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SIMULATION OF COMPLEX BALLOON LIFTOFF

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ABSTRACT: The SDIO High Altitude Balloon Experiment (HABE) requires the launch of a large balloon from the deck of a ship, in moderate sea and wind conditions. In order to insure that the balloon would clear the obstacles on the deck in the required conditions, the liftoff was simulated using a modern continuous simulation applications software package. The system was modeled as two lumped masses (the balloon and the payload) connected by a ridged connection. The equations of motion were solved for various conditions to determine safe environmental conditions for liftoff.

BACKGROUND

The HABE system will be launched from ground or ship in the presence of a relative wind. Based on past experience, it was estimated that the lift off should be satisfactory at winds up to 20knots. With shipboard launches taking place aboard a rolling and pitching deck, a more extensive analysis of lift off is required.

The HABE system will use a tandem balloon configuration (Dwyer,1983) which is characterized by gas confinement in a relatively small "tow balloon" at launch, shown schematically in Figure 1. Later, the payload section separates and drops 500 feet bellow the tow balloon which allows the deployment of the main balloon. For this mission, the payload weighs 8000 lbs, which will require a tow balloon of approximately 70 ft diameter weighing 400 lbs. At liftoff, the balloon is filled with helium until the pull on the payload is nominally 12% higher than the weight of the payload and balloon. At 20knots wind, the expected side force on the tow balloon would be approximately 1,500lbs (Reed 1976).

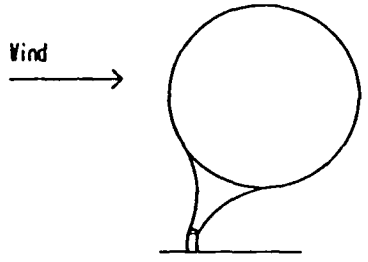

Figure 1. Payload and tow balloon in the wind.

THEORY

Once a payload weight is known, the following analysis is used to estimate the required volume and mass of helium. The lift of a balloon is the buoyant force minus the weight of the helium. By Archimedes' principle, the buoyant force is the weight of the fluid displaced by the balloon. Expressed in terms of density and volume, the lift is:

$$L = (\rho_{air} - \rho_{He})\, g\, V \qquad (1)$$

where:

L is the lift from the balloon
g is the acceleration due to gravity
V is the volume of the balloon
ρ is the density of each gas

The densities of the gasses will vary with temperature and pressure, but if the gasses are at the same temperature and pressure, the density ratio will always equal the ratio of the molecular weights. In terms of the molecular weight, M, and the density of air, the lift is:

$$L = \left(1 - \frac{M_{He}}{M_{air}}\right) \rho_{air}\, g\, V \qquad (2)$$

The ratio of molecular weights is 0.1382. Using the sea level density of air on a standard day, 0.002377 slug/ft^3, and standard acceleration of gravity, the lift in pounds is 0.06590 times the volume in ft^3.

For the HABE mission, the 8000 lb payload, a balloon weight estimated at 400 lb, and an excess lift of 12%, the required lift is 9408 lbs. Using standard conditions, the required balloon volume is 142,800 ft^3, which displaces 10,920 lbs of air, which is the buoyant force. By applying the molecular weight ratio, the required helium weight is computed to be 1509 lb.

The system was modeled as two point masses connected by a rigid rod, as shown in Figure 2. The free body diagram of each mass is shown in Figure 3. The tension depends on the dynamic environment and is the amount required to keep the payload point mass a fixed length from the balloon point mass. A length of 35ft was used for this analysis.

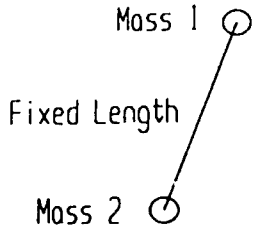

Figure 2. Schematic of the system.

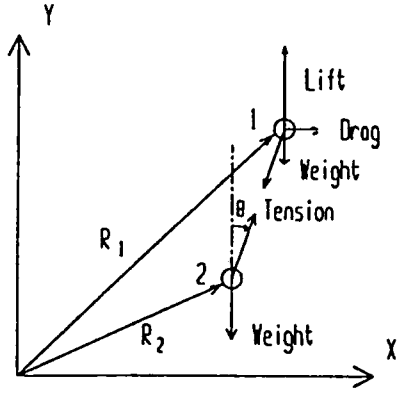

Figure 3. Free body diagram of the masses.

