A Rigid Airship Concept for Future Naval Operations

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A parametric and conceptual design study of advanced airships has been conducted for the U.S. Navy. A point design airship meeting requirements for eight days endurance at a radius of 2950 km and an altitude of 3050 m weighs 188 metric tons and is 239 m long. The airship employs a gas-tight outer envelope with interior ballonets and both stern and side propellers. All airship control, maneuvering, and subsystem functions are automated, and all subsystems are accessible in flight for inspection and maintenance. Using side propellers, the airship can land, moor, and launch without external aid.

Introduction

THE U.S. Navy is one of the few organizations in the world with extensive experience in the operation and maintenance of airships. Thus, it is natural that they should consider whether the airship has a place in the Navy of the future, and what that place should be. As part of an ongoing study of advanced concepts for naval air vehicles in the 1990-2000 time period, the Navy contracted with Martin Marietta to perform a parametric and conceptual design study of fully buoyant airships for projected Navy operations and employing advanced technology appropriate to that time period. This paper describes the conceptual design that was evolved in the study. However, this does not mean that the Navy necessarily endorses the opinions, conclusions, or recommendations expressed herein (see Acknowledgment).

To the surface Navy, the airship is literally a ship in the sky, combining many of the attributes of a displacement ship with the extended visual and radar horizon of air vehicles. Some of the advantages of the airship over other air vehicles are 1) long endurance (ability to "hang" on station for days and weeks); 2) high efficiency (very low power to weight required); 3) extremely low vibration, noise, and acceleration levels; 4) speed range from hover to 40-50 m/s, and transfer of cargo on deck while hovering; 5) large load and space capability; and 6) in-flight maintenance and repair of equipment.

These features precisely fit the Navy's requirement to patrol and monitor large ocean areas at long distance from our continental base, and the Martin Marietta Model 836 is primarily an ocean surveillance and patrol vehicle with secondary applications as a fleet escort or logistic support vehicle. Consideration of a matrix of surveillance operations led the Navy to specify the generalized performance profile shown in Fig. 1.

In addition to the 34 metric tons of deployable weapons and sensors, 14 metric tons of onboard radar, other sensors, communications, and data-processing equipment are carried. Two man-years of engineering analysis of aerodynamics, loads, structure, propulsion, subsystems, and performance produced the design illustrated in Fig. 2. This rigid airship is 239 m long and 50 m in diameter, displacing 263,900 m^3 and weighing 188 metric tons, of which 106 metric tons is useful load. All weights include a 10% allowance for the usual growth between conceptual layout and final fabrication.

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This airship incorporates a number of unique features, most noticeably a large flat area forming its lower surface, both bow and stern control surfaces incorporating gas turbine engines, and a pivoted stern propeller. Interior features include a gas-tight outer envelope with a ballonet system for buoyancy control, a pressurized shirtsleeve crew compartment, fully automated fly-by-wire control, and automated remote monitoring of most of the airship subsystems. Each of these features is discussed in more detail in the next section.

Airship Design Features

The primary function of the flat bottom is to improve operations on and near the ground. A rigid airship is like an eggshell: incredibly strong against distributed loads, but easily damaged by local loads. This characteristic, combined with the relatively high apparent inertia of the airship, has in the past made approach and landing one of the most critical maneuvers of the operation, with the airship descending very slowly and at near-neutral buoyancy. With the flat bottom, the descending airship must force a large mass of air outward, and the momentum thus generated results in a resisting force proportional to the square of the descent rate and inversely proportional to the distance from the ground. For the Model 836 airship descending at a nominal rate of 2 m/s, the resisting force is 35,000 N at 4 m height, 70,000 N at 2 m, and nearly 300,000 N at ½ m. For comparison, the maximum static thrust of the four maneuvering engines is 167,000 N. On flat ground, the flat-bottomed airship is therefore self-protected against inadvertent ground impact.

