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AEROCRANE

A HYBRID LTA AIRCRAFT FOR AERIAL CRANE APPLICATIONS

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ABSTRACT: The Aerocrane, a hybrid aircraft, combines rotor lift with buoyant lift to offer VTOL load capability greatly in excess of helicopter technology while eliminating the airship problem of ballast transfer. In addition, the Aerocrane concept sharply reduces the mooring problem of airships and provides 360° vectorable thrust to supply a relatively large force component for control of gust loads. Designed for use in short range, ultra heavy lift missions, the Aerocrane operates in a performance envelope unsuitable for either helicopters or airships. This paper addresses basic design considerations and potential problem areas of the concept.

INTRODUCTION

The most serious deficiency in U.S. aircraft performance is the lack of a capability to pick-up, carry and implace large, bulky cargos. Present and projected VTOL aircraft offer very limited useful load capacities compared to fixed wing aircraft. Figure 1 illustrates this deficiency plotting aircraft useful load and speed envelope for conventional and VTOL aircraft. Conventional aircraft capabilities are bounded by C-5A performance - a useful load capacity of over 200 tons. Present VTOL capabilities are bounded by the CH-53E - a useful load capacity of only 18 tons. The Army's advanced Heavy Lift Helicopter (HLH) development program will double the present VTOL capability. This is a significant advance when compared to VTOL aircraft, but is insignificant when compared to present fixed wing aircraft.

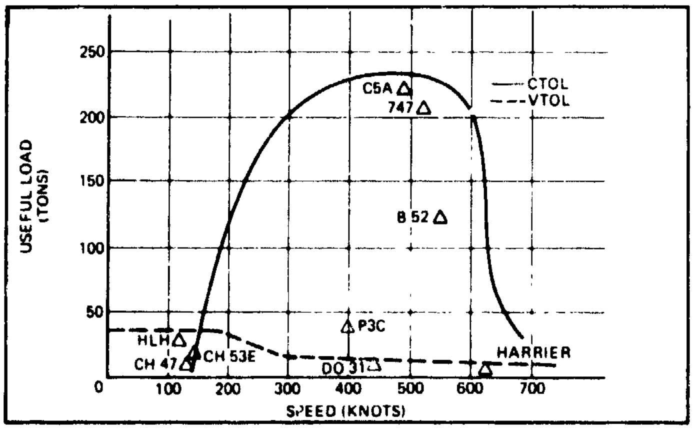

FIGURE 1. Aircraft Performance Spectrum

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This performance gap arises from the impact of the "square-cube law" as aircraft size increases, and the relative inability of helicopter technology advances to compensate for its effects. The helicopter presents a more difficult, constrained, design problem than the fixed wing aircraft. The "square-cube law" states that the aerodynamic lift of an airfoil increases as the square of a basic dimension while its structural weight increases as the cube of that same dimension. Thus, the aircraft structural weight becomes an increasingly larger fraction of total aircraft weight. The application of improved materials, better design techniques, higher wing loadings and gas turbine engines to fixed wing aircraft has been very successful in compensating for the "square-cube law". The helicopter designer, while scaling up power requirements for larger rotors, finds that his transmission design torque loadings have increased at a faster rate because of the reduced rotor RPM. The rotor blade characteristics which are satisfactory for a smaller helicopter are not satisfactory for larger helicopters since the governing aerodynamic, centripetal and inertial forces do not scale similarly. Finally, there is no speed/productivity increase with larger helicopters as the maximum forward speed is limited by a fundamental aerodynamic problem, retreating blade stall.

In spite of these design trends and limitations, the helicopter is the only aircraft providing a military and commercial capability as an aerial crane. Its notable performance for these applications has not produced a widespread market because of its (1) low gross lifting capacity, (2) high acquisition and operating costs and (3) low operational reliability. It does not appear to be technically or financially feasible to achieve a VTOL lifting capability commensurate with conventional aircraft by building larger and larger helicopters. Present helicopters are inherently expensive and hard to maintain for aerial crane applications. Some departure from state-of-the-art design practice is necessary to alleviate this cost problem. Any aerial crane should have as a minimum design goal the operational reliability of commercial fixed wing aircraft. Achieving this goal for conventional helicopters does not appear to be technically feasible in the foreseeable future.

The Aerocrane is a hybrid Lighter Than Air (LTA) aircraft composed of balloon and helicopter elements which conceptually addresses each of the enumerated helicopter deficiencies. (As with any new idea or concept, its reduction to practice may produce other, more substantial deficiencies as yet undisclosed.). The basic concept is to integrate the controllable thrust vector of a rotary wing system with the brute lifting capability of a heavy lift balloon to transcend projected useful load limits of practical helicopters. Applied to the Aerocrane design, aerostatic lift supports two-thirds of the aircraft design takeoff weight, i.e., the full structural weight and up to 50% of the design sling load, while aerodynamic lift only supports the remaining 50% of the sling load.

