AC 2012-4116: A DESIGN-BY-ANALYSIS PROJECT FOR INTRODUCTORY STUDENTS IN AEROSPACE ENGINEERING

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A Design-by-Analysis Project for Introductory Students in Aerospace Engineering

Abstract

Small-scale air vehicle models, launched using a pulse of air supplied by a compressed-air tank, make an ideal project for young children. The air vehicles are typically made from common stationary supplies and are very inexpensive. The compressed-air launch system is safe, noise-free, and does not require flammable liquids or fuels. Variations on this project theme have been used by elementary school teachers, clubs, parents, and hobbyists. This paper will describe how this simple construction project can be augmented with analysis tasks that are appropriate for students entering a university-level program in aerospace engineering. The approach aims to introduce and engender a design-by-analysis philosophy as opposed to the trail-and-error approach that often results when engineering fundamentals are not well-understood.

Introduction

The challenge is to develop analysis methods that are appropriate for students that are only beginning their college curriculum in engineering. Most of these students have not completed a calculus sequence and have limited or no experience in differential equations. At most universities, the comprehensive treatment of engineering statics and dynamics does not begin until the second year. Consequently, any background of statics and dynamics usually stems from a general physics courses taken in secondary school.

The technical approach offered in this paper is to replace complicated performance prediction techniques with simple analytical expressions and pre-computed design charts. For example, students can readily estimate the ballistic coefficient of a rocket configuration, and then predict its apogee altitude using a design chart. This type of performance prediction is normally completed by numerically solving the associated differential equations of motion. However, presenting the same information in the form of a chart makes it possible for beginning students to make structured design choices and systematically optimize an air vehicle's configuration.

Design charts and analysis techniques will be described for three vehicle design projects. The first project attempts to achieve the greatest apogee altitude using a configuration that typically resembles a rocket. Design choices include construction materials, fuselage diameter and length, and the number and size of the tail fins. A second project attempts to achieve the longest range using a wing-borne air vehicle. This project requires students to select wing shape parameters, fuselage length, vertical and horizontal tail surfaces. Design charts for this case focus on maximizing lift-to-drag ratio at the gliding airspeed. The third project involves a decelerator configuration, which aims to maximize flight duration.

Compressed-Air Launcher

A compressed-air launcher is used for all of the design projects. The launcher apparatus is shown in Figure 1. Compressed air is stored in a commercially-available portable air tank. The air tank can refilled by connecting a Schrader valve to a common air compressor or foot pump.

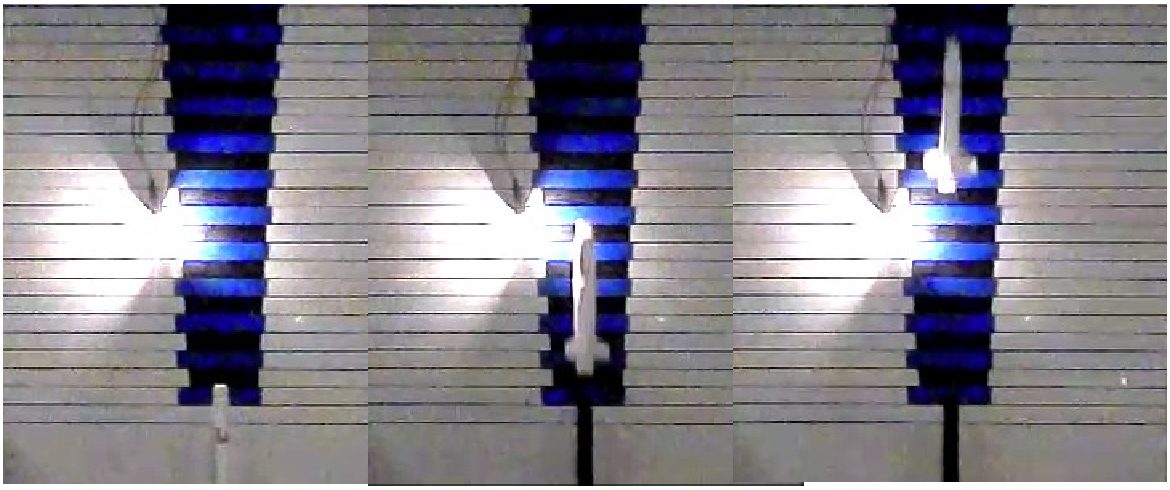
A tank pressure of about fifty to seventy pounds per square inch has been sufficient for launching vehicles constructed mainly of paper and cardboard. Higher air pressures are possible, but structural integrity of the aerial vehicle can become a problem.