Once on the ground, the flat bottom allows a four-point landing gear that is resistant to rolling moments as well as

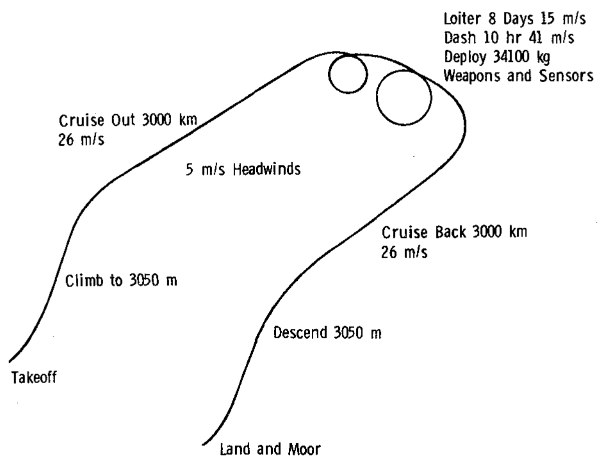

Fig. 1 Flight profile for barrier operation.

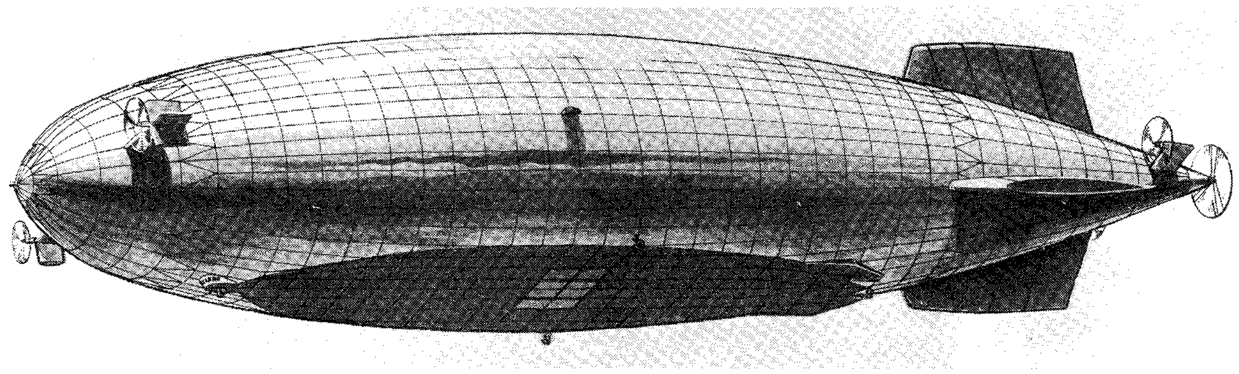

Fig. 2 Model 836 airship conceptual design.

pitching moments, so that the airship can be moored to a ground point in side winds up to 9 m/s without exceeding design landing gear loads due to the wind-induced rolling moment.

Compared to the full body of revolution, the flat bottom reduces the airship height by about 3 m and subtracts about 2½% from its volume, with a slight reduction in wetted area. The aerodynamic effect of the flat bottom is considered to be negligible, although appropriate wind-tunnel tests are required to verify this. The structural penalty is also small, since there are no large inertia loads on the flat bottom except for a short cargo deck, and since the lifting gas pressure is isobaric in horizontal planes. Structural loads are due primarily to external wind and gust loads and are resisted by deep truss beams extending across the flat span. These deep truss beams add the equivalent of 2.2 circumferential rings to the structure, increasing its weight by about 540 kg, or 1.3% of the hull weight.

The three large tail fins and the forward and aft horizontal pylon surfaces afford three independent pitch controls and two independent yaw controls; a third yaw control is afforded by the pivoted stern propeller system. These features permit the airship to be flown at positive or negative dynamic lift without changing the pitch attitude, improve control by permitting both direct-lift and direct-side-force control modes, and provide an unparalleled degree of reliability through redundancy. In severe weather, the independent fore and aft surfaces can be used to reduce the hull bending moments due to gust loads, and the forward rudders not only increase the rate of entry into a turn but also reduce the steady turning radius to less than 2½ airship lengths.

