N76-15032

FLOATING vs. FLYING, A PROPULSION ENERGY COMPARISON

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ABSTRACT: Floating craft are compared to those that fly. Drag/weight for floaters is shown to be proportional to v^2/L, while for flyers it is independent of size and speed. The transportation market will therefore assign airships to lower speeds than airplanes, and will favor large airship sizes. Drag of an airship is shown to be only 11 percent of submarine drag at equal displacement and speed, raising the possibility that airships can compete with some types of ships.

INTRODUCTION

Excitement over airships is again on the rise, and many expect their second coming, including this author. As a result of this ferment, the air is already full of proposals, some alleged to float, others in part to fly, all claiming to be advantageous.

Nor are floating and flying confined to airship proposals. When airships reenter the transportation business, they will be in direct competition with ships that float in water, airplanes that fly in air, and a growing variety of craft that fly on water.

This therefore seems to be the right time, and this Workshop a suitable occasion, at which to take stock of floating and flying in air and in water. The groundwork has already been done, and all that remains is to organize the data so that useful comparisons can be made. Hopefully the results will be helpful both in sorting out airship proposals and in steering airships towards their proper place in the future transportation picture.

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DRAG PER UNIT DISPLACEMENT AS A CRITERION OF COMPARISON

The general standard of comparison in this paper will be the ratio of drag to displacement, both being measured in the same units, or its equivalent for flying machines, drag per unit weight. This is in effect a craft's friction coefficient, the best single index of its energy consumption, and one of only a few important determinants of its economic performance.

Consider for instance a craft traveling a distance E from one place to another, having drag D and displacement or weight W. Then,

$$Q = D\,E \tag{1}$$

Q being the energy consumed by the trip, and

$$T \sim W\,E \tag{2}$$

T being the amount of transportation produced or producible by the trip. It follows that the ratio R of energy consumed to transportation produced is

$$R = \frac{Q}{T} \sim \frac{D}{W} \tag{3}$$

Other things equal, a craft burns fuel in direct proportion to its drag-to-weight ratio. Besides having to be bought, the fuel must also be carried, detracting from the ability to carry a payload in all but nuclear-propelled craft. It follows that, as the drag-to-weight ratio goes up, the upper limit on endurance comes down.

The market for transportation has imposed a selection process on the various types of craft and their particular designs. The market will accept higher drag-to-displacement only if it gets something in return. What it usually gets is more speed, which has value on the market. As a result, if the craft which coexist at any time are ranked in order of ascending drag/weight, most of them will also be in order of ascending speed. The exceptions, many of them watercraft, will be found to have something else to offer, often a combination of lower first cost and access to more numerous or cheaper terminals.

Compared to other craft, airships have never come at a low price per pound, nor are they known for easy handling at terminals. If airships can have any fundamental advantage over competing craft, it is probably a lower drag per ton. It will be shown that this advantage can indeed be substantial, but that proper choices of both size and speed are required to realize it.

FLOATING

Floating Itself

Craft that operate in air or water must be sustained from sinking to the ground, and floating is the most popular method of doing this. In this application, it has two notable characteristics:

Floating in the usual steady state consumes no energy. This no doubt accounts for its widespread use and is part of the reason that boats were already well developed at the dawn of recorded history.

The second feature of floating is that it ties craft volume to craft weight. The buoyant force results from the higher static pressure on the bottom of the craft than on the top, and by Archimedes' principle it is equal to the weight of fluid displaced. The buoyant force on a floating craft must equal its weight. In the usual notation, this requirement is:

$$W = \rho g V \qquad (4)$$

where W is craft weight, ρ the mass density of displaced fluid, g the acceleration of gravity, and V the immersed volume. With airships as with submarines, V is constant. If anything is brought aboard, something else of equal weight must be taken off. During the first airship era, this nearly inflexible requirement cost substantial amounts of time, money and lift gas[1]. The classic Zeppelin cannot actually remain much Lighter Than Air; it has always to be about the same weight.

Drag/Weight for Floating Craft

The weight-volume relationship (4) has an effect on the drag/weight ratio of floating craft, which will now be developed.

