THE HUMMINGBIRD – A PROPOSED HIGH-SPEED ROTORCRAFT CONCEPT

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ABSTRACT

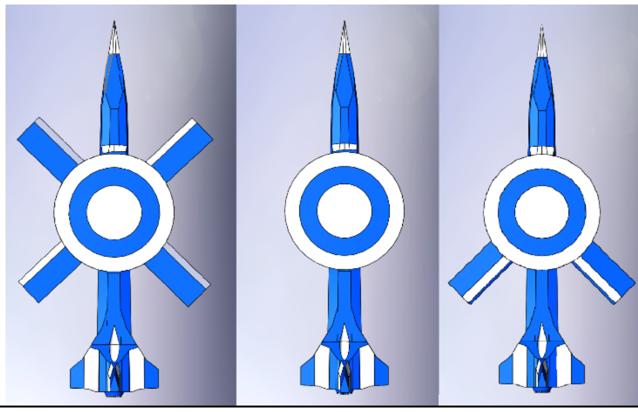
A new high-speed VTOL cargo transport concept, designated "Hummingbird" or H-500 is proposed. It is a small cargo plane propelled by 4 large rotors utilising tipjets in a VTOL mode and propelled by a single hybrid air-breathing rocket engine modelled after the SABRE engine in a more traditional fixed-wing mode. In this way, the H-500 capitalises on the advantages of a helicopter and those of a jet plane, while avoiding the more serious limitations of both. The "500" designation reflects a key design goal of a top speed of 500m/s when under the power of the closed cycle rocket engine mode of the SABRE engines, granting inefficient but incredibly powerful thrust for emergency operations. When under the more efficient power of the airbreathing engine operation the Hummingbird should reach a cruise speed of 200-300 m/s.

The Hummingbird's key unique feature is an unconventional circular hub fairing used to shield the decelerating rotors and provide the lift to support the aircraft during the transitional period between VTOL rotorcraft operation and normal jet-powered flight. The hub has to take the load of the aircraft as if the rotors were still in use at this point the 100% rpm change would create extraordinarily high levels of vertical vibration with potentially disastrous consequences. To combat this critical problem, the rotors retract into the hub before beginning to slow down (See diagram on next page). This slightly reduces rotor efficiency however, and this report considers compensatory options in the "Limitations" portion of the document.

The forward flight characteristics of the H-500 are as yet untested, but parallels can be made with the NASA M-85 passenger plane and the RFSR hybrid "X-Wing" testbed, extensively tested in 1991 and 1972 respectively, as well as the modern V-22 "Osprey" tiltrotor, still in use as a short range transport by the US military. Such is its popularity, in fact, Japan, India, Israel, South Korea and the UAE are all currently in negotiations to purchase V-22's to supplement their respective air forces.

Design considerations, operational benefits and predicted specifications are also included in this report, as are calculations of lifting characteristics and rough feasibility.

INTRODUCTION



Above: *The three rotor configurations of the H-500. From left to right: All rotors extended for VTOL, all rotors retracted for transformation, two rotors extended for high speed flight. Note that although the two rotorpairs have different leading edge orientation, the difference is symmetrical and so does not affect lift.*

The helicopter is typically used in military or civilian applications as a short range craft for congested or isolated areas, where fixed-wing aircraft lack the space to operate effectively. Helicopters have a distinguished record within military history as an essential tactical and strategic tool for transporting key payloads to bases with austere facilities, landing and taking off in suboptimal conditions, and being used as fast-response craft to nearby locations due to their small prep-time before launch. Helicopters' small landing requirements and swift re-role and recovery times will be a great asset to the H-500's operation.

The limitations of helicopters primarily revolve around their short range and lack of speed. Traditional rotorcraft are incapable of truly high speed due to the outer tips of the rotorblades having a speed relative to air being related to the speed of the helicopter as well as the rotors' rotational speed. As a result, the airspeed of the advancing rotorblade can be markedly differed to the retreating blade opposite, resulting in lift asymmetry and a complete loss of control at high speed. This also results in high vertical vibrations that can damage the craft and injure passengers, as well as increasing maintenance requirements significantly.

