Aerodynamics Extra Credit Project: How cool is a flying aircraft carrier?

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Figure 1: Image from the movie *The Avengers* (Marvel Studios, 2012).

Figure 2: Image from the movie *Captain America: The Winter Soldier* (Marvel Studios, 2014).

1 Problem

In the Marvel Avengers movies, the S.H.I.E.L.D. Helicarrier is a kind of flying aircraft carrier (Fig. 1). It can sail on the ocean like a conventional ship, but it can also lift out of the water and fly. Lift for the Helicarrier is provided by four fans,[1] and there are two arrays of engines in the rear. Stills from the movies, for example Fig. 2, seem to show a total of 20 engines.

The means of forward propulsion is not made completely clear in the movies. Small-scale quadcopters fly forward by tilting to an angle-of-attack to generate forward thrust. There is no clear provision for tilting the fans on the Helicarrier, and it is not likely that it can tolerate a significant angle-of-attack. Thus, forward propulsion must be provided primarily by the rear engines. We will assume that these are similar to conventional jet engines.

The challenge for this extra credit project was to analyze the operation of the Helicarrier. The assignment asked for at least the following analysis:

- Plot of power required versus altitude and forward speed
- Estimate of the maximum force produced by the fans and their maximum rotation rate
- Consideration of an alternative design

The assignment also encouraged consideration of the maximum forward speed and the lift provided by the body of the vehicle.

Comparing the size of the aircraft on deck to that of the Helicarrier, it appears to be comparable to the largest existing vessels, such as the United States Nimitz-class air-

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[1] These are rotating blades, not comic book enthusiasts.

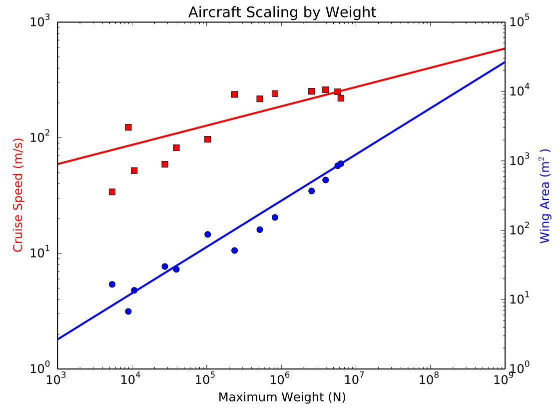

Figure 3: Scaling up from existing large, subsonic aircraft.

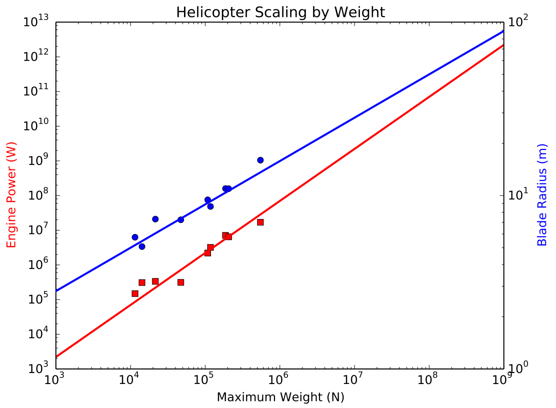

Figure 4: Scaling up from existing helicopters.

craft carriers. To approximate a ship the size of a Nimitz-class carrier [5, p. 809], we will take the total mass of the vehicle to be $M = 1.0 \times 10^8$ kg and the vehicle length to be $\ell = 330$ m. Comparing the size of the fans to the length of the ship in Figs. 1–2, we will take their radius to be $R = 25$ m.

A Nimitz-class aircraft carrier is powered by two Westinghouse A4W pressurized water reactors [7], which produce steam used to generate approximately 1.0×10^8 W electrical power and another 1.0×10^8 W of shaft power. These figures provide a bound on the power available to support flight.