Drag - With hulls as with most other objects, the drag due to motion through a fluid is most conveniently expressed as:

$$D = C \frac{\rho}{2} S v^2 \qquad (5)$$

where v is the velocity of the motion, S is some characteristic area of the object, and C is a dimensionless coefficient. When the object's shape is such as to deflect the flow or to induce strong turbulence, most of the drag is in the form of pressure differences across the object, and C is constant. As $(\rho/2)v^2$ is the stagnation pressure of the flow, it is the custom to take S as the object's cross-sectional area normal to the flow and to think of C as the average fraction of stagnation pressure which acts on the object. Drag of this type is called "pressure drag".

Hulls, however, are designed specifically to minimize pressure drag. They do not as a rule deflect the flow, nor are many turbulence-inducing objects allowed to stick out of them. The passing flow remains attached to a good hull far aft, with the result that the pressure buildup around the bow is balanced by similar pressures on the stern. Net pressure drag can be and often is quite low, in the sense that C is much less than unity.

What hulls cannot be designed to avoid is frictional drag. Be they never so smooth, it is still substantial and is the largest single drag component of ships at low speeds, and of airships and submarines at all speeds. As friction acts tangientally on the hull's envelope, it is customary to use the wetted surface, or area of the envelope, as S when equation (5) is used on a hull. For C_f, the frictional resistance coefficient, one uses the value for a flat plate having the hull's length and speed.

C_f is not quite constant; it diminishes slowly as the Reynolds number vL/ν rises. If frictional resistance were fitted to an equation like (5) with C constant, the exponent of v would be in the range 1.8 to 1.9, slightly less than 2. To simplify the following discussion, it will be assumed for a while that equation (5) holds for turbulent friction with a constant drag coefficient.

Drag/Weight - For goemetrically similar hulls, $\mathcal{V}$ is proportional to L^3 and S to L^2. Calling the constants of proportionality C_V and C_S, and using (5) and (4),

$$\frac{D}{W} = \frac{C_t (1/2) \rho C_S L^2 v^2}{\rho g C_V L^3} = \frac{C_t C_S}{2 C_V} \frac{v^2}{g L} \tag{6}$$

Drag/Weight for a hull is seen to be directly proporational to v^2/L. The non-dimensional quantity v^2/gL happens to be the square of the Froude number, a common speed parameter for surface ships. Two geometrically similar surface hulls will have the same value of wavemaking R/W when run at the same Froude number. Its appearance here, where no wavemaking is involved, is coincidental.

Equation (6) is important, because it points out clearly the direction in which to seek transport efficiency for ships, including airships. Ships should be large and not too fast. A small, fast ship or airship is apt to be a technical tour de force and an economic disaster.

Air vs. Water Performance

At present, nearly all floating craft operate in water. Here in this Workshop we are studying the proposition that more of them should operate in air. It will therefore be in order to make a couple of air/water drag comparisons.

Same Object at Same Speed - Assuming pressure drag for this simple case, every quantity on the right-hand side of (5) is the same for air as for water, except the mass density. Typical values of mass density are 0.00238 $lb\text{-}sec^2/ft^4$ for sea-level air and 1.99 $lb\text{-}sec^2/ft^4$ for sea water at $59^\circ F$. Using these values, with subscripts a and w for air and water, respectively,

$$\frac{D_a}{D_w} = \frac{\rho_a}{\rho_w} = 0.00120 \tag{7}$$

As anyone who has gone wading can testify, air drag is negligible compared to water drag, on the same object. This result explains the typical appearance of ships, clean on the bottom and cluttered on top. In fact, ships have little to fear from wind, while it ranks as a major threat to airships.

Same Displacement at Same Speed - While (7) may be interesting, it is hardly a fair basis on which to compare air and water craft. In this section an airship will be compared to a geometrically similar submarine. Both will have the same displacement, as well as the same speed, making the ratio of their drags an estimate of their relative fuel consumptions to produce the same amount of transportation. Drag will be assumed frictional, though in fact it has a pressure component.

