RE-ENTRY SYSTEMS AE4870B

EXAMINATION

April 18, 2013

Delft University of Technology
Faculty of Aerospace Engineering
Space Engineering Division

This exam contains 4 questions.

PLEASE NOTE

Always write down the correct units for each computed parameter value. Be mindful for any required conversion before making any computations. **Always** write down the derivations of your answers.

Question 1 (15 points)

Determine whether the following statements are "True" or "False". No motivation/explanation has to be given. Each wrong answer (or no answer) deducts 3 points from the total.

(a) The hypersonic portion of a ballistic entry is characterised by a slowly varying flight-path angle

(b) In a skipping flight, the vehicle will encounter the maximum deceleration during the final entry after the skips

(c) Parachute reefing is only used for systems when there is no pilot chute

(d) A gliding entry is characterized by a large angle of attack at the beginning of entry

(e) For a transformation between two reference frames you always need three unit-axis rotations

(f) The exponential atmosphere assumes a constant temperature and pressure

(g) Banking is the process of rolling around the X-axis of the body frame

(h) Parachute clustering is never used for small payload masses

(i) Between accelerometers and gyroscopes, only accelerometers have (constant) bias errors

(j) For a ballistic flight, the larger the drag coefficient the larger the deceleration

Question 2 (30 points)

Consider the motion of an arbitrary re-entry vehicle in the atmosphere of the Earth

(a) **5 points.** Draw a clear sketch of the 2D (in-plane) motion of this vehicle with respect to a spherical, non-rotating Earth with a fixed inertial reference frame. Indicate the state variables velocity, altitude and flight-path angle, as well as the external forces of aerodynamic and gravitational origin. Note to pay attention to the correct orientation of forces and state variables.

(b) **5 points.** Starting with the sketch obtained under a), set up the general equations of motion for a re-entry flight in the directions parallel with and perpendicular to the velocity vector. Also provide the equation for the time rate of change of the altitude.

(c) **12 points.** Assume now that the vehicle is flying a gliding trajectory. Show that the flight range, starting with the equations obtained under b), is given by $\frac{R}{R_e} = -\frac{1}{2}\frac{L}{D}\ln\left(1 - \frac{V_E^2}{V_c^2}\right)$. What is the main assumption with respect to the flight path that you can make to simplify the derivation?

(d) **4 points.** For the gliding re-entry vehicle, the requirement is that it has to cover a range of $R = 6000$ km to reach its landing site. What should be the minimum lift-to-drag ratio (L/D) of the vehicle such that this can be achieved? Assume that the vehicle enters the atmosphere with a velocity equal to 80% of the circular velocity, and that the Earth's equatorial radius is $R_e = 6378$ km.

(e) **4 points.** What can you say about the flight range when the entry velocity V_E approaches the circular velocity V_c? What is the limit value for $V_E = V_c$? What does this physically mean?

Question 3 (21 points)

(a) **4 points.** Give the two main requirements from which the need for a parachute system can be derived.

(b) **3 points.** Explain the functions of the pilot, drogue and main parachute.

(c) **3 points.** What is parachute reefing, and why is it used?

(d) **3 points.** Why are parachute clusters used?

(e) **4 points.** Assuming vertical equilibrium in the final stage of the descent, derive an expression for the impact velocity.

(f) **4 points.** Given a parachute drag coefficient of $C_D = 0.5$ and a surface density of 1.225 kg/m^3, what would be the parachute diameter for given impact velocities of $V_f = 8$, 10 and 12 m/s? The drag due to the payload ($m = 200$ kg) is small with respect to the parachute drag.

Question 4 (34 points)

Consider the motion of an arbitrary re-entry vehicle in the atmosphere of the Earth. Suppose that the re-entry vehicle returns in the atmosphere using a repeating skipping trajectory, entering the atmosphere twice. At first contact with the atmosphere, the entry angle γ_E = -15° and the entry velocity $V_E = 8$ km/s. The lift-to-drag ratio of the vehicle is: $L/D = 1$ (constant).

(a) **9 points.** For the skipping trajectory show that the relationship between velocity and flight path angle is given by $\frac{V}{V_E} = e^{-\frac{\gamma-\gamma_E}{L/D}}$, and the relationship between flight path angle and air density is given by $\cos\gamma - \cos\gamma_E = \frac{g}{2\beta}\frac{1}{\frac{W/S}{C_L}}\rho$, the latter under the assumption of an exponential atmosphere. Indicate which simplifying assumption(s) is/are made in this derivation.

(b) **16 points.** Next, draw a clear sketch of the variation of the velocity as a function of the flight path angle from the moment of first contact with the atmosphere until the second exit. To make this sketch, both parameters have to be computed in the following characteristic points of the trajectory:

- lowest point of the first skipping trajectory;
- exit of the atmosphere at the end of the first skipping trajectory;
- highest point of the (ballistic) flight after the first skipping trajectory;
- atmospheric entry point of the second skipping trajectory;
- lowest point of the second skipping trajectory;
- exit of the atmosphere at the end of the second skipping trajectory.

If you have problems to compute these quantities, then at least try to make a qualitative sketch and motivate your ideas about the variation of the velocity as a function of the flight path angle.

(c) **9 points.** Show that the air density in the lowest point of the skipping trajectory is given by $\rho_p = \frac{4\beta}{g}\frac{W/S}{C_L}\sin^2\frac{\gamma_E}{2}$. Next, compute the altitude of the lowest point of both parts of the dual skipping trajectory. For this purpose it is given that the lift parameter of the vehicle ($W/(SC_L)$) equals 0.2 N/cm^2, while the density scale height $H = 7$ km and the constant of gravitational acceleration $g_0 = 9.81$ m/s^2. The expression for the air density as function of height in an exponential atmosphere may be applied without derivation (density at sea level: $\rho_0 = 1.225$ kg/m^3).