Brass pipe fittings are used to connect a modified solenoid valve to the air tank. The solenoid valve is of the type typically used for lawn sprinkler systems. In Figure 1, the electronics in the solenoid valve have been replaced with a pressure switch to eliminate the need for a battery. The input and output connections are three-quarter inch National Standard Taper Pipe Threads (NPT). The output end of the valve is connected to an adapter and a one-half inch NPT riser pipe. The polyvinyl chloride (PVC) riser pipe is twelve inches long and is used as the primary launch tube. Figure 1 shows a rocket/decelerator configuration positioned on the launch tube and ready for launch.

Figure 1 Compressed-Air Launcher Apparatus

Student teams are given a twelve-inch section of one-half inch PVC pipe to use as a fuselage form. Wrapping paper around the form insures that the internal diameter of the fuselage is large enough that it will fit over the launch tube. However, one of the first design decisions that students must make is how much of a gap to leave between the fuselage and the launch tube. A large gap will reduce friction, but a gap that is too large will result in reduced thrust.

Figure 2 shows still images of a rocket configuration leaving the launch tube. These images were selected from a high-speed movie taken at a rate of three hundred images per second. The background pattern is marked by lines that are spaced one-inch apart. Using the known image frame rate and rocket position, it is possible to estimate the rocket's boost velocity. The boost velocity is defined as the speed achieved when the impulse thrust is completed. It is assumed that the boost phase ends as soon as the rocket fuselage leaves the launch tube.



time = 0 sec   time = 0.02 sec   time = 0.04 sec

Figure 2 Time Lapse Images of Rocket Launch

Equation 1 provides the relationship between impulse thrust (T) and boost velocity (V_b). This equation requires the fuselage length (L), vehicle mass (m), and the gravity constant (g). Equation 2 defines the propulsive efficiency (eta) in terms of the air tank pressure (P) and the launch tube diameter (d). The propulsive efficiency is intended to model all of the pressure losses that may occur between the air tank and the launch tube, as well as losses from the air gap between the launch tube and fuselage.

Eq 1: $$V_b = \sqrt{2L\left(\frac{T}{m} - g\right)}$$ Eq 2: $$T \simeq \eta P \pi (d/2)^2$$

Students may use high-speed camera images to estimate the boost velocity for a given configuration. Equation 1 can then be solved for the impulse thrust, while Equation 2 yields the resulting propulsive efficiency. Students may then adjust the fuselage air gap to increase efficiency. Typical values for propulsive efficiency are in the range of 0.015. Estimates for the boost velocity are also obtained, as they are needed for subsequent analysis.

<u>Rocket Design Charts</u>

A typical rocket configuration is illustrated in Figure 3. This figure shows the overall dimensions and mass distribution of the rocket. A sketch like Figure 3 is required as part of the technical report that each student team must produce. Note that the students are expected to weigh their configuration, as well as estimate and mark the center-of-gravity location.

Design choices are fairly straightforward for a simple rocket configuration. These include: the length of the fuselage, size of the fuselage air gap, and the number and size of tail fins. Construction materials for rocket configurations typically consist of normal copier paper, glue, and adhesive tape. Shipping envelopes made from woven fiber material have proven to be a good material for the fuselage. Nose cones can be made from paper or carved from soft foam.