2 Scaling

It is worth beginning by comparing the Helicarrier to existing large flying vehicles.[2] For example, it is larger than the Saturn V rocket, which had a mass of 3.0×10^6 kg. Very large existing aircraft include the Boeing B747-400 (about 4.0×10^5 kg maximum mass at takeoff), the Airbus A380-800 (5.8×10^5 kg), and the Antonov An-225 (6.4×10^5 kg). We see that an aircraft carrier is more than one-hundred times heavier than the largest existing airplanes.

Data for winged flying objects [6], from insects to large airplanes, indicate that flying speed scales approximately as the one-sixth power of vehicle weight, and that wing area scales as the two-thirds power of weight. This relationship can be derived by assuming a constant lift coefficient, and using the facts that lift equals weight in steady flight, mass scales as length cubed, and wing area scales as length squared.

Figure 3 illustrates this scaling. The solid lines represent the theory and the symbols the properties of a variety of aircraft, including the Boeing B747-400, Airbus A380-800, and the Antonov An-225 at the largest scale. If we can extrapolate[3] by three orders of magnitude with our correlation, a vehicle with a mass of 1.0×10^8 kg would cruise at roughly 600 m/s (around Mach 2), and the wing area would be about 3×10^4 m^2.

The largest helicopters are an order of magnitude smaller than the largest aircraft. The Mil Mi-26 is a very large helicopter, with a rotor diameter of 32 m, total engine power of 17 MW, maximum take-off mass of 5.6×10^4 kg, and a cruise speed of 70 m/s. A four lift-fan system equivalent to four Mi-26s would be about 2×10^5 kg, five-hundred times smaller than an aircraft carrier.

We can also make scaling estimates for helicopters. As we will see in the next section, the engine power of heli-

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[2] The aircraft data presented here were obtained from Wikipedia, *Jane's All the World's Aircraft* [3, 4], and Tennekes [6].

[3] In accordance with the order-of-magnitude accuracy of these calculations, all the numbers will be rounded to one significant digit.

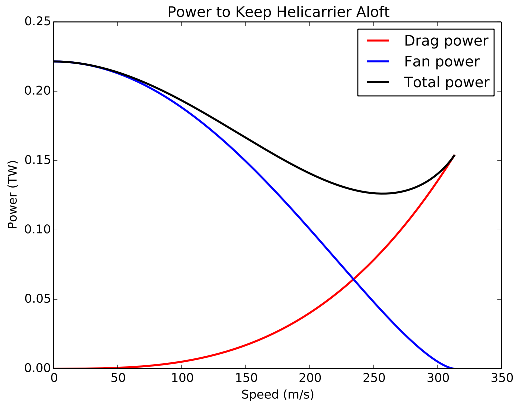

Figure 5: Power required to keep Helicarrier aloft at sea level (1 TW = 10^{12} W).

copters scales as weight to the two-thirds power, and the blade diameter scales as weight to the one-fourth power. Figure 4 illustrates this scaling, along with data from several existing helicopters, such as the Bell 206B-L4, Mil Mi-26, and Sikorsky S-67 Blackhawk. For a helicopter extrapolated to 1.0×10^8 kg, the engine would need to produce 2×10^{12} W and have a rotor blade radius of 90 m.

For comparison, this power consumption corresponds to about ten thousand Westinghouse A4W nuclear reactors, and about twice the total capacity for electrical power generation of the entire United States [8].

3 Estimates of Performance

From actuator disk theory [2, pp. 671–672], the minimum power required to hover with the four lift fans can be estimated as:

$$P = 4\sqrt{\frac{(W/4)^3}{2\rho A}} \tag{1}$$

where $W = Mg$ is the total weight of the vehicle, the acceleration of gravity is $g = 9.8$ m/s, $\rho = 1.2$ kg/m^3 is the sea-level density of air, and $A = \pi R^2$ is the area of each fan. Each of the four fans is assumed to support one quarter of the total weight. The minimum power required to hover is about $P = 2 \times 10^{11}$ W.