Using (4) with $W_a = W_w$ and with the density ratio in (7) the hull size ratios are first obtained:

$$\frac{V_a}{V_w} = \frac{\rho_w}{\rho_a} = 836 \tag{8}$$

$$\frac{L_a}{L_w} = 836^{1/3} = 9.42 \tag{9}$$

$$\frac{S_a}{S_w} = 836^{2/3} = 88.7 \tag{10}$$

showing that the airship is enormously larger than a submarine of equal displacement. The ratio of their Reynolds numbers will now be computed using for dynamic viscosities, $\nu_a = 1.56 \times 10^{-4}$ ft^2/sec for air at sea level, and $\nu_w = 1.28 \times 10^{-5}$ ft^2/sec for sea water at 59°F.

$$\frac{R_{na}}{R_{nw}} = \frac{L_a}{L_w} \frac{\nu_w}{\nu_a} = 0.77 \tag{11}$$

To use (11), let $R_{nw} = 10^9$, which is entirely possible. That makes $R_{na} = 7.7 \times 10^8$. From the table of Schoenherr flat-plate friction coefficients[2]

$$\frac{C_{fa}}{C_{fw}} = \frac{1.58 \times 10^{-3}}{1.53 \times 10^{-3}} = 1.03 \tag{12}$$

With little difference between air and water frictional drag coefficients, and no difference between the two pressure drag coefficients, the drag ratio that is about to be obtained will be a robust approximation, insensitive to the proportions of frictional and pressure drag, and therefore valid for a wide variety of hull forms, appendages, etc.

Using (12), (10), and (7) in (5), the desired drag ratio is obtained:

$$\frac{D_a}{D_w} = 0.11 \tag{13}$$

The airship has only 1/9th the drag of a submarine of equal displacement at the same speed! It follows that the airship could go from port to port about three times as fast as the submarine without burning any more fuel.

The writer, a card-carrying naval architect, was at first unsettled by result (13), which makes it appear that airships might put ships totally out of business. Further reflection made this appear less likely.

For one thing, many ships can carry two or three times their light weights, while the navigable classes of Lighter Than Air craft do well to carry loads equal to their light weights. For an airship to be competitive with tankers in energy consumption, it would have to be more than 7000 feet long by 1000 feet in diameter, while operating at less than 50 knots. Winds being what they are, such a low-powered behemoth would be unsafe.

Airships look much better for some of the marine express trades. Container ships, Roll-on, Roll-off (RoRo) ships, seagoing ferries and passenger ships operate at much higher values of D/W than tankers, often five or six times as high. All of them are lighter than the big tankers, and in many cases their payloads are less than half of full-load displacement. Moreover, as is not the case with tankers, many of these ships' customers wish they were faster and would be willing to pay a premium for more speed.

All this adds up to the possibility of a large commercial market for airships. They are more difficult and costly to build than water ships, but in the matter of fuel costs, equation (13) leaves airship designers plenty of room for maneuver.

FLYING

Flying as an Escape from Hull Drag

Where cheap transportation or long distance endurance is called for, a floating hull at low speed is unbeatable. As equation (6) makes clear, however, the same hull will encounter rapidly increasing, arbitrarily high drag as speed is increased. To make a craft go faster without becoming much bigger or heavier, one must do something drastic to decrease the drag of the hull.

In airplanes (and in land vehicles, for that matter) the strategy is to shrivel the hull, making it much denser than the air it passes through, so that its "wetted" surface is far smaller than that of an airship of the same weight. This approach fails underwater, because only solid lumps of metal have the required density, and they do not make useful hulls. The system used by high-speed marine craft is to lift the hull out of water, or almost out of water, so as to achieve the type of drag reduction illustrated by (7).

Whatever is done, the result is a hull which cannot float while operating at design speed and must be supported by other means. The simplest and most popular such means, for aircraft at least, is a wing fixed to the hull which generates the needed lift. This method, called "flying", will be used for illustration here.

Induced Drag, the Price of Flying

Wing performance data can be condensed by the use of expressions analogous to (5).

$$C_L = \frac{L}{1/2\,\rho S\, v^2} \qquad (14)$$

$$C_D = \frac{D}{1/2\,\rho S\, v^2} \qquad (15)$$

where the symbols the same as before, except that L is the lift force, at right angles to the flow, and S is the wing's planform area, slightly less than half its "wetted" surface. For a flying craft, L = W, the craft's weight.