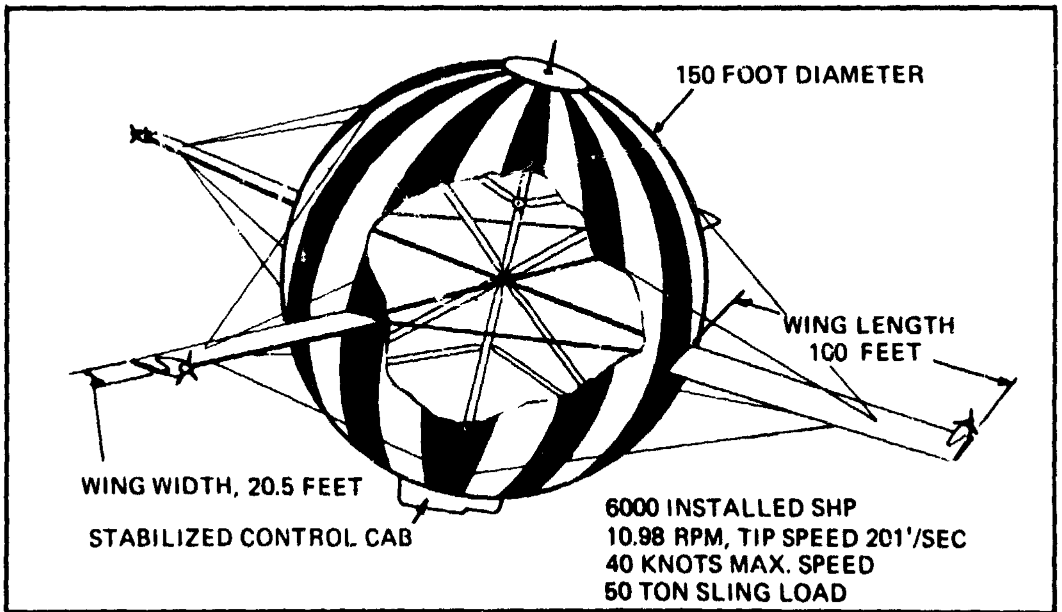

Figure 2. Aerocrane

AEROCRANE

The Aerocrane concept is characterized by wings attached to a large rotating central spheroid containing helium (Figure 2). Vectoring the aerodynamic thrust by collective and cyclic variation of wing angles of attack provides all propulsive and maneuvering forces in a manner directly analagous to a helicopter rotor system.

Since the Aerocrane wings are very lightly loaded (about 6.6 lbs/sq. ft. of wing area) and operate a low tip speeds (about 200 ft./sec.), centrifugal forces are not a significant factor in the structural support of the wings. These low forces allow tip propulsion eliminating the main transmission of a conventional helicopter. Because of the low tip speed, a braced wing structure may be used without a large power penalty, and the large centerbody provides space for a deep cabane section without an additional aerodynamic penalty. The internal cabane structure and wire bracing are arranged to support the wings in the vertical, axial and equatorial directions. This bracing system alleviates wing root in-plane and vertical bending moments. The central structure is principally composed of pin-ended compression and tension members. In addition to transferring loads between wings and sling load, the center structure provides focal points for transferring aerostatic lift.

Wing construction is anticipated to follow fixed wing rather than helicopter rotor design practice. Engines and propellers are mounted conventionally on the wing spar with additional structural support to resist centrifugal and gyroscopic forces. Fuel supply lines, hydraulic and electrical lines, control and instrumentation signals must pass from the wing into the center section thru a flexible joint.

The control cab and sling load are attached at the bottom of the centerbody and are isolated from rotation by low friction bearings and a retrograde drive system, either mechanical or aerodynamic.

Construction of the helium containing envelope follows the practice used by Goodyear for their blimps. A single gas containment envelope is used without partitions. A ballonet system to provide internal pressure adjustments for ambient changes is located in the lower portion of the centerbody. An emergency helium valve is also provided to assure against critical over-pressure and allow free balloon control, if necessary.

The control system governs collective and cyclic wing angle of attack variation and is the most sophisticated component of the Aerocrane. Hydraulic actuation of wing root, pitch horns is contemplated for setting collective pitch. Cyclic pitch will be controlled by aerodynamic flap adjustments near the wing tip. This dual wing angle of attack control system also allows for a torsionally flexible wing (if feasible) introducing an ideal wing twist distribution. An electronic or electromechanical equivalent of a helicopter swash plate system will be located in the control cab feeding control signals to the hydraulic actuators. Some form of automatic gust sensing and load relief may be required. Standard aircraft practice for control reliability will be used in the control system design.

Lift Distribution

The required distribution between aerodynamic and aerostatic lift is governed by two design conditions resulting from the Aerocrane's concept of flight. During loaded flight the wings generate positive thrust to supplement the aerostatic lift thus supporting the total aircraft weight. In the unloaded condition the wings provide a downward aerodynamic thrust to compensate for an excess of aerostatic lift. Dual modes of flight are possible because of the geometric symmetry inherent in the Aerocrane design. Assuming equivalent aerodynamic thrust requirements for loaded and unloaded flight, the following relationships apply.

$$\text{Loaded Condition: } W_F + W_P + W_E = L_B + L_W \qquad (1)$$

$$\text{Unloaded Conditions: } W_F + W_E = L_B - L_W \qquad (2)$$

where
W_F = Fuel weight
W_E = Aircraft operating weight empty
W_P = Payload weight
L_B = Aerostatic Lift
L_W = Net aerodynamic lift

Solving these expressions, we find that:

$$L_W = W_P/2 \text{ and} \tag{3}$$

$$L_B = W_F + W_E + W_P/2 \tag{4}$$

The net aerodynamic lift equals 50% of the design sling load weight. In addition, aerodynamic thrust must be provided for translation and control power demands. The aerostatic lift supports the entire aircraft operating weight, fuel and 50% of the design sling load. Estimates of aircraft structural weight for hypothetical Aerocrane designs indicate operating aircraft empty weight fractions between .31 and .34. For these values the aerostatic lift supports approximately 67% of aircraft takeoff gross weight and aerodynamic lift 33%. It is worthwhile to note that this hybrid aircraft allows a modulation in total lifting capacity of around 66% of design takeoff gross weight. This very substantial capability is achieved without requiring a large installed power or ballast transfer.

Wing or Rotor Characteristics

The aerodynamic performance of the Aerocrane follows directly from the selection of rotor parameters. These characteristics are projected for a hypothetical 55-ton useful load Aerocrane (50-ton sling load and 5 tons of fuel).

Disk loading, DL = .688
Solidity, σ = .149
Maximum design tip speed, VT = 200 ft./sec.
Blade loading, BL = 6.59
Balloon radius ratio, χ_1 = .43

The first and most significant parameter is disk loading. By examining disk loading of any actuator disk such as a rotor, one can immediately determine its ideal lifting efficiency - i.e. pounds of thrust per unit of power required. From classical momentum theory, the following expression relates lift efficiency to disk loading for a free rotor.

$$\frac{T}{RHP} = \frac{550}{\sqrt{\frac{DL}{2\rho}}} \tag{5}$$

where

T = Rotor thrust
RHP = Rotor power required
ρ = Ambient air density
DL = Disk loading, thrust per unit disk area

Comparing an Aerocrane with a disk loading of .7 to a large helicopter with a disk loading of 10, we see that the Aerocrane can ideally produce 45.3 lbs. of thrust per rotor horsepower compared to 12 lbs./rhp for the helicopter. Large helicopter rotors are designed to less efficient, higher disk loadings because of several design considerations and constraints not applicable to Aerocranes. As helicopter disk loading decreases for a constant tip speed, transmission weight, rotor blade weight and rotor profile drag all increase substantially. Practical design considerations such as sufficient rotor kinetic energy for entry into autorotation, coning angle constraints and further transmission weight growth place a lower limit on helicopter tip speeds. The Aerocrane, on the other hand, with no main transmission and externally braced wings achieves good rotor performance at its low disk loadings only because of a concurrent reduction in rotor tip speeds. Thus, a high blade mean lift coefficient is maintained, and profile drag is only a small fraction of the induced drag.