The motion of the system is determined by applying Newton's 2nd law (Equation 3) to each point mass.

$$m\frac{d^2R}{dt^2} = \sum_i F_i \tag{3}$$

Where: m = mass
R = position vector to center of mass
F_i the i^{th} force vector

Assuming that the Earth is essentially flat for the dimensions of the problem, and using the two dimensional Cartesian coordinate system shown in Figure 3, where y is positive up and x is positive in the downwind direction, the equations for the system are:

$$\begin{aligned} m_1^* \frac{d^2x_1}{dt^2} &= D_1 - T\sin\theta \\ m_1^* \frac{d^2y_1}{dt^2} &= B - D_y - T\cos\theta - W_2 \end{aligned} \tag{4}$$

$$\begin{aligned} m_2 \frac{d^2x_2}{dt^2} &= T\sin\theta \\ m_2 \frac{d^2y_2}{dt^2} &= T\cos\theta - W_2 \end{aligned} \tag{5}$$

Where: T = Tension in the connection
W = Weight
B = Buoyancy
D = Drag
Subscripts:
1 = Balloon and Helium
2 = Payload

Mass 1 has a superscript,*, as a reminder to include the apparent mass of the air around the balloon which must be accelerated with the balloon mass. For a spherical shape, the amount of air which must be included is approximately half of the mass of the air displaced by the helium.

The relative positions of the masses is controlled by the constraint equation:

$$(x_1 - x_2)^2 + (y_1 - y_2)^2 = L^2 \tag{6}$$

Where L is the constant distance between the masses. The problem is easier to solve if we incorporate the constraint into the problem by specifying the position of the second mass relative to the position of the first mass and the angle _ (the layover angle) as follows:

$$\begin{aligned} x_2 &= x_1 - L\sin\theta \\ y_2 &= y_1 - L\cos\theta \end{aligned} \tag{7}$$

Differentiating the equations twice results in the following:

$$\begin{aligned} \frac{d^2x_2}{dt^2} &= \frac{d^2x_1}{dt^2} - L\cos\theta\frac{d^2\theta}{dt^2} + L\sin\theta\left(\frac{d\theta}{dt}\right)^2 \\ \frac{d^2y_2}{dt^2} &= \frac{d^2y_1}{dt^2} + L\sin\theta\frac{d^2\theta}{dt^2} + L\cos\theta\left(\frac{d\theta}{dt}\right)^2 \end{aligned} \tag{8}$$

These results are substituted into Equations (5) to obtain:

$$\begin{aligned} m_2\left[\frac{d^2x_1}{dt^2} - L\cos\theta\frac{d^2\theta}{dt^2} + L\sin\theta\left(\frac{d\theta}{dt}\right)^2\right] &= T\sin\theta \\ m_2\left[\frac{d^2y_1}{dt^2} + L\sin\theta\frac{d^2\theta}{dt^2} + L\cos\theta\left(\frac{d\theta}{dt}\right)^2\right] &= T\cos\theta - W_2 \end{aligned} \tag{9}$$

Using algebraic methods, the equations can be reduced to the following equations for angular acceleration and tension:

$$\frac{d^2\theta}{dt^2} = \frac{1}{L}\left(\frac{d^2x_1}{dt^2}\cos\theta - \frac{d^2y_1}{dt^2} - \frac{W_2}{m_2}\sin\theta\right) \qquad (10)$$

$$T = m_2\left[\frac{d^2x_1}{dt^2}\sin\theta + \frac{d^2y_1}{dt^2}\cos\theta + L\left(\frac{d\theta}{dt}\right)^2\right] + W_2\cos\theta \qquad (11)$$

Equations (4), (10), and (11) can now be numerically integrated to determine the position of the two masses as a function of time. The equations were solved on the software applications package "Advanced Continuous Simulation Language (ACSL)" (MGA 1991). On a procedural note, ACSL will not solve the equations in the form shown, but when Equation Set (4) is solved for the second derivatives of x_1 and y_1 and they are substituted into Equations (10) and (11), ACSL can integrate the set.