At normal airspeeds, the fins and pylons enable the airship to be controlled by aerodynamic forces alone. At lower speeds and for hovering, gas turbine engines with fully reversible propellers are mounted on the rotatable horizontal pylons, and the stern propeller is pivoted on a vertical axis, thus affording vectored-thrust control. For pitch, translation, and vertical motion, the pylons are pivoted ± 60 deg (limited by the engine lubrication systems); for yaw and lateral motion control, the forward rudders act as slipstream deflectors, and the stern propeller is pivoted ± 60 deg; engine thrust on all engines is controlled by changing the propeller pitch. The computerized command system compensates and purifies such mode interactions as the change in descent acceleration due to a pitch change command.

Although the destabilizing effect of the forward pylons is not quite compensated by the aft pylons and there are no vertical surfaces on the aft pylons corresponding to those on the forward pylons, the improved controllability afforded by the bow controls should permit satisfactory operation with less stability than classically required. The aerodynamic penalty due to the bow controls is therefore small, especially since the four pylons double as engine pylons. This double function also negates a structure or drag penalty due to the bow surfaces except the provisions for rotation.

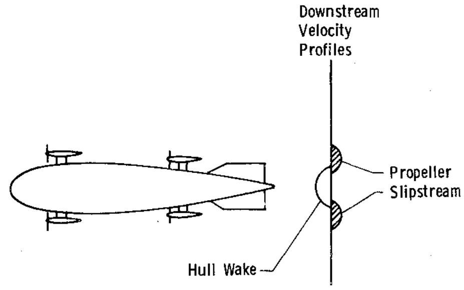

Fig. 3 Airship wake with traditional propulsion.

Gas turbine engines, driving large-diameter reversible propellers, are mounted on each of the four horizontal pylons. An exhaust water condenser is also incorporated in each pylon. The gas turbines are used for control and lift during takeoff and landing but are sized to produce the power required for the high-speed dash condition of 41 m/s at 3050 m alt. During cruise and loiter, these engines are normally off, and their propellers are feathered. The rotatable pylons function as thrust vector controls during hovering; thus, both thrust direction and magnitude can be controlled at five points on the airship without requiring articulated or cyclic pitch rotors. (The fifth point is the stern propeller.)

The advantages of a stern-mounted propeller for an airship are generally accepted by now, although not as well documented as might be desired. However, the reasons for this are easy to see, as follows. In the traditional arrangement (Fig. 3), velocity is imparted to the airstream by side-mounted propellers, and the reaction of the airstream against the blades is the thrust. As sketched on the right, the area under the velocity increase curve exactly balances the area under the velocity decrease caused by friction and flow separation along the airship hull. The ship is in equilibrium and moves forward at constant speed. However, although the average velocity change in the wake is zero, a good deal of excess energy has been left behind, and the work represented by this energy is lost. By increasing the amount of air worked on (more propeller diameter or more propellers not in tandem), the energy loss can be reduced, but it can never by reduced to less than the energy decrement left in the wake.

Now consider a bow propeller, designed so that it imparts a velocity increase distributed exactly like the velocity decrease due to the wake. As sketched on the right in Fig. 4, the velocity increments left in the wake can be made very small. However, the propeller cannot be credited with the energy subtracted from its wake by the hull. As far as the propeller is concerned, the energy that it added to the air is gone. Moreover, because of the increased velocity in the slipstream as it passes along the hull, the friction losses are increased so that the bow propeller must produce more thrust than required of the side-mounted propellers.

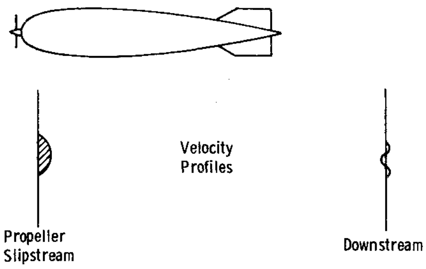

Fig. 4 Airship wake with bow propeller.

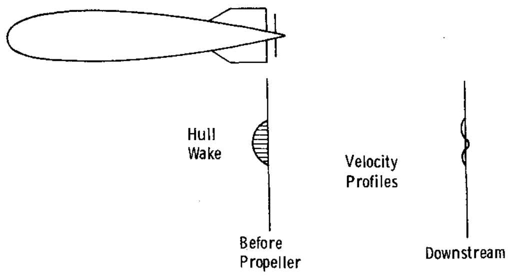

Fig. 5 Airship wake with stern propeller.