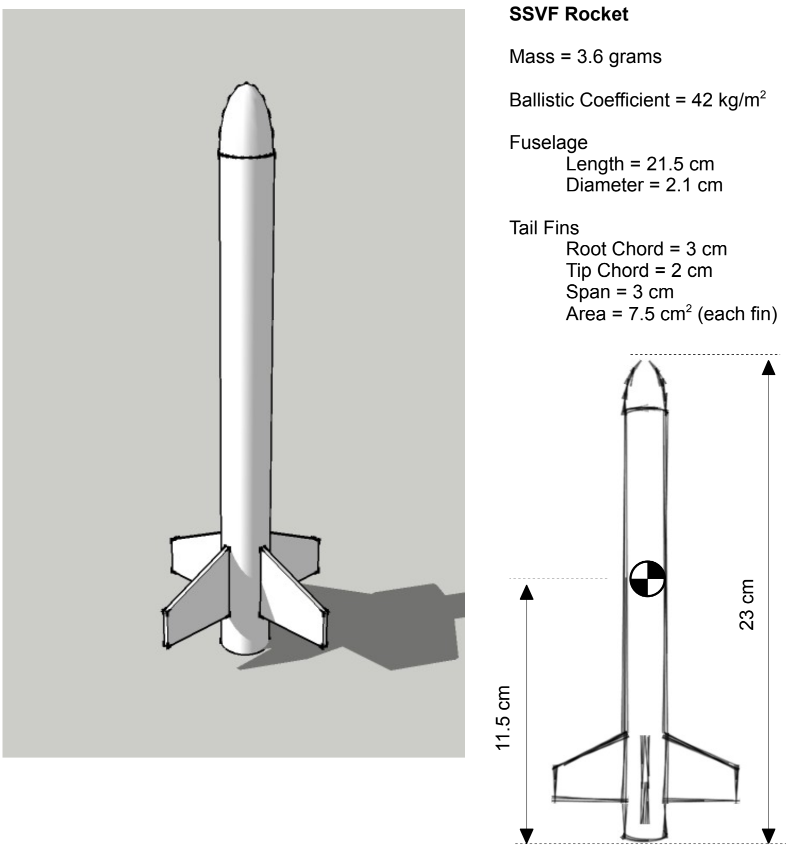


Figure 3 Rocket Configuration Sketch

Equation 3 defines the ballistic coefficient (B), which is a key parameter of the rocket design.[1] The ballistic coefficient is related to the mass of the vehicle (m), the drag coefficient (C_D), and a reference area (S). Students are given analytical expressions for estimating the total drag coefficient. The fuselage contribution is estimated using a graph published by McCormick.[2] This graph shows a nonlinear relationship between drag and the fuselage length. A minimum drag point is shown on the graph, but the resulting fuselage length results in a fairly low boost velocity. As a result, students are forced to consider how fuselage length affects the entire flight trajectory of the rocket.

Eq 3: $$B=\frac{m}{S\,C_D}$$

The differential equations for vertical motion of the rocket, after boost is complete, are given as Equations 4 and 5. The following definitions are used in these two equations: V = airspeed, rho = air density, g = gravity, and h = altitude. Introductory aerospace engineering students do not yet have the background needed to solve these equations, either analytically or numerically.

Consequently, a design chart has been created so that the students can estimate the performance of their rocket configuration.

Eq 4: $\frac{dV}{dt} = -\left(\frac{\rho V^2}{2B} + g\right)$ Eq 5: $\frac{dh}{dt} = V$

A rocket design chart example is illustrated in Figure 4. This chart is created by numerically integrating Equations 4 and 5. It assumes that the performance objective is to maximize peak altitude or apogee of the rocket flight trajectory. Once the boost velocity and ballistic coefficient are known, the design chart provides an estimate of the maximum achievable altitude. Boost velocities are typically in the range of ten to twelve meters per second, leading to a peak altitude of usually somewhat less than seven meters. Competitions are held in the recreational gymnasium, where the ceiling is approximately seven meters high.

The altitude design chart helps the students to quickly relate how design parameters ultimately influence performance of the configuration. For example, Figure 4 reveals that, for a given boost velocity, a considerable improvement in flight altitude can be obtained if the ballistic coefficient is increased from 20 to 40 kg/m^2. However, very little benefit is obtained if the coefficient is raised from 40 to 60 kg/m^2.