The interplay among Aerocrane rotor design variables is best examined by developing an expression for the Aerocrane rotor figure of merit, M, analogous to a conventional rotor figure of merit. This is easily accomplished following the conventional rotor analysis contained in reference (1). Using conventional blade element theory and assuming an ideally twisted rotor, a uniform induced rotor velocity, v, hover flight, a constant blade profile drag coefficient and no blade taper; an expression for rotor blade element thrust may be derived. Integrating that expression over each blade from balloon surface to blade tip results in the following equation for rotor thrust.

$$T = \tfrac{1}{4}\rho\Omega^2 R^2 a\left[\theta_T - \frac{v}{\Omega R}\right] bcR(1 - \chi_1^2) \tag{6}$$

where

Ω = Rotor rotational velocity

R = Total rotor radius

a = Rotor blade lift curve slope

θ_T = Blade tip angle of attack

v = Induced inflow velocity across a blade element

b = Number of blades

c = Blade chord

χ_1 = Balloon radius r_B divided by R

ρ = Ambient air density

Defining the rotor thrust coefficient, C_T, in the conventional fashion based upon an annulus of a disk,

$$C_T = \frac{T}{\rho\pi R^2 (1 - \chi_1^2)\Omega^2 R^2} \tag{7}$$

and defining rotor solidity, σ, as the projected blade area (including balloon cutout) divided by the total disk area (including balloon cutout),

$$\sigma = \frac{bcR}{\pi R^2} \tag{8}$$

the classic expression for the thrust coefficient of a conventional rotor results.

$$C_T = \frac{\sigma}{4} a[\theta_T - \lambda] \tag{9}$$

where

$\lambda = \frac{v}{\Omega R}$ = rotor inflow ratio

others as defined previously

Similarly, an expression for rotor torque coefficient, C_Q, may be derived composed of induced power and profile power terms.

$$C_Q = \frac{Q}{\rho\pi R^2 (\Omega R)^2 R(1 - \chi_1^2)} \tag{10}$$

$$= \frac{\sigma}{8} C_{D_0}(1 + \chi_1^2) + \lambda C_T$$

where

C_{D_0} = Mean blade profile drag coefficient

others as defined previously

Now, assuming that momentum theory is valid for the Aerocrane rotor annulus,

$$T = 2\rho\pi R^2 (1 - \chi_1^2) v^2 \tag{11}$$

combining equations (7), (11) and the definition of rotor inflow ratio, λ leads to:

$$\lambda = \sqrt{\frac{C_T}{2}} \tag{12}$$

Thus,

$$C_Q = \frac{\sigma}{8} C_{D_0}(1 + \chi_1^2) + \frac{C_T^{3/2}}{\sqrt{2}} \tag{13}$$

To these conventional terms an allowance for the sphere's effects on rotor thrust and torque required must be added. The sphere may cause an increase in rotor power required to produce a given rotor thrust because of energy lost to frictional drag of the sphere acting on the airstream inflow velocity. On the other hand, the presence of the centerbody which eliminates conventional rotor recirculation at the center may exhibit a favorable pressure gradient across its surface adding to the rotor thrust. As the induced velocity is quite low for Aerocrane disk loadings and the centerbody radius unusually large compared to the rotor radius, it will be assumed that these two effects cancel. A second source of wasted power is the sphere frictional drag acting on the tangential velocity component at the sphere's surface in the plane of rotation. As the sphere skin speeds near its equator are considerably higher than the inflow velocities, this term may not be negligible. The torque required for this frictional drag may be derived by computing the elemental torque for an infinitesimal area on the surface of the sphere and integrating over the sphere's surface. This leads to:

$$Q = 1.178\rho(\Omega r_B)^2 \tau_s \pi r_B^3 \qquad (14)$$

where

τ_s = local sphere skin friction drag coefficient

r_B = Centerbody radius

Combining equation (14) with the definition for Aerocrane torque coefficient leads to an expression for the torque coefficient due to sphere drag.

$$C_{Qsf} = 1.178 \frac{x_1^5}{(1 - x_1^2)} \tau_s \qquad (15)$$

The Aerocrane's hover figure of merit, M, may be defined conventionally by dividing the induced rotor power required by the total power required, or in torque coefficient form,

$$M = \frac{\dfrac{C_T^{3/2}}{\sqrt{2}}}{\dfrac{C_T^{3/2}}{\sqrt{2}} + \dfrac{\sigma C_{D_0}}{8}(1 + x_1^2) + 1.178\dfrac{x_1^5}{(1 - x_1^2)} \tau_s} \qquad (16)$$

(Reference (2) presents an alternate development for the Aerocrane figure of merit based upon different assumptions about the centerbody's influence on the rotor.)