RESULTS

The equations were solved for the nominal 20 knot wind case. The input parameters are shown in Table I. The assumed initial velocities were zero for both masses. The initial position of the payload was zero height and range, The balloon position and initial angle were determined by the static condition:

$$\tan\theta = \frac{D_x}{B - W_1} \qquad (12)$$

The predicted position of both balloon and payload trajectories for the first 5 seconds is shown in Figure 4. The nearly vertical lines connect the simultaneous positions of balloon and payload every half second. The original balloon layover was nearly 10 degrees. Since this angle balances the side force with the connector tension, the initial balloon motion is nearly straight up. As the payload swings in toward the vertical position, the horizontal component of tension is reduced and the balloon accelerates to the side. This causes the balloon's horizontal acceleration to be higher than the payload, so the pendulous swing is truncated, which is shown in Figure 5, a plot of layover angle versus time. Since the vertical ascent of the balloon is faster than the loss in altitude due to the swinging payload, the net effect is an ever increasing payload height which results in a satisfactory lift off.

Observation of the system for a longer time period shows that within a minute linear velocities become nearly constant, as shown in Figure 6. The secondary oscillation on the horizontal velocity is the result of the varying pull from the tension of the connecting arm. As accelerations diminish, the oscillation of the layover angle becomes more symmetrical and lower in amplitude, as shown in Figure 7.

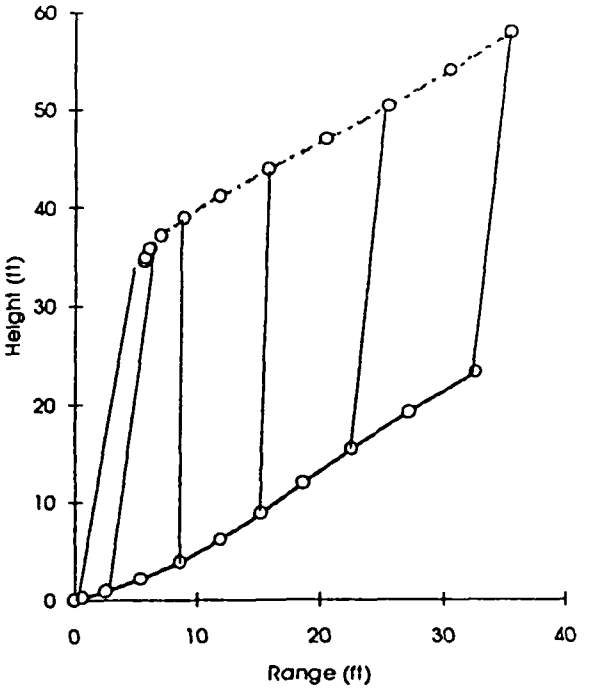

Figure 4. Balloon and Payload position. The nearly vertical lines connect the mass points at one second intervals.

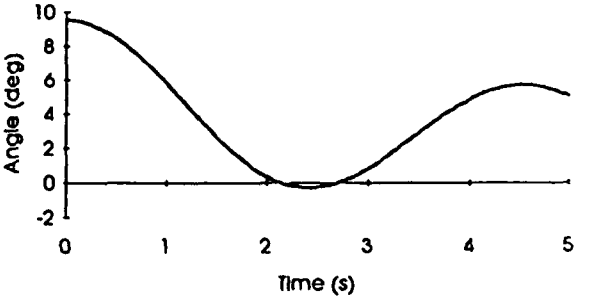

Figure 5. Layover angle versus time.

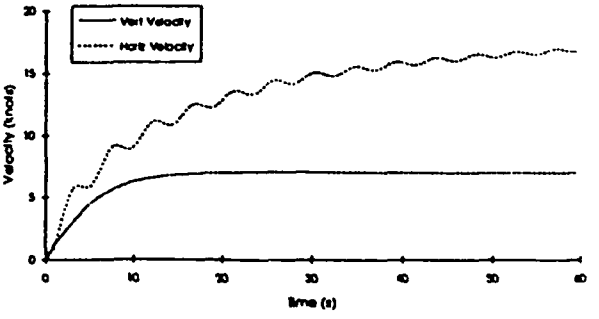

Figure 6. Vertical and horizontal velocity.

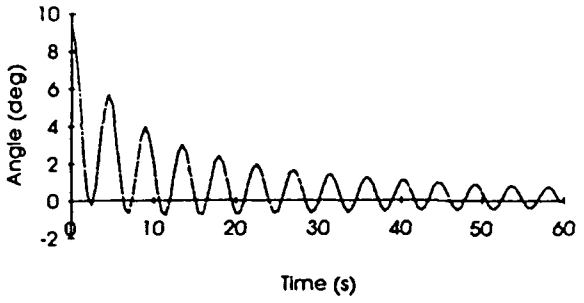

Figure 7. Layover angle versus time for longer period.