The proposed H-500 would capitalise on the advantages of helicopters - high manoeuvrability, few requirements for runway facilities - and negate the disadvantages by incorporating the new SABRE engine design into a jet-configuration allowing the H-500 to retract the rotors and extend two into a more conventional swept-wing profile and reach speeds that should exceed Mach 1.5, greatly extending the range and practical use of the craft. Features of the SABRE engine allow the H-500 to take on multiple performance roles at once at relatively little expense - something explored in greater depth in the "Description" section. The H-500 is not suited to a direct combat role, but is better used in a reconnaissance, diversionary or transport role due to its complex and non-robust take-off and landing operations.

This is not a wholly new idea, and the feasibility of such a multirole craft has been showcased in various past case studies, suggesting its practicality. This aircraft is distinct from designs such as the Boeing V-22 Osprey and the RSRA X-Wing as it is unprecedentedly ambitious in its payload and speed goals - the V-22 has a max speed of just over 125m/s, less than a quarter of that of the H-500. In terms of payload capacity the H-500 will aim to take a similar role to the Learjet 35, used by the US military as a VIP transport and small cargo jet. For the H-500 to warrant research and development costs, it must be demonstrably superior or equal to existing in-use aircraft in certain roles. To justify this, the following key capabilities are essential.

1. Hover efficiency and manoeuvrability approximating that of a helicopter when taking off and landing.

2. An efficient cruise of ~300 m/s under the airbreathing engine power of a SABRE engine, significantly higher than the Learjet 35 and double that of the Fairchild C26 cargo jet.

3. An emergency top speed of 500 m/s under closed-cycle rocket engine power, slightly lower than an F-22's cruise speed.

4. A payload capacity of 4000kg with space for 8 passengers on-board - superior to that of a Learjet 35 cargo jet

The cargo transport of the Learjet 35 has proven to be of immense use - its 3800kg payload capacity has been used with great success to drop medical supplies and evacuate casualties by the US Air Force and as part of the Argentinian Air Force in a reconnaissance role during the Falklands War. The Learjet is also used by many civilian contractors as a luxury jet - 630 are owned by private companies for this purpose. It seems likely that in peacetime or between deployments the H-500 could be hired out to civilian organisations, granting another angle to its multi-role capabilities. If the H-500 can fill this role while possessing the crucial advantage its helicopter-like capabilities grant it will be a powerful tool for any country's arsenal.

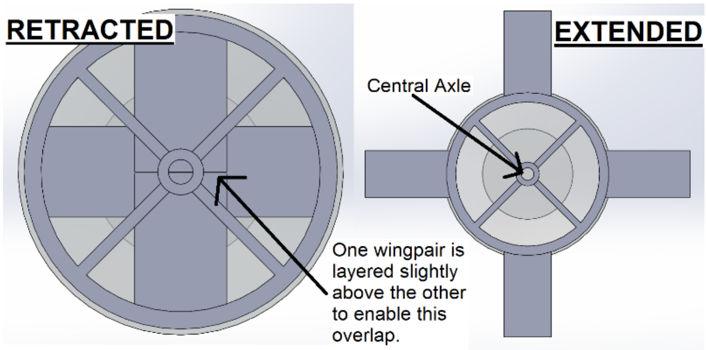
It is the belief of this report that such an outcome is not only possible but probable should investigation on the project proceed further.

DESCRIPTION OF THE H-500 CONCEPT

The H-500 "Hummingbird" incorporates a rotary quad-wing system to generate lift during takeoff and landing and during acceleration to a suitable speed for transitioning to a double fixed-wing one for high speed flight. For this transformation, the rotors retract under the diskhub before decelerating to a complete stop. The rotors are rotated under the hub and two are extended backwards to form 45 degree swept wings. A top-down image of this is on page 1. The 45 degree sweep angle is a little high (more typical would be 30-35 degrees), but still well within acceptable parameters for a relatively-low performance jet.