To examine the influence of tip speed selection, it is necessary to derive an expression for C_T in terms of σ and a blade mean lift coefficient, $\overline{C}_L$. By definition, $\overline{C}_L$ is defined from:

$$T = \overline{C_L}\int_{r_1}^{R} bc\tfrac{1}{2}\rho(\Omega r)^2\,dr \qquad (17)$$

Solving and substituting in equation (7) gives:

$$C_T \quad \frac{\overline{C_L}}{6}\sigma \frac{(1 + x_1 + x_1^2)}{(1 + x_1)} \qquad (18)$$

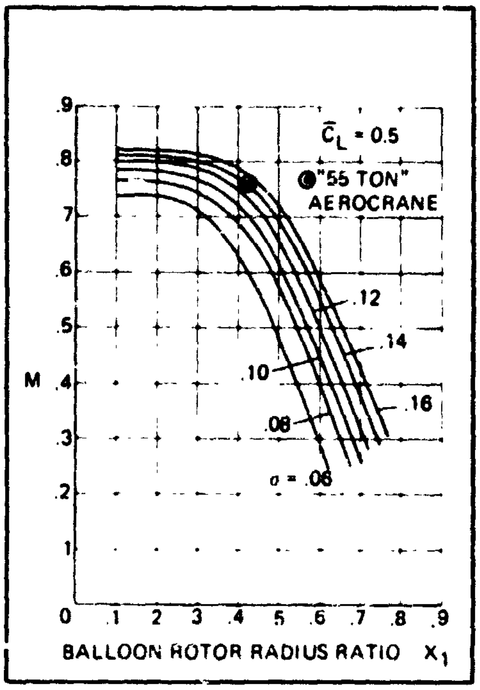

FIGURE 3.
M vs Balloon Rotor Radius Ratio

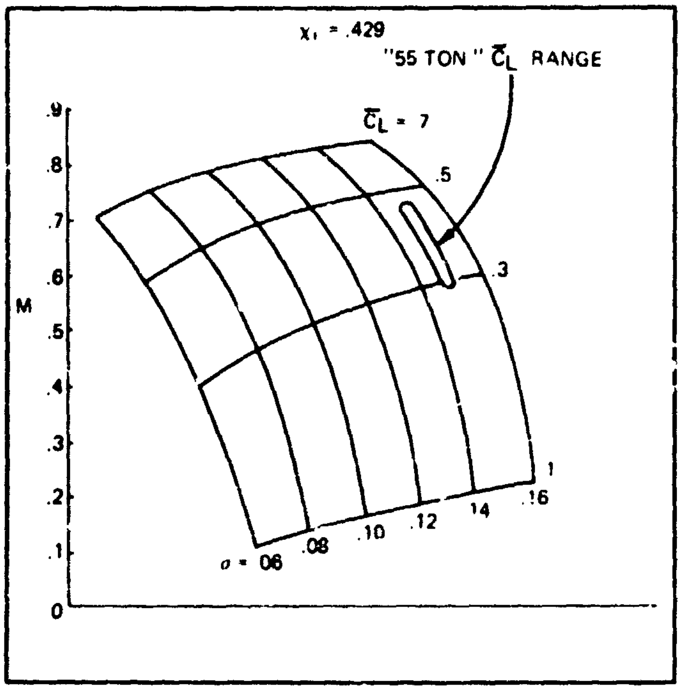

FIGURE 4. M vs Solidity and $\bar{C}_L$

Figure 3 plots M against balloon/rotor radius ratio for several values of rotor solidity for a constant $\bar{C}_L$. Rotor performance falls off drastically for values of χ_1 greater than .5.

Figure 4 is a carpet plot of M against rotor blade mean lift coefficient and solidity. Here we see the expected result that minimizing profile drag maximizes rotor efficiency. For a constant thrust, χ_1, and disk loading, higher lift coefficients combined with higher solidities produce higher figures of merit. This amounts to nothing more than maximizing rotor thrust coefficient by reducing tip speeds to maintain a constant thrust. Note that the Aerocrane may operate in hover over a substantial range of values for $\bar{C}_L$ by reducing rotor tip speed below the forward flight condition.

On each figure, the design point for a 55-ton useful load Aerocrane is indicated. Initially, the selection of Aerocrane solidity may seem unduly high compared to a helicopter rotor. Modern helicopter rotors will have solidities between .06 and .09. If the Aerocrane solidity is corrected for the inclusion of the balloon cutout, then:

$$\bar{\sigma} = \frac{\sigma}{(1 + \chi_1)} \qquad (19)$$

For a defined solidity of .149, an actual blade solidity (by conventional rotor definition) of .104 results. This value is still high for a rotor which operates at an advance ratio, μ, less than .35. A partial explanation is the impact of the relatively large balloon drag and substantial aerostatic lift on the relationship between forward thrust and vertical thrust requirements; and, thus, different solidity requirements for a given advance ratio.

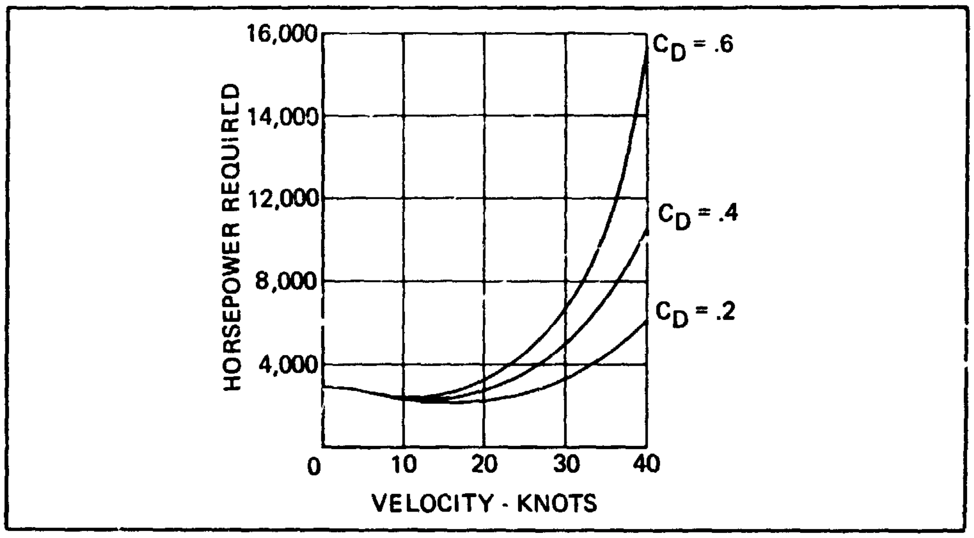

FIGURE 5. Installed Horsepower Required

Forward Flight Performance

The Aerocrane is, of course, an inherently low speed aircraft as its translational speed capabilities are constrained by the high drag of its balloon centerbody. Power requirements of a 55 ton useful load Aerocrane are shown in Figure 5 for hover and translational flight assuming several values for centerbody drag coefficient. Design conditions for this graph are discussed in a later section of this paper. It is clear from the graph that a substantial imbalance between hover power and translational power requirements exist [illegible] reasonable assumed values of sphere lift and drag at forward speeds greater than 35 knots. This power imbalance reduces as aircraft size increases because of "square-cube law" effects.

