsubishi Zero
Lockheed P-38
Messerschmitt 109
North American P-51, T-6
Republic P-47
Supermarine Spitfire
Vought F4U Corsair

World War II-Era Bomber/Transport

Boeing B-17, B-29
Consolidated B-24
Convair B-36
Douglas A-26, C-54
Lockheed L1049 Constellation
North American B-25

Post WWII Military Airplanes

Convair B-66
Douglas A-4, F3D, F4D
Gloster Meteor
Grumman F9F
North American FJ-4, F-86,
AJ-1, F-82, B-45, OV-10,
T-28
Northrop F-89 Scorpion

Lockheed F-80, T-33, T2J, F-88,
U-2
Vought A-7, F-8
McDonnell F2H, F3H, F4H
Republic F-105

Contemporary Fighter/Reconnaissance

Boeing F-15, F-18
Dassault Mirage III, Rafale
Eurofighter
Fairchild Republic A-10
Lockheed Martin F-16, F-22,
U-2, F-35
MiG-23/27/29/31/35
Northrop Grumman F-14
Panavia Tornado
SAAB Gripen
Shenyang J-20, J-31
Sukhoi Su-25/27/33. 35, T-50

Experimental

X-Planes
Convair XF-92A
Scaled Composites Proteus,
V-Jet II, Voyager,
GlobalFlyer, Triumph,
Stratolaunch
Boeing Bird of Prey
Republic XF-91
WhiteKnightTwo

Uninhabited Air Vehicle

AeroVironment Pathfinder,
Global Observer, Raven,
Wasp III
Boeing X-45, ScanEagle,
Integrator
General Atomics Predator,
Reaper, Avenger
Northrop Grumman Global
Hawk, X-47A/B
LM/Boeing DarkStar
Micro-UAV -- various