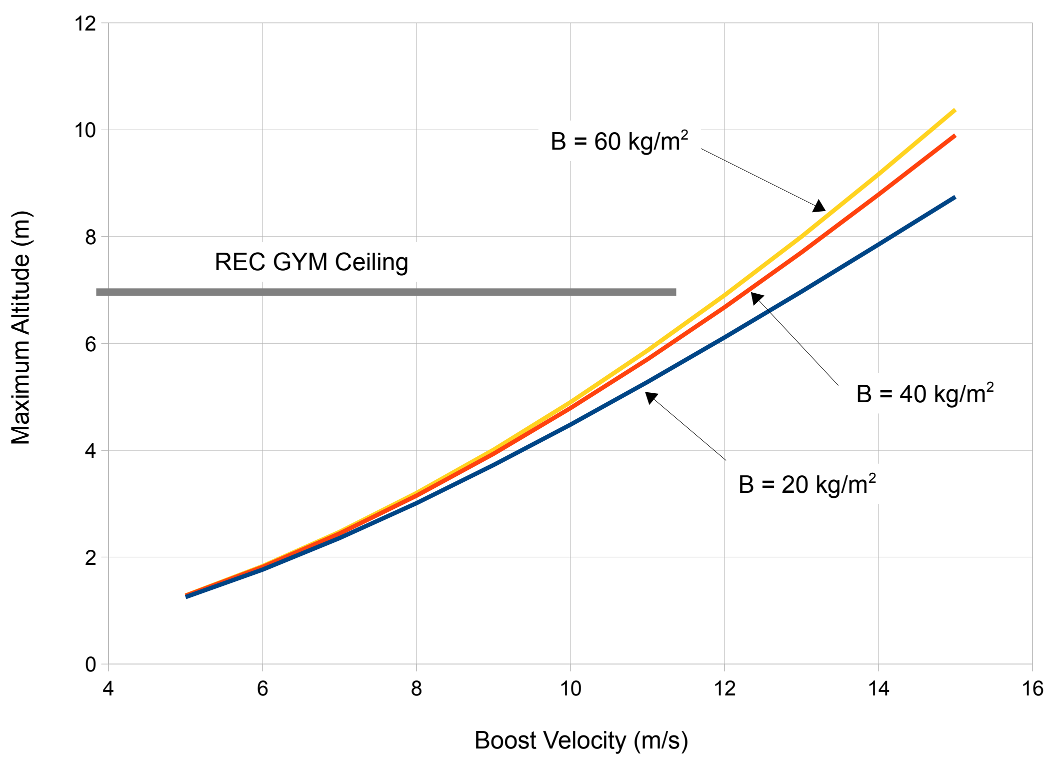


Figure 4 Rocket Design Chart to Maximize Altitude

Airplane Design Charts

Figure 5 provides a sketch of a typical configuration that has been designed for the airplane project. The airplane configurations include a wing surface. The compressed-air launch apparatus is typically tilted to an angle of less than forty-five degrees for airplane launches. Despite the low launch angle, the boost velocities that are achieved by the airplane configurations are similar to those obtained by the rockets. The effect of gravity is reduced by the low launch angle, but friction between the fuselage and launch tube seems to offset this effect.