Aerocrane Blade Environment

Rotor blade design considerations and problems are substantially different from helicopter rotor design experience. Aerocrane wings (or blades) operate in a much more benign aerodynamic environment where achieving a critical balance between rapidly varying, large aerodynamic and centrifugal forces does not dominate the design problem. A first major difference is in rates of cyclic pitch change accommodated by the control system. Figure 6 shows an order of magnitude difference between rates of rotor rotation and cyclic pitch variation for equal capacity aircraft. A disk loading of 10 and blade tip speed of 750 ft./sec. were assumed for the helicopter.

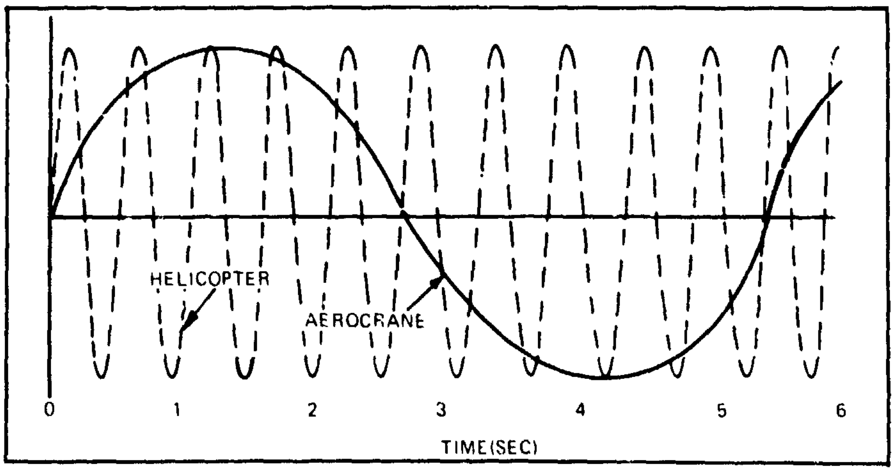

FIGURE 6. Cycles of Rotor Motion

A second major difference between helicopters and Aerocranes is in the magnitude and variation of the blade aerodynamic pressures seen by the respective blades. The tangential velocity component, V_T, seen by a blade section along the rotor is given by:

$$V_T = V_f \cos\alpha \sin\psi + \Omega r \qquad (20)$$

where
V_f = Forward flight speed
α = Angle of rotor plane inclination with respect to free stream velocity
ψ = Blade azimuth angle

Neglecting the effect of rotor tilt angle, the dynamic pressure, q, is given by:

$$q = \rho/2(V_f \sin\psi + \Omega r)^2 \qquad (21)$$

and integrating over the appropriate rotor span and dividing by the blade length gives:

Helicopter

$$\overline{q} = \rho/2 V_f^2 \sin^2\psi + \rho/2 V_f \sin\psi \Omega R + \rho/6(\Omega R)^2 \qquad (22)$$

Aerocrane

$$\overline{q} = \rho/2 V_f^2 \sin^2\psi + \rho/2 V_f \sin\psi \Omega R(1+\chi_1) + \rho/6(\Omega R)^2(1+\chi_1+\chi_1^2) \qquad (23)$$

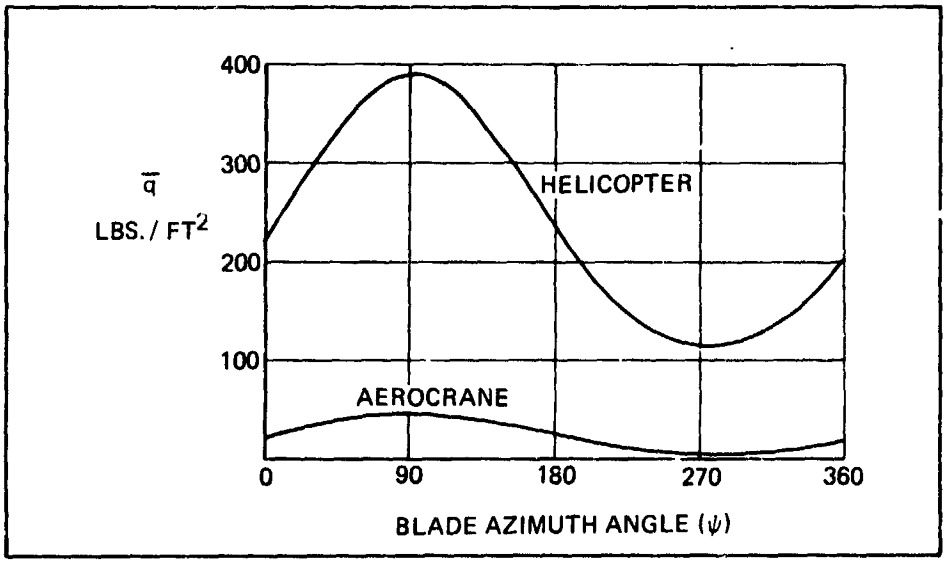

FIGURE 7. Blade Mean Dynamic Pressures

Figure 7 shows that a helicopter blade is exposed to dynamic pressures an order of magnitude greater than those experienced by an Aerocrane wing.

A third major difference between Aerocrane and helicopter blade environments is the magnitude of centripetal forces. The expression for this force, F_C, at a blade station r is:

$$F_C = mgr\Omega^2 \quad \text{or} \quad F_C/m = r\Omega^2 g \qquad (24)$$

where
g = Force of gravity
m = Mass of rotor blade element

At the helicopter blade tip, an acceleration equal to 272 g's is experienced. At the blade tip of the Aerocrane, a force equal only to 7.1 g's is experienced.

Other differences which have a first order impact on the blade design problem are blade aspect ratio and blade root bending relief. In contrast with a helicopter rotor blade, an Aerocrane wing (or blade) has a much lower aspect ratio, and tends to exhibit greater torsional stability. Root bending moments are relieved by cable bracing. Column stability of the wing will be an important design consideration. In many respects the Aerocrane wing design problem is more comparable to standard, light aircraft fixed wing design than to helicopter blade design.