Both lift and C_L are directly proportional to the wing's angle of attack. The drag has frictional and pressure components, as with a hull, but its characteristic component is the induced drag, the drag due to lift. For a wing of elliptical planform (the most efficient planform), the drag coefficient is[3]:

$$C_D = c_d + \frac{C_L^2}{A} \tag{16}$$

where c_d is the coefficient of the hull-like drags and A is the aspect ratio, defined as b^2/S, where b is the wingspan. Using (14), (15) and (16), it is possible to write as expression for D/W while flying:

$$\frac{D}{W} = \frac{D}{L} = \frac{C_D}{C_L} = \frac{c_d + \frac{C_L^2}{A}}{C_L} \tag{17}$$

Bearing in mind that C_L is determined by the wing section, angle of attack and A, all geometric properties of the wing or the flow past it, (17) has a remarkable property. Speed, size and weight all are absent. To this first-order approximation, flying may be done at any speed (and size) with equal efficiency. At craft design stage, more speed merely produces a smaller wing, leaving the product Sv^2 unchanged.

Proof that flying D/W is indeed approximately constant can be found in what has happened to commercial aircraft since World War II. As soon as suitable engines became available, their speeds tripled. The cost of this advance was low in drag and fuel consumption. In fact, the new jet airlines showed better overall economy than their slower predecessors.

FLOATING COMPARED TO FLYING

The behaviors of D/W in floating and flying craft contrast strongly, the former varying as v^2/L, the latter scarcely changing over a wide speed range. From this it is clear that low speed and large size favor airships over airplanes. This section presents the results of some rough airship performance calculations compared to typical flying performance. One result is estimates of the speeds and weights at which both have the same drag, and would therefore burn about the same amounts of fuel.

For the airship hull, DTMB Model number 4165 was used. This is the best member of Series 58, a related group of bodies of revolution that were tested underwater at what is now the Naval Ship Research and Development Center, Carderock, Md. Its ratio of length to diameter is 7.0 and its prismatic coefficient 0.60. It looks suitable as an airship hull, and tests[4] indicated its residuary resistance coefficient (pressure drag coefficient) to be 0.00037, based on wetted surface and using the Schoenherr friction line.

Experience with past airships[5] indicates that a generous allowance should be made for the drag of control surfaces and other protrusions, which often had drag comparable to that of the bare hull. In the calculations presented here, residuary resistance coefficient is taken as 0.0004, and the allowance for non-hull drags as 0.0016, for a total non-frictional drag coefficient of 0.0020, based on wetted surface. For comparison, the friction drag coefficients ranged from 0.0019 to 0.0013, and were taken from the Schoenherr line[2]. This makes the sum of the non-frictional drags greater than the frictional drag at all speeds. It is intended to represent an airship performance level that can be achieved easily.

Calculations were made at displacements of from 200 to 2000 tons in sea-level air and at speeds to 200 knots. The dimensions of the different-sized airship hulls are given in Table 1, while D/W is plotted vs. speed in knots on Figure 1.

Table 1.

Dimensions of Geosim Airships

Displacement, Long Tons	Length, Feet	Diameter, Feet
200	847	121
500	1149	164
1000	1449	207
1500	1658	237
2000	1825	261

For comparison to the airship results, figure 1 also shows two levels of flying performance, lines of constant D/W at 0.05 and 0.10. The former represents very good flying performance, well above average for flying generally but closer to a par performance for an airplane that might compete with airships. Many sailplanes can do better, reaching D/W's in the neighborhood of 0.03, but a great majority of powered aircraft operate above the 0.05 line.

The other line, at D/W = 0.1, is closer to typical performance for airplanes generally, but most planing hulls and many hydrofoils have higher D/W than this. Taken together, these two lines bracket most of the flying competition for airships.

The speeds below which airships consume less energy than nearly all airplanes can be read directly from figure 1, ranging from about 90 knots at airship displacement 200 tons to 135 knots at 2000 tons. Airship speeds at D/W = 0.1 range from 125 knots at 200 tons to just over 180 knots at 2000 tons. Higher speeds than these are unlikely to make sense, unless justified by special conditions.