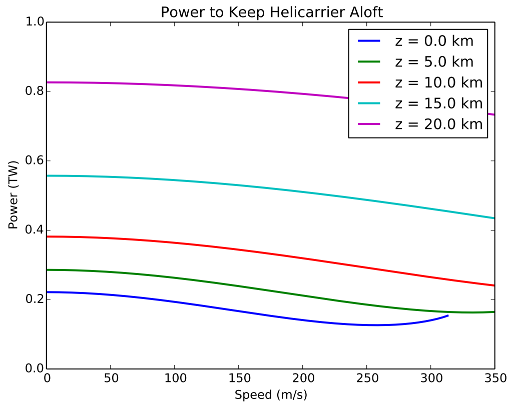

Figure 6: Power required to keep Helicarrier aloft at various altitudes.

We now consider the combined effects of the lift from the fans and the forward motion for different altitudes and speeds. As an upper bound on performance, we generously[4] estimate the lift and drag coefficients of the hull to be $C_L = 0.6$ and $C_D = 0.3$. The total power to keep the helicarrier aloft is given by:

$$P = 4\sqrt{\frac{[(W-L)/4]^3}{2\rho A}} + DV \tag{2}$$

where the lift is $L = C_L S \frac{1}{2}\rho V^2$ and the drag is $D = C_D S \frac{1}{2}\rho V^2$. Here the reference area is taken as $S \approx 0.25\,\ell^2$. The speed at which the full weight of the vehicle is supported by the lift due to forward motion is:

$$V_s = \sqrt{\frac{2W}{C_L \rho S}} \tag{3}$$

This is a form of the stall speed. Below this speed, the fans must provide part of the lift that supports the vehicle.

Figure 5 shows the minimum power required for sea level conditions for speeds up to V_s. At low speed, the fans provide most the required power (blue line), and their contribution drops to zero as the speed approaches V_s. A constant drag coefficient has been assumed, so the drag

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[4] A large commercial airplane at cruise typically has about $C_L = 0.6$ and $C_D = 0.04$; a blunt object has $C_D \approx 0.5$.

power (red line) increases as the cube of speed. The sum of these two components gives the total power (black line, Eq. 2), which has a minimum at relatively high speed.

The total power required to stay aloft at altitudes between sea level and 20 km is shown in Figure 6. The density and temperature as a function of altitude were taken from a correlation given in Ref. [1]. The power required increases substantially with altitude because the efficiency in producing lift with both the fans and the forward motion decreases as the density drops. The minimum power required is greater than 0.1 TW under all conditions.

We should also check if it is possible to produce the required thrust with the fans and the engines. The total thrust from the four fans is given by [2, pp. 652–654]:

$$T_f = 4\, C_T \frac{\pi}{2} \rho n^2 R^4 \tag{4}$$

where the thrust coefficient for a helicopter is on the order of $C_T = 0.01$, and n is the angular rotation rate (rad/s). The maximum rotation speed of the fans is limited by compressibility. If the blade tips are limited to sonic speed, the maximum rotation rate is around 100 rpm. This gives a thrust from the four fans of 6×10^6 N, or a thrust-to-weight ratio of $T_f/W = 6 \times 10^{-3}$. The fans cannot provide sufficient lift.

The typical thrust for a jet engine at zero speed is about 2×10^5 N, and stills from the movie seem to show a rack of 20 engines at the back of the Helicarrier (Fig. 2). The maximum flight speed would be:

$$V = \sqrt{\frac{2T_e}{C_D \rho S}} \tag{5}$$

The total thrust[5] of $T_e = 4 \times 10^6$ N gives a maximum speed of about 30 m/s. The corresponding lift is 8×10^6 N, for a lift-to-weight ratio of $L/W = 8 \times 10^{-3}$. Insufficient thrust is available to produce significant lift.

4 Redesign

Considering these estimates, we have to conclude that the Helicarrier design as conceived here is not feasible. It is not possible to provide sufficient power abord the craft, nor can the fans develop sufficient thrust to lift the vehicle.