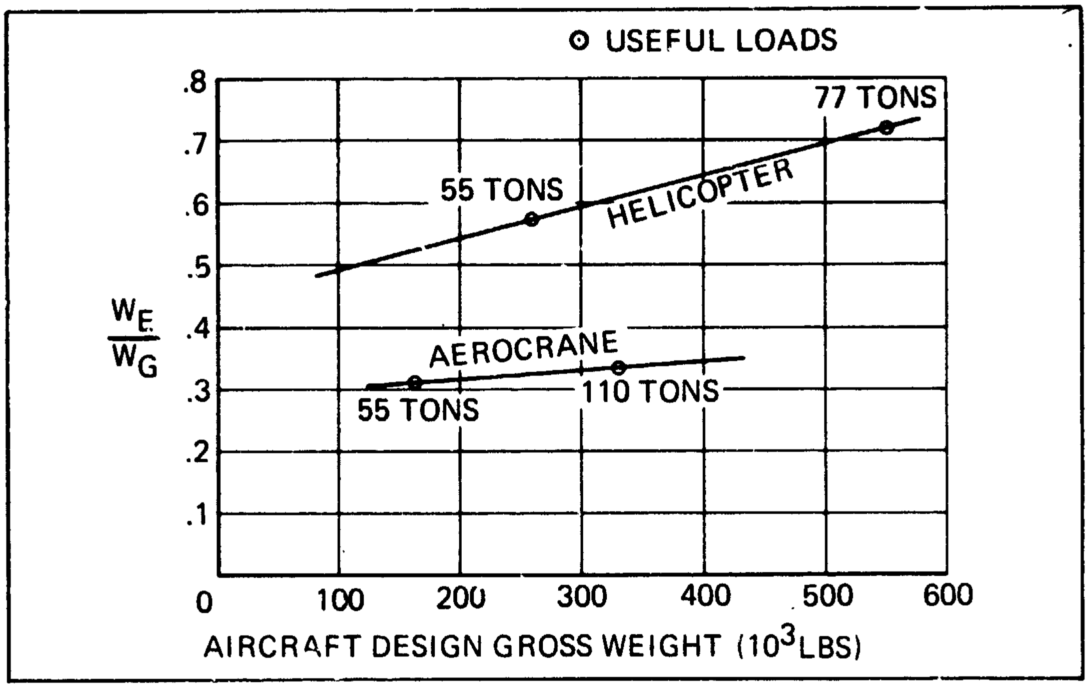

FIGURE 8. Aircraft Empty Weight Fraction

Size and Weight Comparisons Between Helicopters and Aerocranes

Although still in the first stages of preliminary design, it is worthwhile to attempt comparisons between projected Aerocranes and projections of helicopter technology. Figure 8 plots aircraft empty weight fraction as a function of design gross weight for very heavy lift helicopters and Aerocranes. It shows the Aerocrane to have a significant advantage compared to an equivalent capacity helicopter, and this advantage increases with aircraft size. The Aerocrane's very low projected empty weight fraction may seem more reasonable when one considers that 66% of the Aerocrane lift is produced by the balloon element, and existing heavy lift balloon designs exhibit empty weight fractions equal to .15 for this size. Figure 9 compares installed shaft horsepower of the point designs examined. The large installed shaft horsepower advantage shown by the Aerocrane is a direct result of its lower gross weight for a given payload, partial balloon lift and lower rotor disk loading. The Aerocrane is a substantially larger, more cumbersome aircraft than the helicopter, but as payload capability increases, the Aerocrane grows at a slower rate. The Aerocrane's centerbody is actually a dimensionally efficient lifting surface in large sizes. If its disk loading is defined as the buoyant lifting force divided by cross-sectional area, then the 55 ton useful load Aerocrane has a balloon disk loading of 5.94 lbs./sq. ft. This disk loading increases in proportion to centerbody radius.

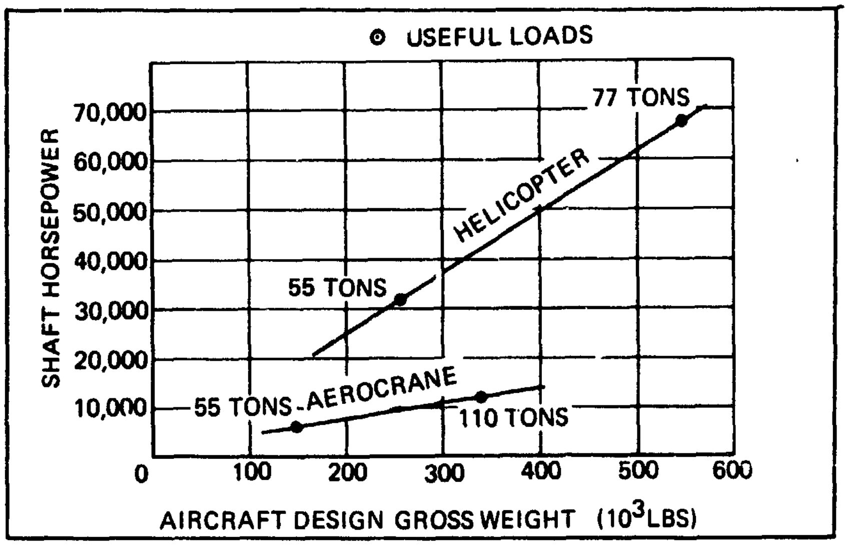

FIGURE 9. Aircraft Power Requirements

The Aerocrane weight trends were developed based upon preliminary design work completed to date. Estimates were made for a MIL STD 1371 weight breakdown format suitably modified to account for special features of Aerocranes. A design ultimate load factor of 5.25 was used. The Aerocrane's main structure is a truss with column and tension members. Column weights were estimated using the allowable compression stress for primary stability using 24 ST aluminum, and the tension members were assumed to be 1 x 19 steel aircraft cable. Weights of the wing fairing, controls and control cab were estimated by analyzing the design point Aerocrane in comparison to similar aircraft structure. Power plants and installation weights were estimated using engine manufacturer's data and fixed wing installation experience. Auxiliary equipment weights were derived from published heavy lift helicopter data. Parametric weight trends supplied by Raven Industries were used to estimate weights for the aerostatic envelope and gas management system. Installed shaft horsepower was calculated by determining rotor horsepower requirements for the forward flight design condition and assuming a propeller efficiency equal to .75.