At the intermediate speeds, for instance 90 to 125 knots at 200 tons or 135 to 180 knots at 2000 tons, airships will have flying competition. The flying competition will probably operate at higher speeds, because, once enough drag is incurred to make flying possible, increase of speed is relatively cheap. An airship, on the other hand, always has the choice of operating more slowly, thereby achieving greater economy and longer range. Many water ships are doing this right now, the practice having become widespread about a year ago, when ship fuel first became scarce, then tripled in price. This feature of floating craft has both commercial and military survival value, and no flying machine can do likewise.

To conclude, figure 1 suggests the speculation that, within a generation or so, air transportation will have come to resemble the existing marine system. The heavy hauling will be done by large, floating ships, while most passengers and some freight of high intrinsic or time value will still fly.

Figure 2 is provided for direct comparison of airships to craft for which readers may have data, being a plot of effective horsepower vs. speed in knots for the five displacements tried. Those displacements were, as it happens, chosen with our co-host the Navy in mind. Several hydrofoil and military planing-hull craft have displacements in the neighborhood of 200 tons, while 2000 tons matches both pre-World War II destroyers and the prototype Surface Effect Ships (SES's) now in development.

Those destroyers made about 36 knots on 70,000 shaft horsepower. Their effective horsepowers must therefore have been around 40,000, possibly higher. Had they been airships, that much effective horsepower would have been good for about 100 knots.

Winged airships have been proposed, which partly float and partly fly. A major motive behind these proposals is apparently to replace the balky buoyancy controls of past airships with something more accurate and faster-acting. This analysis shows, however, that such a mixed-lift craft will incur a drag penalty.

Suppose, for instance that such a craft has a hull of 500 tons displacement and a wing that supports another 500 tons, and that it operates at about 105 knots, where according to figure 1 both hull and wing have D/W of 0.05. As also shown by figure 1, the same lift and speed could be achieved by a 1000-ton pure airship at D/W of about 0.04, burning 20 percent less fuel.

This is not to say that mixed lift is wrong, because the problems it could solve are substantial. However, the cost in added drag inclines the author to think that dynamic lift for airships should be used in moderation, much as it is in submarines. If only enough is provided to give the buoyancy controls time to respond to emergencies, then safety will be enhanced at small cost in fuel.

CONCLUSIONS

To recapitulate, the foregoing investigation suggests the following conclusions:

Airships should be large, but not too fast.

Bigger is better, just as with ships. Large airships can have an operating speed which is, at the same time, high enough to stem head winds and avoid storms, and low enough to make them more economical to operate than airplanes. For displacements under 2000 tons, this analysis suggests 80 to 120 knots as about the right speed range. The upper limit could be increased a few tens of knots by careful design.

For small airships, the demands of safety and economy conflict. If made fast enough for all-weather operation, they become non-competitive with airplanes through higher fuel consumption.

Airships may become competitive with the faster types of ships.

Compared to such ships, airships appear to offer the possibility of more speed without more fuel consumption, while carrying the same payloads for the same distances.

Wings on airships cause added drag.

Small wings may well be worth having as fast-acting backstops for the buoyancy control systems, but large wings are suspect. Wings improve airship drag-weight only at speeds so high that pure flying would be better yet.