In considering a redesign, we have to examine the value that the product gives to the customer. What does a Helicarrier do for S.H.I.E.L.D.?

A conventional aircraft carrier is a device for efficiently positioning around 100 aircraft and their supporting infrastructure anywhere on the ocean. A Nimitz-class carrier has a speed of over 30 knots (15 m/s), and essentially unlimited range (about 20 years between refuelings).

The Helicarrier apparently provides the capabilities of an aircraft carrier, along with the ability to fly. As a large, non-streamlined vehicle, a Helicarrier cannot provide much additional speed over that of a conventional ship, but it does have the advantage that it can travel inland. It has no need of the Panama or Suez canals, and can travel a direct route around the world. Flight also offers another degree of freedom in evading attack. A Helicarrier would be hard to target with torpedos and missiles.

Perhaps the main advantage of flight is surprise. Indeed, the Helicarrier in the 2012 movie *The Avengers* has some sort of active camouflage [9], a capability that supports the hypothesis of a strategy of surprise.

The first issue to consider is the vehicle weight. Perhaps a lighter vehicle could provide the same capabilities of surprise and versatility. A typical US Navy fighter plane, the F-14D, has a mass of about 2.8×10^4 kg when fully loaded. Thus, the mass of 100 flighter planes is about 3×10^5 kg, with a corresponding weight of 3×10^6 N. A comparable mass of extra fuel and infrastructure would be required to support the planes, giving a required Helicarrier mass of perhaps 1×10^6 kg. This is equivalent to about twenty fully-loaded Mil Mi-26 helicopters or two fully-loaded Antonov An-225 cargo planes.

Another possibility is a redesign of the lift system. Inspecting Eq. (4) carefully, we see that thrust varies as the fourth power of the fan radius, and the maximum rotation rate decreases as the square of the fan radius. The net effect is a quadratic increase in thrust with fan radius. Thus we should consider an increase in the size of the fans.

In order to reduce drag, the hull should be shaped more aerodynamically. The tower on the carrier deck should be replaced with a retractable mast, and floating stability provided by retractable pontoons and hydrofoils. Small wings could provide lift along the lines of a compound he-

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[5] The change in thrust with speed is neglected in this analysis because the maximum vehicle speed is relatively slow.

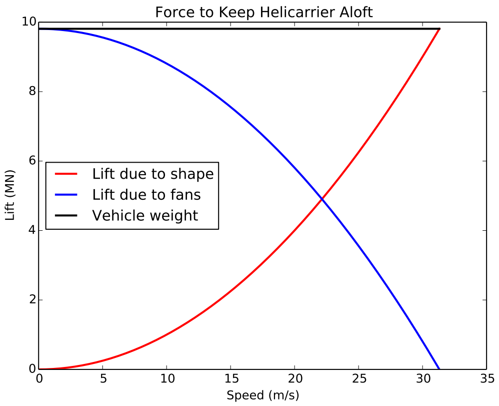

Figure 7: Force required to keep redesigned Helicarrier aloft at sea level.

licopter (also called a rotodyne, gyrodyne, or heliplane).

Consider a compromise design with $M = 1 \times 10^6$ kg and $R = 50$ m. With a more streamlined design, we'll assume that $C_L = 0.6$ and $C_D = 0.06$ at cruise. Considering sea-level conditions, the power required to hover drops to 1×10^8 W, or about half of a reactor's output. The maximum fan rotation rate (sonic blade tips) is about 70 rpm, providing up to 2×10^7 N of thrust, for a thrust-to-weight ratio of about two. The total thrust of the rear engines of 4×10^6 N provides a maximum speed of 60 m/s, several times faster than a large sea vessel. The corresponding lift due to the forward motion is 4×10^7 N, or about four times the vehicle weight.

The components of lift as a function of forward speed are given in Fig. 7 for sea-level conditions, and Figure 8 shows the corresponding power. Forward speeds shown here are well within the limits of engine thrust. The optimal flight speed at sea level would be about 30 m/s.