For the take-off and landing portions of the flight the H-500 uses 4 wings/rotors 90 degrees from each other, under a large circular hub that covers 50% of the rotors' length. The rotors are necessarily an unblown aerofoil to minimise asymmetry, and after consulting with technical manuals (see bibliography) a rotorblade chord thickness of 15%, this being judged as "adequate for structural and airducting purposes and permitting a sufficiently blunt trailing edge to yield good Coanda turning. At the same time, adverse compressibility effects that would occur at the high subsonic propeller tip speeds are limited" **[1]**. For rotor propulsion, we considered either a separate engine attached to a helicopter-style swashplate and centrally located under the diskwing, some kind of rotary system on the diskwing or propulsion located on the outer edges of the rotors themselves.

The third option seemed the most attractive. Airjets mounted on the outer edge of each rotor remove the need for a traditional and un-aerodynamic helicopter tail rotor as an anti-torque system and offer some perks such as weight savings, lower cost, and simplicity of design. Pressurised "tipjets" will have significant efficiency losses, especially with the requisite afterburners for spinup/down, but as the rotors will only be in use for short periods this is an affordable compromise. Pitch of each blade is separately controlled by servo motors mounted on the rotor hub and there is no option for a more traditional helicopter-type swashplate due to the attachment system having no suitable central location for actuator placement. The rotors are mounted on a metal rotating band under the diskhub, and are actually half their apparent length, giving them space to retract under the diskhub. See below.



Control systems for this are not yet in existence, but should be a simple corollary of modern tiltrotor systems, using traditional cyclic and collective controls - anti-torque pedals are not needed due to the "tipjet" propulsion. Training for this should be straightforward.

The body of the plane is relatively small for a transport, and is 15 metres in length. The cargo storage space should fit in addition to 8 passengers a further 2m^3 of supplies, although due to optional additions such as EW modules or luxury fittings this may not reflect actual space available.

The central-mounted SABRE engine, behind an S-duct to maintain supersonic streamlining, allows the aircraft in its fixed-wing configuration multiple options - a fuel efficient but slower cruise with the airbreathing functionality suitable for everyday usage and civilian operation, and a significantly more powerful but inefficient mode of operation with the rocket engine mode of the SABRE engine. This would be used for high-altitude high-speed flights, a relevant capability if the H-500 is used in the emergency transport role this report envisions - this kind of fast-response might be essential in delivering medical supplies or crucial personnel to medium-ranged destinations. The SABRE engine's refined and unprecedentedly versatile altitude compensating intake allows the Hummingbird an unusually high flight ceiling, even more so when under closed-cycle rocket propulsion and is not reliant on certain air densities to feed the compressor

The SABRE engine's as-yet unreplicated frost control is an essential enabling technology for this ability, and would afford the owner of the Hummingbird a significant edge in comparative capabilities.

The SABRE engine's immense power is similarly intrinsic to the design, as its T/W ratio of 14 (over double that of a conventional jet engine) allows the aircraft to "push past" the induced skin friction and drag from the diskwing. The SABRE engine's precooler also allows lighter and weaker alloys to be used in construction (by eliminating the requirement for extreme heat resistance) as an ancillary benefit **[2]**.

There are no especially noteworthy structural requirements for the H-500, and it can be constructed from the usual titanium and aluminium alloys employed in jet construction. The weight tolerance of the H-500 is generous, and the quoted payload weight is conservative if anything - no novel ideas are necessary to make weight.

LIMITATIONS

The circular hub necessary to prevent vibrations from destroying the craft during transition from rotorcraft to jet plane presents several unusual challenges, and these challenges are why the proposed NASA M-85 diskwing was never put into production. For example, the circular hub covers 50% of the rotorblades' length, resulting in a loss of lift. The lift of a rotorblade is given by the basic blade equation

$$\frac{\partial(bladelift)}{\partial(r)} = \frac{\rho C_L c(\Omega r)^2}{2}$$

Where $\Omega r = V$. Integrating for r = 0 to 1R,

$$\int_0^{1R} \frac{\rho C_L c \Omega^2 r^2}{2} = \frac{\rho C_L c \Omega^2 R^3}{6}$$

If we integrate for r = 0 to 0.5R, the ratio of R^3[old] to R^3[New] is 1:0.875 This means that by eliminating the inner 50% of the lifting surfaces, we only lose 12.5% lift. This loss is easily compensated for by increasing c by only 4% at the same rotational speed (Ω). We can conclude that the obstruction of the inner 50% of the rotor lengths is not significant.