A stern propeller, however, sees not the free airstream but rather the wake of the hull with all its velocity decrements, and for steady motion it must simply add those lost velocities to the wake so that, as shown in Fig. 5, the final wake shows only minor residual disturbances. Therefore, the energy left in the wake is small, and the efficiency of propulsion approaches 100%. If the stern propeller does not make up all the lost velocity in the wake but is assisted by side-mounted propellers as in the Model 836, that propeller will operate at more than 100% efficiency. However, the overall propulsion efficiency will still be less than 100% due to the wake energy lost by the side propellers.

The Model 836 airship does not use stern propulsion exclusively, for several reasons. First, it is required to be capable of precision hovering under conditions of excess or deficient buoyancy, as well as during static equilibrium. This dictates a quadrilateral platform of vertical thrust control. Second, for the small fraction of the mission time when high thrust is required, lightweight engines of relatively high fuel consumption are preferable to the heavier but more fuel-efficient engines desired for cruise and loiter. This dictates a mix of propulsion engines rather than a single type. Finally, if the propulsion engines were to be concentrated at the stern, where only a small volume is available for lift, a large static bending moment would be produced in the hull, requiring increased structural weight and penalizing the useful load of the airship.

The airship structure is a fairly conventional arrangement of wire-braced transverse frames, longitudinal girders, and diagonal shear wires enclosed in a fabric envelope. For the relatively low design speed, this structure is lighter than any other unpressurized approach that was considered, amounting to only 20% of the total airship weight. The lift system, however, is unconventional in that it is a system of ballonets rather than separate gas cells. Each of the 11 lens-shaped ballonets illustrated in Fig. 6 encloses a main frame and is sealed against the outer cover. This system divides the airship into 14 compartments, 12 containing the airship's helium, and the fore and aft end compartments containing airship and payload equipment. This arrangement not only eliminates the weight of support netting for gas cells but also increases the maximum volume of each cell, improves heat transfer to maintain aerostatic equilibrium with the atmosphere and, perhaps most important, immerses most of the aluminum structure in inert helium that is largely free of the corrosive influence of the ocean atmosphere, prolonging the life and reducing the maintenance required for the structure. The ballonet system expands to 28% of the lift volume, giving the airship a theoretical pressure height of 3140 m (10,300 ft).

The several sets of independent aerodynamic surfaces and thrust-vectoring propellers lend themselves to a fully automated fly-by-wire system. This system not only maintains the airship on its programmed heading, altitude, and attitude but also computes and displays the static buoyancy and balance; climbs, descends, or turns at commanded rates; and maintains headings and attitude automatically during hover and VTOL operations. Ballast deployment is computer-controlled so that moment balance is maintained automatically. In the hover mode, where the aerodynamic surfaces are ineffective, the fly-by-wire system controls the five propellers to accomplish the commanded movements that