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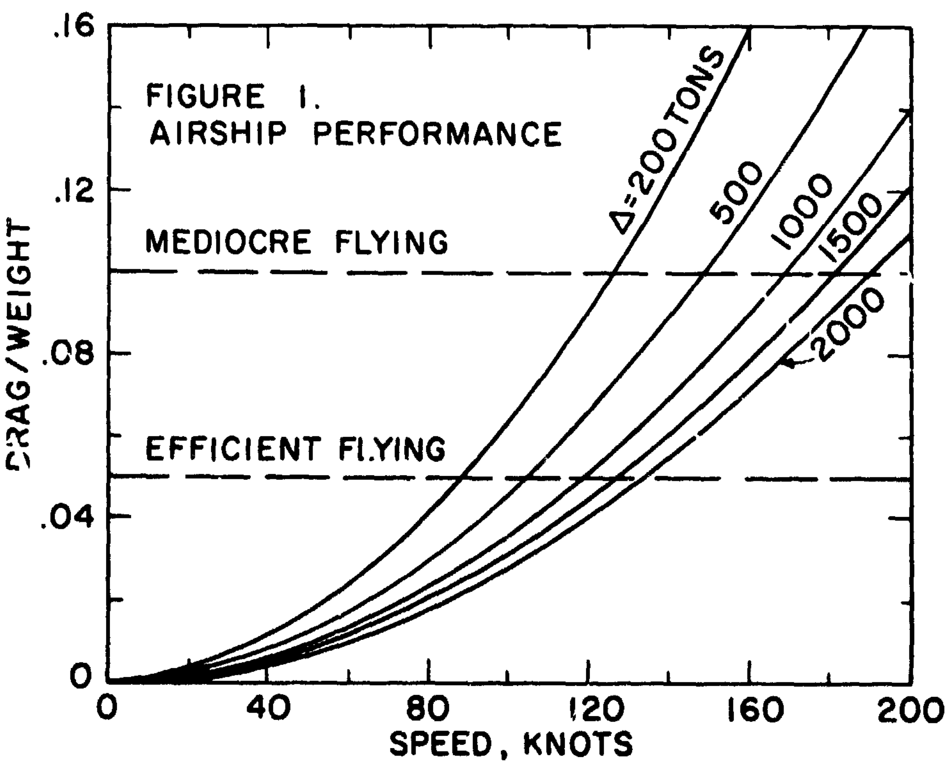

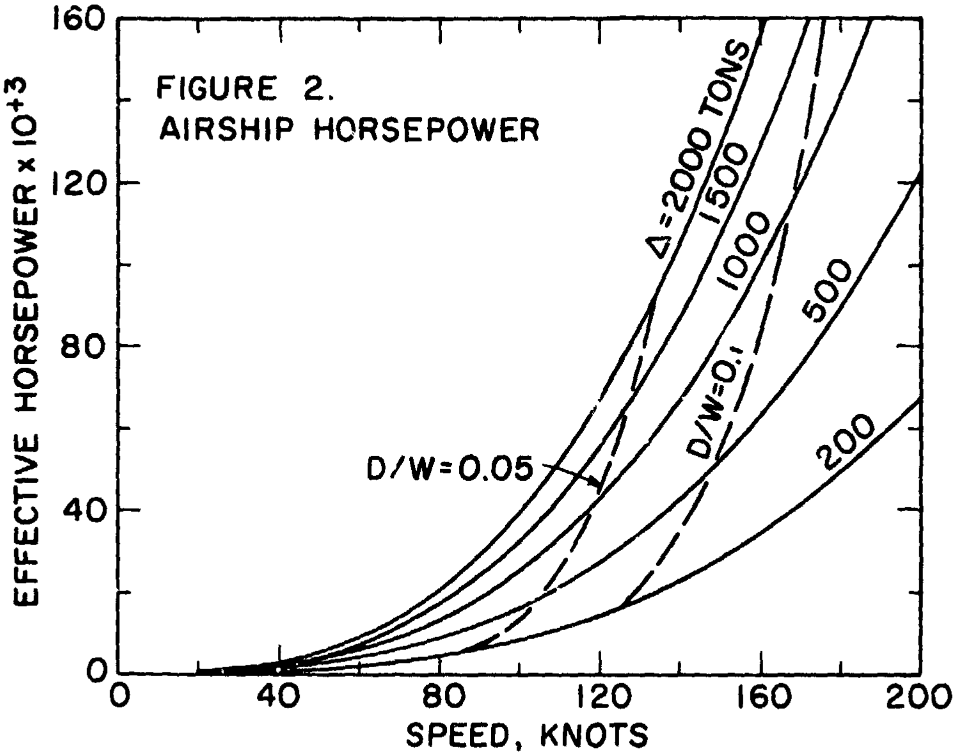
FIGURE 2.
AIRSHIP HORSEPOWER
EFFECTIVE HORSEPOWER x 10+3
SPEED, KNOTS
Δ=2000 TONS
1500
1000
500
200
D/W=0.1
D/W=0.05
0
40
80
120
160
200