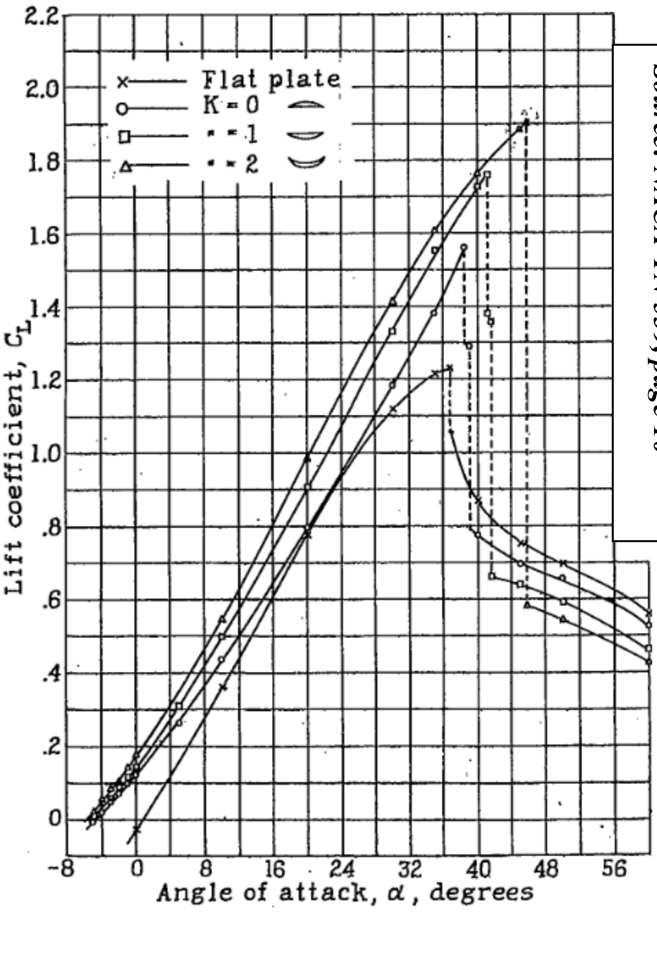
Another vital question is whether the disk's aerodynamics might inhibit high-speed flight. A disk-shaped wing has been evaluated before in two iterations: a thin flat plate, and a disk with 1:0.12 chord/diameter ratio with various cross-sectional designs **[3]**.These are not exactly the same as the H-500's and were not tested in identical situations, but the data is still very relevant and can be used as an approximation in the place of actual data which is difficult to come by without a wind tunnel. The most useful figure comes from the graph below, where the $C_L$max of a thin disk is experimentally determined as 1.2 at an angle of attack of 0.7 radians. Some back of the envelope calculations to evaluate the practicality of a stopped disk radius 2.88m as a lifting surface follow.

$$RequiredVelocity = \sqrt{\frac{2Lift}{\rho C_L Area}}$$

Setting the vertical component of lift required as 8000g (approx. the max weight of the craft), the C_L as 1.2 and ρ as 0.84 atmospheres (equivalent to air at a height of 1500m), the required velocity for the disk-wing to provide the desired lift is roughly 19 m/s.

This assumes an angle of attack of 0.7 radians, however, and a large disk at this angle will produce large amounts of drag. Although there is not much that can be done about this, the effect can be lessened by filleting the leading edge to produce a rounder edge and increase leading-edge suction. **[4]** If we instead consider the lift at a more reasonable angle of 0.35 radians, we get a C_L of 0.8, and a required velocity of 24m/s, still very achievable but with a much more reasonable drag profile due to the decreased angle of attack.

When the transition is over and the craft has assumed its jet-configuration, the angle of attack is then reduced yet further to reduce the diskwing's drag, something that becomes more important as speed increases. The drag coefficient of such a disk at subsonic speed is just 0.0151, a very reasonable figure.