Experience with large balloons has shown that if the layover angle is too large, the balloon will have a tendency to swing down when released, which could result in damage to the payload. The phenomena was investigated by predicting payload trajectories with higher wind speeds. At 25 knots the liftoff was successful. At 30 knots the payload initially dropped a barely perceptible distance prior to rising, as shown in Figure 8. The maximum drop was 0.005ft at a range of one foot. At 35 knots the drop was more prominent. The payload dropped about 4 inches below launch altitude, at a range of about 6 feet, before the starts to rise.

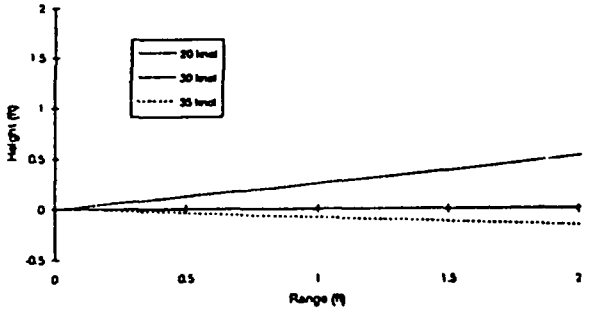

Figure 8. Effect of wind speed on liftoff.

Another potential problem is not having the desired 12% excess lift. In practice, helium is added until the upward tension on the lines is the desired excess lift, which would be difficult to discern in a cross wind. The problem was analyzed by simply reducing the excess lift, computing a new balloon gas volume and performing the dynamic calculation. The payload trajectory for the 6% excess lift is compared to the nominal 12% in Figure 9. While the lower lift trajectory does not result in a negative height, it does skim the surface for more than 5 feet before executing a much shallower climb angle.

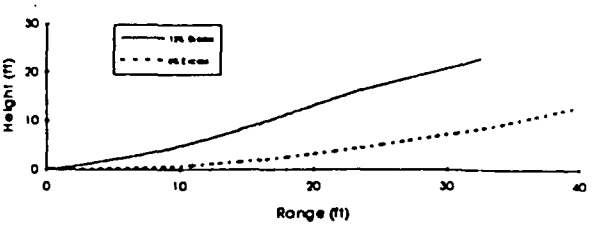

Figure 9. Effect of excess lift on the liftoff.

CONCLUSION

To within the accuracy of this simple model, it appears that a successful lift off can be accomplished with a 20knot cross wind. The system exhibits an interesting trajectory as it accelerates to nearly constant ascent and down range velocities. The layover angle oscillates in an initially unsymmetrical fashion which decreases in amplitude from the initial value of 10 degrees and becomes more symmetrical as accelerations decrease.

The model predicts that wind speeds must be increased to 30knots before the payload has a tendency to drop below launch altitude prior to rising.

The effect of lower than specified excess lift was checked by reducing the excess lift from 12% to 6%. While this reduction did not result in a non-satisfactory launch, it probably is the least amount of free lift that could be tolerated.

This model is only an approximation of the complicated phenomena of a balloon lift off; therefore caution is advised in applying the results to an actual launch. If possible, initial balloon launches should be performed in low wind conditions. Balloon and payload positions should be carefully monitored to determine the adequacy of the model for trajectory predictions.

ACKNOWLEDGMENTS

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Item	Value	Units
Payload Weight	8,000.	lb
Balloon Weight	400.	lb
Excess Lift	12.	%
Balloon Lift	9,408.	lb
Buoyant Force	11,072.	lb
Helium Weight	1,508.	lb
Side Force in 20 Knot Wind	1,500.	lb
Vertical Drag at 10 Knots Ascent	1,008.	lb
Connector Separation Length	35.	ft

Table 1. Values used in the calculations.

BIOGRAPHY

George Jumper received his PhD in Mechanical Engineering in 1975 from the Air Force Institute of Technology, Wright Patterson AFB, OH. He taught at the United States Military Academy and Worcester Polytechnic Institute. In his current position, he perfomrs engineering analysis of satellites, rockets, balloons, and payloads. His research interests include the simulation of atmospheric and space vehicle trajectories, and thermal, mechancial and biological systems.