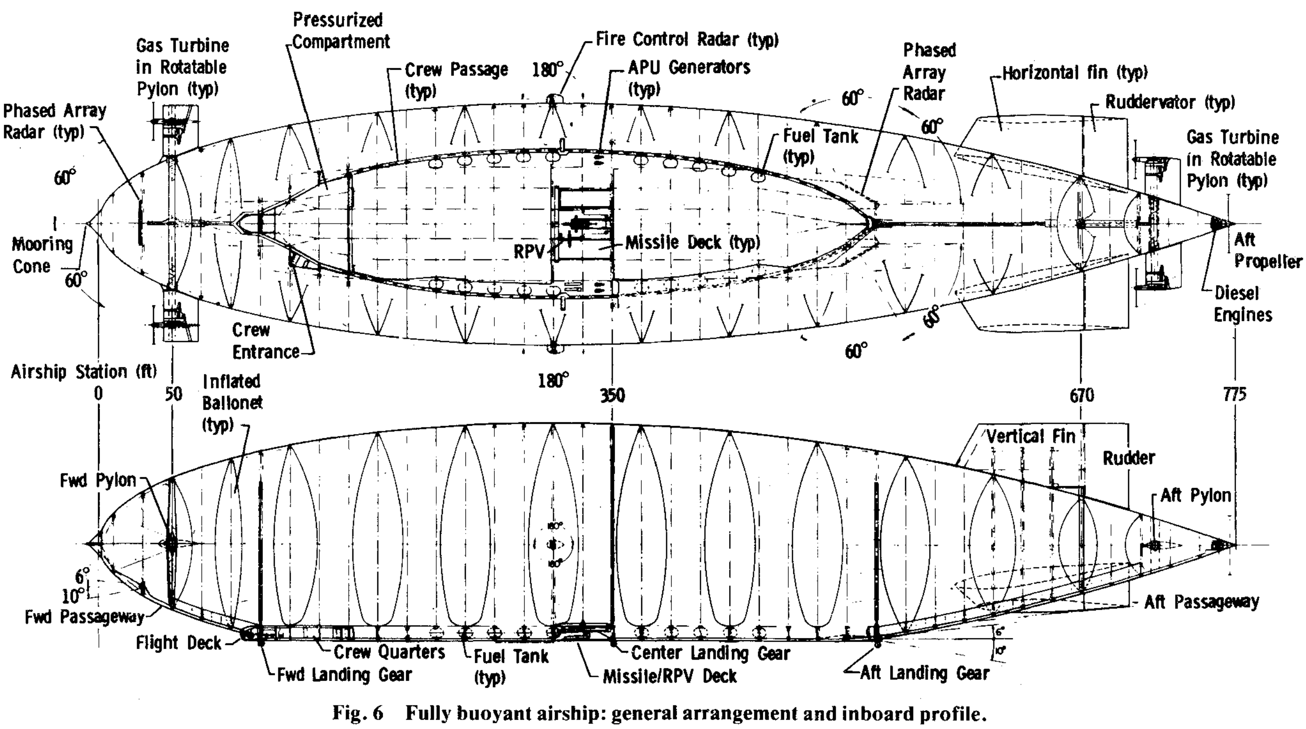

Fig. 6 Fully buoyant airship: general arrangement and inboard profile.

are controlled from the same flight console as in normal flight. Landing and mooring are accomplished by landing downwind from the mast in VTOL mode, holding the airship at negative lift by thrust vectoring, and taxiing to the mast with the traction motors built into the landing gear. The operation is conducted from the flight console and monitored via remote TV located under the mooring cone.

The automatic control system removes the need for a continuously manned helm, frees the commander from the complex task of maintaining ship's balance during critical operations, and greatly reduces the number of crew required. Normally, one man can fly the airship completely unaided and without continuously attending the controls. Landing and takeoff can be accomplished without a ground party in winds up to at least 10 m/s. The electrical control system also eliminates the many cables, sheaves, and tensioners formerly used in the large airships, representing not only a weight saving but also a reduction in inspection and maintenance requirements. Naturally, all control system components and sensors include miltiple redundancy as well as in-flight access for maintenance and replacement of failed components.

Finally, automatic remote monitoring is also used for subsystem operation and maintenance. Remote sensors monitor and transmit data on engine operation, structural integrity, helium quality and condition, fuel, ballast, electrical system, cabin air, etc., to a central computer. These data are stored and displayed on command at the flight engineer's console. Normally, each subsystem is identified by a green light indicating satisfactory or normal operation; malfunctions are indicated by warning lights and CRT displays. The flight engineer then traces the trouble by calling appropriate data from the computer and selects alternate systems or modes of operation until the malfunction can be corrected.

Of the 188 metric tons gross weight, 61 tons are structure, 33 tons are subsystems and equipment (including military radars, computers, and other built-in sensors), and 12 tons are crew, spares, and initial emergency ballast for an operating empty weight of 106 metric tons. Of the 82 metric tons disposable load, 48 tons are fuel, reserves, and rations, leaving a disposable military payload of 34 metric tons.

The stern propeller requires 932 metric hp at 26 m/s cruise speed, and the four side-mounted gas turbines develop 4280 metric hp (sea level) to give the airship a dash speed of 41 m/s at 3050 m alt. Auxiliary power is provided by four independent motor-generator sets, of which any three can provide the maximum requirement of 225 kVA with a 30% excess capacity. The flight crew of nine and the military payload crew of 26 are housed in a pressurized, shirtsleeve compartment at the forward end of the flat lower surface. Off-duty facilities include individual sleeping quarters, messroom, and lounge.