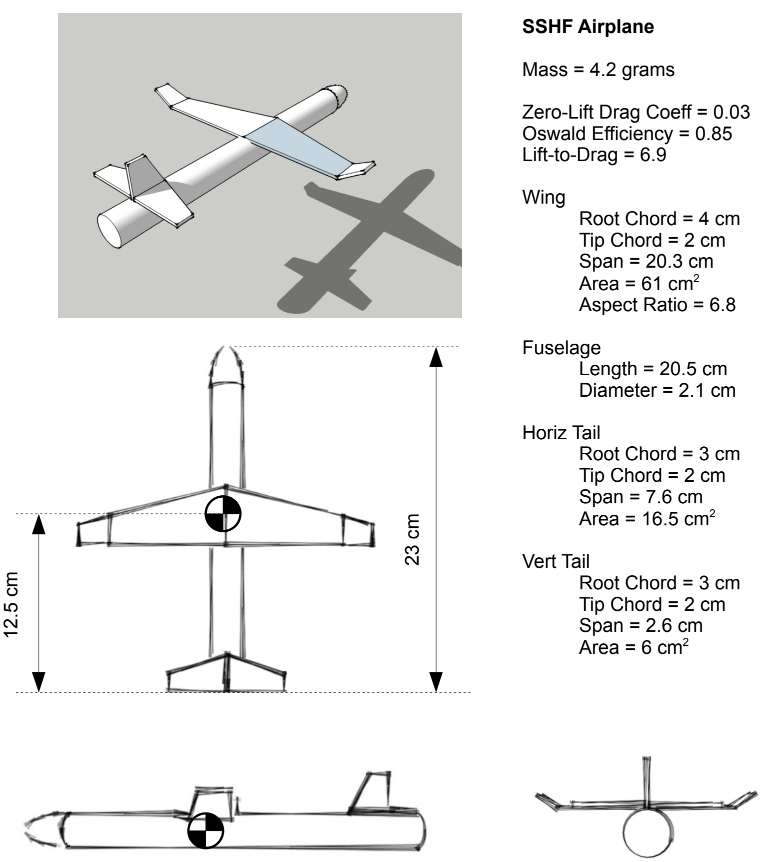


Figure 5 Airplane Configuration Sketch

The equations of motion for gliding flight are listed as Equations 6 to 8.[3] Variables used in these equations are: V = airspeed, t = time, rho = density, g = gravity, gamma = flight path angle, x = range, and h = altitude. These equations are difficult to solve analytically and introductory students are not prepared to solve them numerically.

Eq 6: $\frac{dV}{dt} = -\frac{\rho V^2}{2B} - g \sin\gamma$ Eq 7: $\frac{d\gamma}{dt} = \frac{1}{V}\left[\frac{\rho V^2}{2A} - g\cos\gamma\right]$

Eq 8: $\frac{dx}{dt} = V \cos \gamma$ Eq 9: $\frac{dh}{dt} = V \sin \gamma$

Two parameters are determined by the airplane geometry. Equation 10 is found by assuming the achieved boost velocity is sufficient to sustain lift. This equation defines the parameter A in terms of the boost velocity (V_b) and the initial launch angle (theta). The ballistic coefficient (B) can then be solved in terms of A and the lift and drag coefficients, C_L and C_D respectively. This expression is shown in Equation 11.

Eq 10: $A = \frac{\rho V_b^2}{2 g \cos \theta}$ Eq 11: $B = A \left(\frac{C_L}{C_D} \right)$

Numerically solving Equations 6 through 11 results in the airplane design chart shown in Figure 5. This design chart applies to a 36-degree launch angle. It reveals how the airplane lift-to-drag ratio, L/D, or equivalently C_L/C_D, effects the maximum achievable horizontal flight distance. The general trend is that a higher lift-to-drag ratio leads to longer range flight. However, the chart also shows that increasing the lift-to-drag ratio above a value of six does not significantly improve gliding performance. A good design strategy might then be to find a geometry that leads to a lift-to-drag ratio slightly above six. Once that geometry is found, attention can then be turned to another design parameter, such as vehicle mass, to improve boost velocity.