The effect of altitude on the required power, Eq. (2), is illustrated in Fig. 9, and the effect on the fan thrust-to-weight ratio is shown in Fig. 10. The maximum altitude at which the fans can support hovering is about 6 km. Optimal speed and power vary with altitude, but are on the order of 30 m/s and 4×10^7 W. Notice the significant contribution of forward motion to reducing power consumption that occurs because of the low drag coefficient.

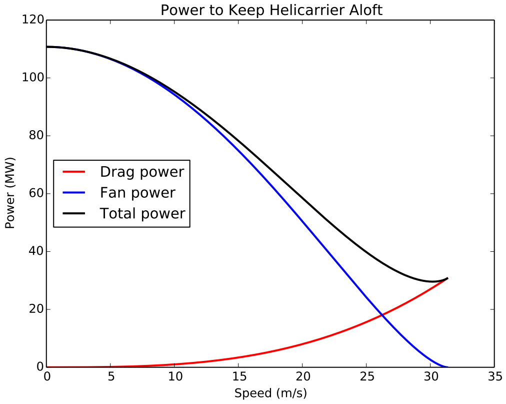

Figure 8: Power required to keep redesigned Helicarrier aloft at sea level.

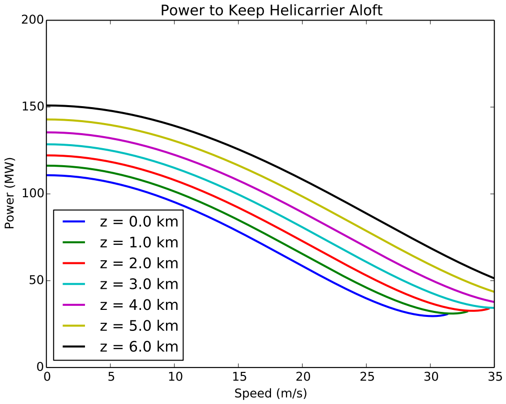

Figure 9: Power required to keep redesigned Helicarrier aloft at various altitudes.

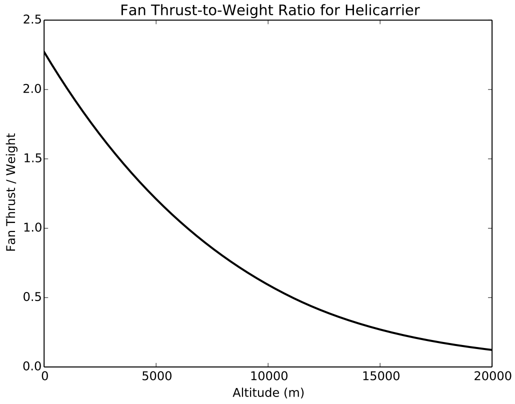

Figure 10: Fan thrust-to-weight ratio for redesigned Helicarrier.

5 Concluding Remarks

The Helicarrier as depicted in the movies is not feasible; it is far too heavy to fly. Nonetheless, a redesign with larger fans and substantially reduced weight looks promising.

A consideration that has been neglected here is the use of the fans to provide forward thrust, like a helicopter. That capability could increase the maximum vehicle speed. Another important consideration is sea worthiness, particularly stability in floatation. A design compromise would have to be made between aerodynamic efficiency and floating stability as for a sea plane.

We should also consider the effectiveness of many small fans over four large fans. There would certainly be structural limitations on very large lift fans, and in general on vehicle.

If we were advising S.H.I.E.L.D. on purchases of military equipment, we would have to recommend reconsideration of the Helicarrier. We have to assume that the cost of one unit would exceed that of a Nimitz-class aircraft carrier, about $4.5 billion [10]. Maintaining a secret fleet of Helicarriers would seriously stretch the budget of S.H.I.E.L.D. The value to the customer of surprise and versatility might also be provided by several smaller, lower cost vehicles, rather than a few, large, expensive craft.

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