Airship Performance

Flying the profile shown previously in Fig. 1, the airship takes off at sea level, climbs to its cruise altitude of 3050 m, and cruises at 26 m/s to its patrol station 3000 km distant. It loiters on station for eight days at 15 m/s, periodically accelerates to 41 m/s dash speed for a total of 10 h, and intermittently discharges a total of 34 metric tons of weapons and disposable sensors. The airship then returns to its base, cruising at 26 m/s, descends to sea level, and lands. A continuous headwind of 5 m/s is assumed, and fuel reserves of 5% plus 20 min at cruise speed are provided, as well as the fuel required for 225 kVA continuous power, and rations (including potable water) of 3.4 kg per man per 24-h day.

The gross volume required to accomplish this operation is 263,900 m^3, of which 255,100 m^3 are available for lift. Assuming 95% pure helium, this gives the airship 100% buoyancy at its gross weight of 188 metric tons at its pressure height of 3140 m, which is 90 m above the design operating altitude of 3050 m. In its military configuration, the disposable load of 82 metric tons at this altitude can be increased by adding more helium and thereby decreasing the maximum operating altitude, as shown in Fig. 7. In this way, the disposable load can be increased to more than 120 metric tons at a maximum operating altitude of 1200 m. For operation above the design altitude, as might be required for long-range military observations, either the airship must valve helium and later allow the helium to be contaminated with air when it descends below the height for full ballonet inflation, or auxiliary ballonets must be installed.

The propulsion system is capable of driving the airship to its maximum speed at any altitude. However, the hull is designed for an equivalent airspeed of only 35.4 m/s (69 knots). Below 3050 m alt, the speed is structurally limited and should be exceeded only if there is virtually no chance of encountering a gust that would impose severe loads on the hull.

High speeds are detrimental to the airship's range and endurance, as shown in Fig. 8, which shows the conversion of payload to range at several airspeeds. At slow speeds, appreciable payload can be carried to any spot on the globe (20,000 km range), even at the relatively high altitude of 3050 m. Conversely, at dash speed the range is extremely limited for any payload at all.

In determining these results, 12 metric tons of fuel used by the auxiliary power system to power the onboard military equipment is regarded as payload. However, the fuel required to provide the approximately 69 kVA of onboard power for the airship controls, environmental control, lighting, communications, and other ship's functions is included with the propulsion fuel.

Because a portion of the fuel is used at a constant rate, there is a speed at which the range will be a maximum. This is

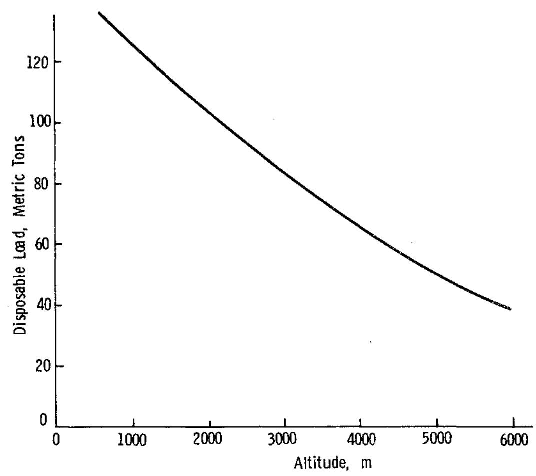

Fig. 7 Airship disposable load at operating altitude.

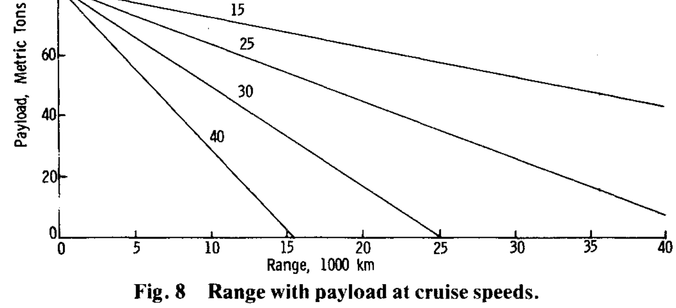

Fig. 8 Range with payload at cruise speeds.

apparent from the equation for the range at constant speed, which is

$$R = W_F V / (C + KV^3) \quad (1)$$

where W_F is the fuel weight; C is the rate of expenditure of auxiliary fuel, rations, and other consumables; and KV^3 is the rate of expenditure of propulsive fuel. (Because the airship has no aerodynamic lift, its power required for propulsion is proportional only to the speed cubed.) Then the range maximizes at the condition

$$KV^3 = C/2 \quad (2)$$

The fuel consumed for propulsion is therefore one-third of the total fuel and supplies consumed.