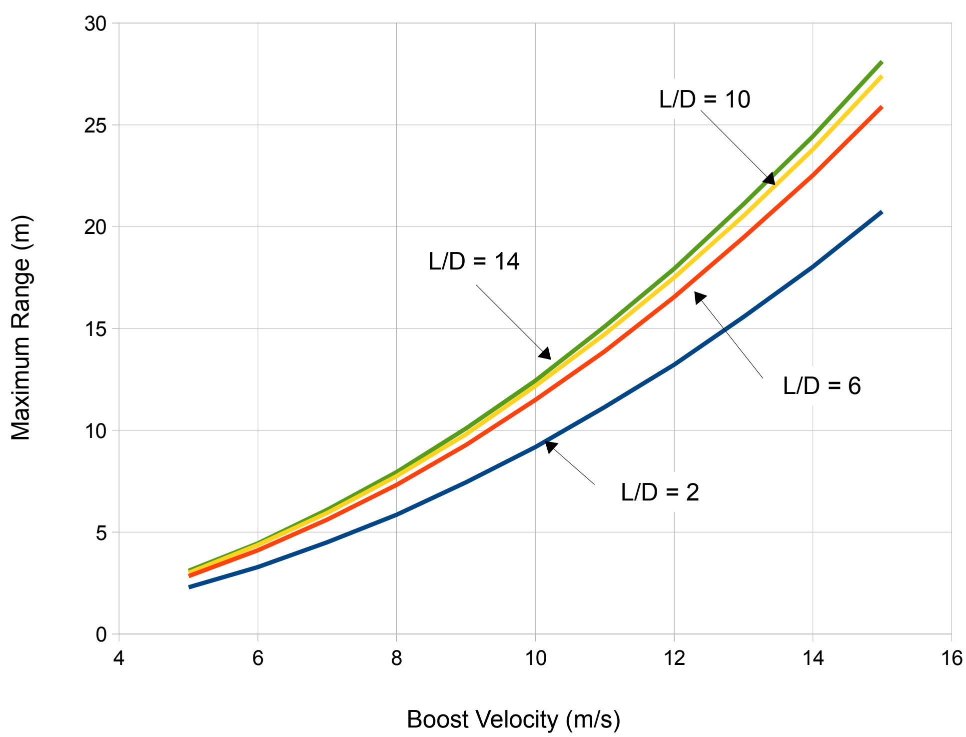


Figure 5 Airplane Design Chart to Maximize Range

Decelerator Design Charts

Figure 6 shows two decelerator configurations that were developed for the class. The objective of the third compressed-air launcher project is to maximize flight duration. These configurations combine a rocket body with a deployable decelerator mechanism. The top-left configuration uses rigid rotors to slow vehicle descent. The bottom-right configuration uses a non-rigid parachute for deceleration.

Figure 6 Example Decelerator Configurations

Analysis of a parachute decelerator configuration is simple enough that a design chart is not required. Equation 12 provides the expression needed to compute the descent airspeed (V). Minimizing the descent speed will tend to maximize flight time. The drag coefficient (C_D) for a typical non-rigid parachute is about 0.7, when the flat canopy area is used as the reference area (S).[4] Students quickly see that descent airspeed is minimized with a large parachute canopy. However, they also quickly learn, after a few test launches, that large parachutes tend to reduce the boost velocity as they will significantly decrease the ballistic coefficient. Again, achieving an appropriate trade-off becomes a critical factor in a successful design.

Eq. 12: $$V=\sqrt{\frac{2mg}{\rho S C_D}}$$

Design of a successful rigid-blade decelerator is very challenging. The blades must be rigid, but they also must be very lightweight. Larger, heavier blades move the center-of-gravity toward the nose of the vehicle, reducing stability in both the boost and descent phases of flight. One of the key design choices is the length of the rotor blades, or equivalently, the radius of the rotor. A design chart has been generated to aid in this decision.

The pertinent relationships for an auto-rotating decelerator are provided as Equations 13 through

16.[5] Variables used in these expressions include: sigma = rotor solidity, N = number of blades, c = blade chord, R = rotor radius or blade length, C_T = thrust coefficient, C_L = average blade lift coefficient, C_D = average blade drag coefficient, OMEGA = rotor speed, m = mass, g = gravity, and rho = atmospheric density. These algebraic equations are readily manipulated by first-year engineering students. However, converting these expressions into a design chart helps to reveal fundamental insights that may be difficult to find within the number and complexity of the equations.

