Journal of Physics Special Topics

P5_6 A Hovering 747

B. Woodward, S. Humayun, F. H. Davies

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

November 26, 2014

Abstract
The *Halicarnassus* is a highly modified 747, capable of hovering, featured in Matthew Reilly's novel, *Seven Ancient Wonders*. The following paper examines this aircraft by first trying to validate its ability to hover with statistics from the components specified in the novel and then by proposing the use of solid rocket boosters instead. The feat accomplished in the novel of making the *Halicarnassus* hover is validated, an equation for the use of a solid fuel rocket is derived and an example of a solid rocket booster that exceeds the requirements placed upon it is found.

Introduction
Seven Ancient Wonders by Matthew Reilly features a modified Boeing 747 called the *Halicarnassus*, or sometimes the *Hali*. In the book, the *Halicarnassus* is said to be capable of hovering tail-down with the assistance of eight Rolls-Royce Pegasus engines as used by the Harrier family of aircraft[1] (p. 489). This paper attempts to verify these modifications by evaluating the feasibility of the *Hali* using the technical specifications of the original 747 and the proposed engines, and postulates the alternative use of solid rocket boosters in the place of the Pegasus engines.

Pegasus Engine
The *Halicarnassus* as presented in the book shall be considered. In this case, eight Rolls-Royce Pegasus engines are attached to a Boeing 747, allowing for the *Halicarnassus* to hover in the air. So that the possibility of success is increased, the lightest 747 variant, the 747-100B will be used. The 747-100B has an empty operating mass of 162400kg and a maximum takeoff mass of 333390kg [2]; the empty operating mass includes fuel and other fluids required for flight that are not a part of the aircraft's structure. The most powerful engine used by this 747 variant is the Rolls-Royce RB211-524B2, each one generating 223kN, giving a total of 892kN for a full set of four.

$$M_{100B}g - T_{RB211} = F_R \tag{1}$$

In the event of the aircraft being vertical with its nose pointing upwards, Eq. [1] describes the resultant force, F_R, by taking the difference between the thrust of the engines, T_{RB211}, and the weight of the aircraft, where g is acceleration due to gravity and M_{100B} is the empty operating mass of a 747-100B. Using the values given in the paragraph above, the resultant force is calculated as 701kN acting in the direction of the ground. For the inclusion of the Pegasus engines to have the intended effect, they must produce enough thrust to negate this force and their own weight.
Each Rolls-Royce Pegasus 11-61/-408/Mk107 engine has a mass of 1796kg and produces a thrust of 105.9kN [3], meaning that eight engines would have a weight of 141kN while producing 846.9kN of thrust, giving the total force acting on eight connected Pegasus engines while running as 706kN acting in the direction of the thrust. By factoring these values into the force equation, weight acting downwards while thrust is acting in the exact opposite direction, it gives a resultant force of 5.11kN acting in the direction of the thrust. This value means that as long as the support structure and fuel for the additional engines does not exceed a weight of 5.11kN and the assumptions made about the unmodified aircraft were accurate, then the *Hali* could hover in the nose up vertical position and even ascend.

Rocket Boosters

Even though the assertion that the *Halicarnassus* could float was verified, the success was tenuous enough to merit research into an alternative propulsion system such as a solid rocket booster (SRB). SRB's have been selected due to their rather light weight and high thrust output, which compensate for their near universal lack of active control and single use operation. For this configuration we shall use the specifications for the Boeing 747-400ER in our model, as it has a payload capacity of 228175kg, the largest of the 747 variants. The 747-400ER (ER meaning extended range) has an empty operating mass, M_{400ER}, of 184600kg and a maximum takeoff mass of 412775kg. Subtracting the former from the latter approximates the payload capacity as seen above. This type of 747 is propelled by four General Electric CF6-80C2B5F engines, each one producing 276kN giving the total thrust of all four, T_{CH6}, of 1104kN.

$$T_{Rocket} = \frac{dm}{dt} v_e + (P_e - P_a) A_e \tag{2}$$

Equation (2)[4] describes the thrust given by a rocket engine when surrounded by an atmosphere, where T_{Rocket} is the rocket thrust, dm/dt is the mass loss rate, v_e is the exhaust velocity, P_e and P_a represent the pressures of the exhaust and the surrounding atmosphere respectively and A_e is the cross-sectional area of the exhaust. It is reasonable to assume that the boosters would only be used at fairly low altitudes and as such they would be optimised for these conditions. To optimise a rocket exhaust is to design it so that the pressure in the exhaust is equal to the pressure of the surrounding atmosphere, meaning that the second term of Eq.2 is reduced to zero.

Since the thrust of an SRB can always be reduced and for the sake of finding the requirements placed on a rocket in this case, an inequality is introduced into the following equations. To simplify the problem further, the effective weight, $M_{eff}g$, of the aircraft, which is the weight of the aircraft operating its engines while pointing upwards to reduce the effect of gravity, is considered; $M_{eff}g = M_{400ER}g - T_{CH6}$ which is 707kN.

$$M_{eff}g \le \frac{dm}{dt} v_e \tag{3}$$

Equation (3) describes the condition for hovering or ascent of a rocket propelled system. By separating dm and dt then integrating over the time period t where the mass of the rocket is reduced from an initial mass, M_i, to a final mass, M_f, Eq. (4) is acquired.

$$t \le \frac{v_e}{g} \ln\left[\frac{M_i}{M_f}\right] \tag{4}$$

The fraction inside the natural log is inverted because if it were not, t would always be negative (since $M_f/M_i < 1$). The negative sign can be transferred to the other side of the equation and made into a power inside the logarithm, thus inverting the fraction. Since values for dt and dm exist as t and $M_i - M_f$ respectively, the exhaust velocity term in Eq. (4) can be replaced with a rearrangement of the simplified version of Eq. (2). This results in a t on both sides which is cancelled to give Eq. (5).

$$(M_i - M_f)g \le T_{Rocket} \ln\left[\frac{M_i}{M_f}\right] \tag{5}$$

Conclusion

Equation (5) does not provide numerical values but does allow for the evaluation of existing systems to see if they satisfy the thrust and mass requirements. An example of a rocket that does exceeds these conditions is ATK's CASTOR 120 SRB[5]. The CASTOR 120 produces 1.7MN of thrust and weighs 53067kg with fuel and 4126kg without. A 747-400ER is conceivably capable of carrying multiple CASTOR 120 should the need arise, however, a smaller, weaker rocket would be more appropriate.

References

[1] Reilly, M., 2005. *Seven Ancient Wonders*, Pan Macmillan.

[2] http://en.wikipedia.org/wiki/Boeing_747 accessed on 26/11/14

[3] http://www.rolls-royce.com/defence/products/combat_jets/pegasus/ accessed on 26/11/14

[4] http://www.nakka-rocketry.net/th_thrst.html accessed on 26/11/14

[5] http://cms.atk.com/SiteCollectionDocuments/ProductsAndServices/ATK-Motor-Catalog-2012.pdf accessed 26/11/14