When the airship must cruise against a headwind, the range expression becomes

$$R = W_F (V - V_W) / (C + KV^3) \quad (3)$$

where V_W is the headwind. For this expression, the range maximizes under the condition

$$(C + KV^3) - 3KV^2 (V - V_W) = 0 \quad (4)$$

The first term is the total fuel consumption, and the second term is that part of the fuel which moves the airship along its course. Note that this again is one-third of the total fuel and supplies used. Generally, then, for maximum range an airship should cruise at that airspeed where one-third of the fuel consumed is producing forward progress of the airship. If the optimum speed is so slow that adequate aerodynamic control is difficult, this is not usually practical, since only a few degrees of sideslip can increase the drag considerably. To the extent that fly-by-wire and feedback control system augmentation can improve the controllability, the optimim speed can be more nearly approached.

In loitering on station, precise control of heading and course are generally not required, and theoretically the airship could stop engines and drift with the wind for much of the time. For performance calculations, a continuous loiter speed of 15 m/s has been assumed.

One of the most appealing features of an airship is its ability to hover or, more precisely, to float without the expenditure of power. However, this is a condition of equilibrium whose delicacy is masked, but not eliminated, by the airship's inertia. Just as a man leaning against an ocean liner will eventually push it away from its dock, so will that man's weight eventually bring the airship to the ground if it is not compensated by buoyancy or dynamic lift. It is therefore no simple matter to transfer materials to or from a hovering airship or to cause it to hover in the first place. This problem is solved by providing 1) a vertical thrust system, 2) an automatic, stability-augmented control system, and 3) continuous monitoring and computation of the airship's static buoyancy. The key, however, is the variable vertical thrust system, which is used to compensate for changes in buoyancy, as well as wind disturbances, as soon as they occur and until ballast can be shifted, dropped, or accumulated to restore the ship to buoyant equilibrium. The automatic control system senses the motions and accelerations of the airship and commands compensating thrust from the engines, whereas the buoyancy monitoring system senses the weights of materials brought onboard or discharged and the thermodynamic equilibrium and purity of the lift gas, and furnishes data on the buoyancy and static balance of the airship to the control system.

In VTOL mode, the forward pylon is tilted 60 deg up, and the aft pylon is tilted 60 deg down with its propellers in reverse pitch, thus producing vertical lift at each end of the airship with opposing horizontal components, as shown in Fig. 9. To maneuver, the pitch of the propellers is changed to produce vertical forces and couples, and the pitch of the stern propeller is changed to neutralize the unbalanced horizontal thrust that results and, if necessary, to maintain headway against any wind. Heading is maintained or changed by controlling the forward rudders (acting as slipstream deflectors) and yawing the stern propeller as necessary. Unwanted interactions among the several thrust vectors are eliminated by the software of the flight control computer.

Figure 9 shows the use of the VTOL system in landing. The airship descends to some hundreds of feet above the ground and transitions to the hover (VTOL) mode. It then descends vertically to the landing area (downwind of the mooring point), engages the traction motors, and taxis to its mooring, which can be a ground point if winds are fairly light or a mooring mast if winds are expected to be stronger. If statically light or if cargo is to be discharged, a ground car is required to prevent the tail from rising. For maximum effectiveness of the flat bottom, a flat, obstruction-free landing surface is required; it need not be paved.