Weight of the 110-ton useful load Aerocrane was established by applying growth factors to the 55-ton design point which was divided into three categories: (1) load bearing structure, (2) non-load bearing structure, and (3) special equipment. Load bearing structure was assumed to increase in proportion to the four/third power, non-load bearing structure increased directly and special equipment was held constant. The 110-ton projection produced an aircraft empty weight equal to 110,700 lbs. Adding 20,000 lbs. fuel, 600 lbs. crew, 120 lbs. of fluid residues and 200,000 lbs. of sling load, an aircraft gross weight equal to 231,420 lbs. and an empty weight/gross weight ratio equal to .334 results.

Helicopter empty weight trends were those discussed in reference (3). In that paper projections of future heavy lift helicopter empty weight fractions were developed based upon recent U.S. and Soviet helicopter design trends. A reasonably good check was applied to this trend by comparing the results of an advanced helicopter design study and data from the Army's HLH program. As might be anticipated, the hardware technology program came in high and the design study low. Using this trend hypothetical helicopter design points were selected. Installed shaft horsepowers were calculated for the design points examined by assuming a design disk loading of 10 lbs./sq. ft., a tandem rotor configuration and a rotor figure of merit equal to .74. A transmission mechanical efficiency equal to .975 and a 4% hover download were used, and no losses were deducted for cooling and auxiliary power requirements.

Although it may be argued that the helicopter weight trend represents a far more established trend than the Aerocrane projections based upon the limited studies completed to date, it may also be argued that a more detailed understanding of the Aerocrane design will allow better definition of design loading conditions, more optimal selection of aircraft configuration parameters and a subsequent reduction in aircraft weight. In this paper, it is assumed that these considerations mutually cancel.

The significance of Figures 8 and 9 is that (1) the Aerocrane concept allows much larger capacity aircraft to be built than our present and foreseeable helicopter technology base, and (2) for equal capacity, the significantly lower structural weight fraction and installed shaft horsepower of the Aerocrane should imply a considerable savings in investment costs compared to an ultra heavy lift helicopter. These potential savings are discussed in reference (2).

NAVY AND MARINE CORPS APPLICATIONS

The Navy and Marine Corps anticipate growing future requirements for crane services (or vertical lift) in fleet support and amphibious assault operations. While many operational requirements for aerial lift have been established such as VERTREP and general amphibious assault support, many times the need exists to lift or transfer loads so far in excess of present aircraft capabilities that no real recognition of many situations as aerial problems has been made. If cost effective aerial cranes were available in the 100-ton range, military effectiveness would improve in many areas including transportation of special combat equipment, harbor preparation, construction of elevated causeways, combat road construction, ship repair and salvage, and submarine rescue operations. A principal application of the Aerocrane concept may be to support amphibious assaults and subsequent operations ashore. Aerocranes would be complementary to medium and heavy lift helicopter forces providing the very heavy lift capacity to complete a vertical envelopment in transporting heavy equipment critical during the different phases of operation.

In addition to the primary amphibious assault functions, the Aerocrane potentially offers effective operations in a wide variety of peacetime support missions. This includes recovery of damaged equipment, support of military construction projects, transportation of DSRV's for submarine rescue operations and mobile crane services for ship repairs.

REVIEW OF SELECTED PROBLEM AREAS

As with any new concept a particular advantage or new performance capability is easily projected. What is not as clear are the extent of technical unknowns and problems to resolve before a successful aircraft may be developed. The Aerocrane is not an exception. In this section, a number of potential problem areas are highlighted and peculiar design conditions discussed.

Presently, the most serious technical unknown is the increase in basic drag and lift of the Aerocrane centerbody due to Magnus forces. Magnus lift and drag are the result of the rotation of a body of revolution about its principal axis perpendicular to the free stream velocity. Its most serious effect on the Aerocrane concept is not the growth in thrust requirement as Magnus forces increase, but the increase in angular tilt of the Aerocrane required to produce compensating forces and the subsequent effects on rotor control moments, blade stall and other design considerations. The relationships for equilibrium flight are easily derived after construction of a free body diagram. Figure 10 is a free body diagram for an Aerocrane in equilibrium loaded flight. Summing the forces about each axis and algebraic manipulation leads to the following equations.

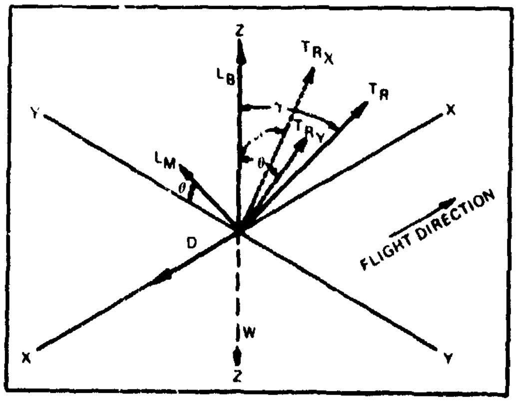

FIGURE 10. Free Body Diagram

$$\sin\gamma = \sqrt{\frac{D^2(W-L_B)^2 + L_M^2(W-L_B)^2 - L_M}{(W-L_B)^4 + (W-L_B)^2(D^2-L_M^2)}} \qquad (25)$$

where

γ = Angle of Aerocrane inclination required to compensate for Magnus lift and total Centerbody Drag