Eq 13: $$\sigma = \frac{N c R}{\pi R^2} = \frac{N c}{\pi R}$$

Eq 14: $$C_T \simeq \left(\frac{\sigma}{6}\right) C_L$$

Eq 15: $$\Omega = \frac{1}{R^2}\sqrt{\frac{m g}{\pi \rho C_T}}$$

Eq 16: $$V = \Omega R \left[\sqrt{\frac{C_T}{2}} + \frac{\sigma C_D}{8 C_T}\right]$$

An example design chart for an auto-rotating decelerator is depicted in Figure 7. This chart assumes nominal values for the blade aerodynamic characteristics, vehicle mass, and atmospheric conditions. The design chart is intended to aid in sizing the rotor blades to minimize the speed of descent. A large blade solidity implies use of many rotor blades, or wide blades with larger chord. The Figure 7 design chart reveals that the speed of descent is reduced as blade solidity is increased. However, Figure 7 also shows that this benefit is reduced as the blade length (rotor radius) is increased.

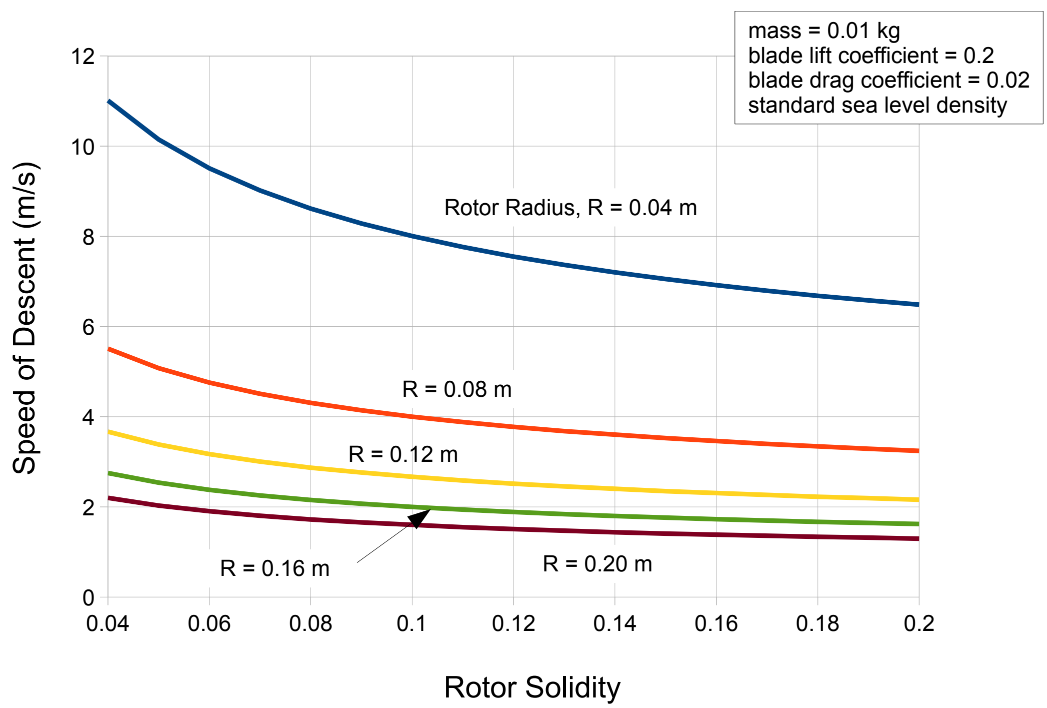


Figure 7 Decelerator Design Chart to Minimize Speed of Descent

Conclusion

Development of projects involving a compressed-air launcher has proven to be a cost-effective way to deliver a hands-on project experience that is appropriate for new aerospace engineering students. Construction of vehicle configurations is simple, but accurate and meaningful analysis is not. First-year students typically do not have the analytical or numerical skills needed to solve the required equations. Design charts offer a way to introduce the design-by-analysis approach that is a key part of aerospace engineering.

Three compressed-air launcher design projects were described in this paper. The design charts associated with each project demonstrate that fundamental insights could be expressed in graphical form. The primary benefit is that the students can actually test the charts by constructing a series of vehicles that change only one design parameter. For example, students can readily build three paper rockets, each with a different fuselage length, in order to verify trends seen on the rocket design chart. This verification process helps to establish a connection between theory and practice that should be carried throughout the student's undergraduate experience.

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