Another attractive feature of the airship is its efficiency as a low-speed transport, combined with no need for a prepared roadway or channel. Figure 10 compares the transport efficiency, defined as weight times velocity over power required, of the airship with other types of transportation. At comparable speeds, the airship is as much as twice as efficient as a large surface ship or a heavy truck, and just as efficient as a freight train. Among air vehicles, although the airship is superior to the helicopter and the light airplane, it is far inferior to the fast transport. It is apparent that, at speeds up to about 50 m/s, the power required by a buoyant hull is less than the power required to generate circulation lift, whereas at higher speeds the reverse is true.

A large, slow-moving airship would seem to be extremely vulnerable to attack. However, much of its bulk is empty

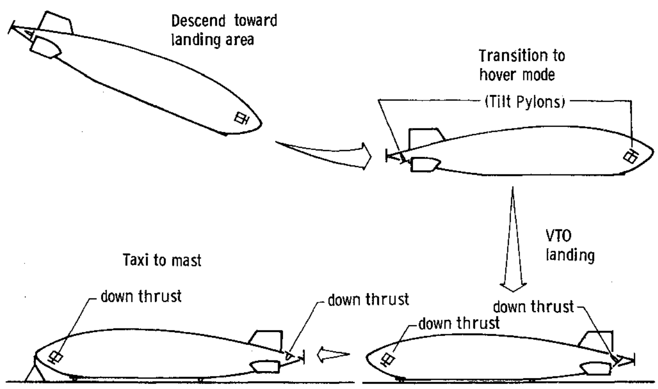

Fig. 9 Fully buoyant airship: approach and landing sequence.

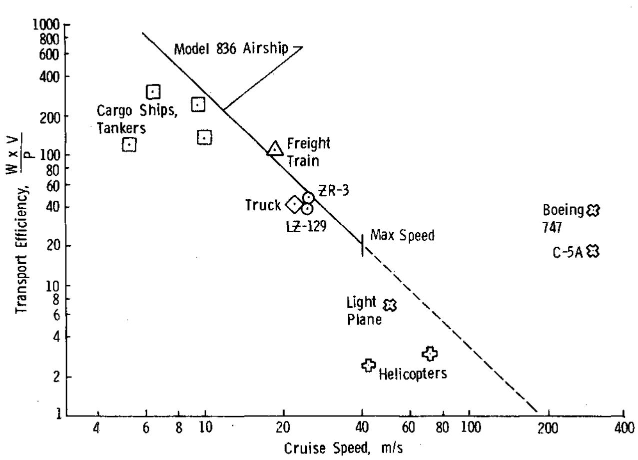

Fig. 10 Comparison of transport efficiencies.

space; an approaching missile sees, in effect, a large cloud of chaff, within which are vulnerable areas (cockpit, propulsion systems, armament, etc.) that aggregate those of a large airplane but are widely scattered. A single hit is, therefore, far from disabling and moreover can be repaired in flight. As regards the hull, an explosive warhead produces about 1 m^2 of shrapnel; if all of this shrapnel pierces the hull, the resulting helium leak averages about 800 kg of lift loss per hour. Total lift is not lost because the hull is divided into 14 lifting compartments. Finally, the airship is equipped with self-defense radar and missiles, as well as offensive weaponry. In short, the airship is comparable in size, detectability, and defensive measures to a surface ship and requires the same sort of air cover and defensive support, although its cost and crew requirements are much lower than those of a surface ship.

Conclusions

In conclusion, a Navy-sponsored conceptual design study of an advanced technology airship has shown that it is well-suited to long-range, long-endurance operations, and is a very efficient moderate-speed transport. Maximum structural efficiency is obtained with a conventional truss structure, using advance composite materials as tension components. With modern control and stability augmentation concepts, the airship can be operated by one or two men and without ground assistance under most conditions. An airship sized for a 12-day patrol operation at 3050 m alt weighs 188 metric tons, with 82 metric tons disposable load exclusive of crew and supplies. As a low-altitude cargo carrier, the same airship could circumnavigate the globe with a payload of 44 metric tons. With an assumed headwind of 5 m/s, such a journey would take 45 days.

Acknowledgment

The work reported in this paper is a highly condensed version of one section of a final report on work performed under contract to the Advanced Naval Vehicle Concepts Evaluation Project (OP-96V) monitored by the Air Vehicle Technology Department of the Naval Air Development Center, Warminster, Pa.