L_B = Aerostatic lift

L_M = Magnus lift

D = Total Centerbody Drag

W = Total aircraft weight

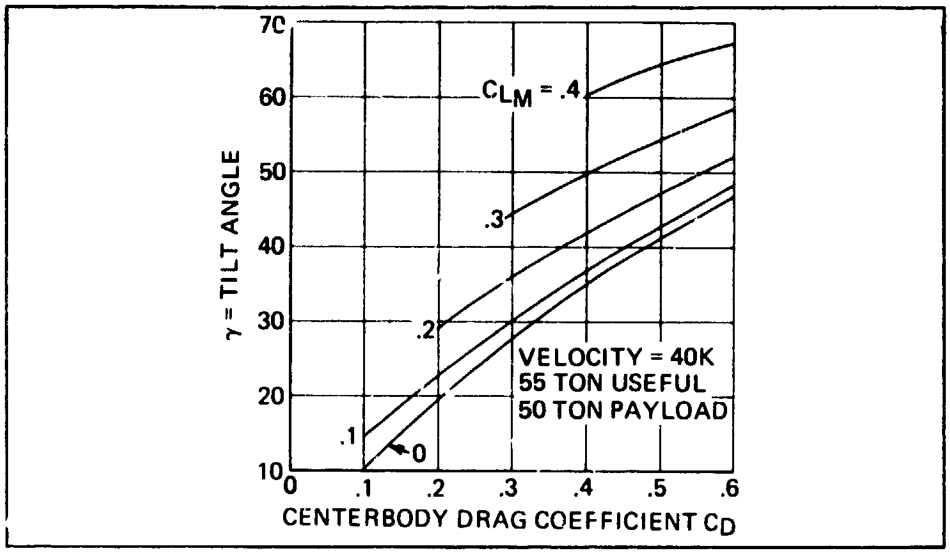

FIGURE 11. Aerocrane Skew Angle

Figure 11 plots total angular tilt as a function of assumed centerbody lift, C_{L_M}, and drag coefficients for a 40 knot design cruise speed. Practical aircraft designs must demonstrate lift and drag coefficients permitting reasonable skew angles for the forward flight design conditions.

A literature survey has not produced experimental data appropriate to the Aerocrane problem. The closest experiments involved small, rotating spheres in a high speed flow. Here, sphere lift and drag coefficients as high as $C_{L_M} = .4$ and $C_D = .6$ were measured for some values of sphere equatorial surface and free stream velocity ratios.

However, the applicability of this data to the Aerocrane problem is highly questionable for several reasons. First, the experiments were run at sub critical Reynold's numbers, below that Reynold's number where a sharp drop in non rotating sphere drag coefficient occurs. Second, the effects of inclination of the rotational axis into the free stream were not examined. All recorded data is for the perpendicular condition. Finally, the effect of the rotor on the airflow around the sphere is unknown.

A second technical unknown is the influence of the centerbody turbulent wake during forward flight on the rotating wings as they pass behind the sphere. This wake may represent only another structural loading to be considered in the design of the wing or it might produce a complex interaction effecting wing angle of attack variation, and hence, control system design and aircraft flying qualities.

A third area requiring extensive investigation to establish concept feasibility are the dynamics of aircraft motion. In the case where the control cab is attached to the centerbody surface, the rotor is separated a substantial distance from the control cab. Thus, unusual cab motions arising from rotor tilt to compensate for gusts or similar disturbances may confuse the pilot. In the unloaded condition rotor compensation for a gust disturbance causes the cab to translate against the direction of the disturbance, a stabilizing effect. However, in the loaded condition, tilting the rotor for gust compensation initially causes the cab to translate in the direction of the disturbance - an undesirable, destabilizing effect. When maneuvering a load before release, the pilot will be queing on the motion of the load and an analysis of the total aircraft-payload system including the effects of payload pendular motion is necessary. If a significant problem exists, suspending the load and cab nearer to the sphere's center may be a viable alternative.

In addition to the previously mentioned major technical concerns, there are a number of peculiar design conditions not known to be previously encountered in aircraft design. Some of these are:

1. Exposure of the engines and propellers to continuous centripetal and gyroscopic forces.
2. The propellers located near the wing tips will have an unsteady flow field as a design condition.
3. A dual mode flight control system is required for loaded and unloaded flight.
4. Aerostatic forces must be integrated into a central rigid structure which supports aerodynamic and payload forces.

Operational Considerations

The Aerocrane exhibits to a lesser extent all of the size and inertia disadvantages of airships. Large aerodynamic forces will be generated by changes in ambient wind conditions. With an installed vectorable thrust at least equal to 34% of aircraft weight, substantial maneuvering forces in any direction may be generated to compensate for wind gusts and to accelerate and decelerate the Aerocrane. Accelerations will be faster than an airship, vectorable, but slower than a helicopter. Mooring may be accomplished anywhere a fixed attachment point to the ground is available. This simple mooring arrangement is in sharp contrast to the elaborate needs of the normal airship.

The Aerocrane's peculiar design will require many unusual maintenance features. Most important is access to the engine and wing flight controls. This will require special access routes within the wing and balloon structure. Electric winches must be integral to the wing design to allow an engine change without requiring a ground crane.

CONCLUSIONS

The Aerocrane concept offers a potential for order of magnitude improvements in maximum VTOL lift capacity and reduced acquisition costs compared to an equivalent lift helicopter. The mechanism which allows this is the partial substitution of low cost, heavy lift balloon technology for high cost, rotor technology. The penalties are the reduced forward speed envelope and the reduction of the excellent flying qualities of the helicopter. Operating weight empty fractions between .31 and .35 are estimated for Aerocranes compared to between .57 and .72 for very heavy lift helicopters. The Aerocrane's design simplicity, benign flight environment and potential for rugged construction because of a relaxed emphasis on minimizing structural weight fraction may result in a substantial improvement in aircraft operational availability. Principal areas of uncertainty to be addressed in a development program are aircraft stability and control characteristics, adequacy of forward speed capability and modes of operation considering its airship-size bulk and gust sensitivity.

These considerations clearly limit the normal missions of the Aerocrane to short range, high load/unload cycle requirements where loads are in excess of helicopter capabilities. In rare cases of heavy equipment transport, where high surface transportation costs are coupled with a need for controlled delivery to a construction site, the Aerocrane might find an area for service. Thus, the Aerocrane does not compete directly with either helicopters or future airships as the Aerocrane concept does not scale down to helicopter load size nor can the Aerocrane offer efficient long range service comparable to the airship. However, within the operational spectrum of the Aerocrane lies a significant area of use where lighter-than air technology may be of service.

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