Source: NACA-TN 539, page 10

SUBSONIC DRAG CHARACTERISTICS

The aerodynamic performance of objects under sub- and supersonic motion in air differ markedly, and must be considered in turn. Subsonic drag is the more straightforward, and will be evaluated first.

The subsonic drag coefficient is given by the formula:

$$C_{drag} = C_{skinfriction} + C_{formfriction} + \frac{C_L^2}{\pi ARe}$$

Where **AR** is the aspect ratio and '**e**' is the efficiency factor of the chosen aerofoil, sometimes referred to as the "Oswald Number". The final fraction in the equation is the induced lift, caused by the reaction force from the aircraft's lift. The coefficient of drag is most effectively found through experimentation, but we can make a theoretical prediction using known values previously determined. Firstly, we combine the two coefficient terms under the name C_{D0}, found like so:

$$C_{D0} = C_{fe}\frac{S_{wet}}{S_W}$$

C_{fe} is typically approximated as 0.003-0.004 for jet aircraft **[5]**. S_{wet} is the area of the aircraft "wetted" by the flow of air around it. This is a highly lengthy and unremarkable calculation, and spans many pages of simple geometric calculations – not included here to save space. The outcome is 154.65 square metres for the H-500, with a 2.5% tolerance due to unaccounted for elements like antenna or similar.

S_W is the wing reference area. To find this we only need to refer to the previously decided wing dimensions of our plane. With a chord length of 0.861m and a halfspan of 5.74m, the reference area is 19.76 square metres for the entire plane.

Plugging these values in we receive a C_{D0} of 0.0235, to three significant figures. Referring back to the original drag coefficient formula at the top of the page:

$$C_{drag} = C_{D0} + \frac{C_L^2}{\pi ARe}$$

The precise aerofoil used for our craft was not investigated, as such a challenge in optimisation could be a whole report of its own. Instead, we used the common Clark Y aerofoil as a temporary stand-in. This means that the results we get will be conservative estimates, and that a real design should perform better. The Clark Y aerofoil has an Oswald Number ('**e**') of 0.9 **[6]** - plugging in this value allows us to complete the formula and find the drag coefficient relatively easily **[7]** (NB: actual calculations done with exact values).

$$C_{drag} = 0.0235 + \frac{1.6^2}{13.33\pi \times 0.9}$$

$$C_{drag} = 0.0916$$

This is larger than most normal planes of this type, but not excessively so. The extra-ordinarily high-performing X-15 hypersonic jet had a similar drag coefficient of 0.095. In the X-15's case the extra drag was caused by the structural requirements created by its high top speed (Mach 6.72), whereas the H-500 suffers here due to the large skin friction caused by the diskwing and the suboptimal nature of the chosen rectangular wing shape. There is no way to avoid this concession however, as the wings have to serve additionally as rotors. Given the power behind the SABRE engine pushing past this drag will not be a problem, although material stresses may have to be considered in further detail later on.

From the derived calculations we can conclude that the increased drag during subsonic flight from the H-500's unconventional design is noticeable, but not overly significant and certainly not an insuperable problem.

SUPERSONIC CONSIDERATIONS

The main difference between super and sub-sonic flight is the "blind flow" of air through a system – as the flow is incapable of moving away from the aircraft (because the aircraft is moving faster than the maximum speed of pressure waves in air), small and sharp disturbances of flow have no way to dissipate and create damaging shockwaves which travel downstream across the body of the plane. The resultant compressibility effects are what distinguish subsonic and supersonic design. This is why supersonic planes almost never have straight wings perpendicular to the main body, as swept wings allow for these shocks to be channelled and delayed down the wing's edge. Supersonic flow at transonic speed also requires complex and unintuitive "supercritical" aerofoil design – something that is far beyond the scope of this report but can be developed further at a later date.

To enable supersonic flight for the H-500, several design tweaks were necessary, such as developing an original but preliminary design for a shock-delaying S-duct, a more closely grouped profile and modifications to the rear stabilisers. To aid in explanation, these are included on the next page with other annotated notes of our final design.

REFERENCES:

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3. *Aerodynamic Characteristics of Several Airfoils of Low Aspect Ratio,* C H Zimmerman, 1935
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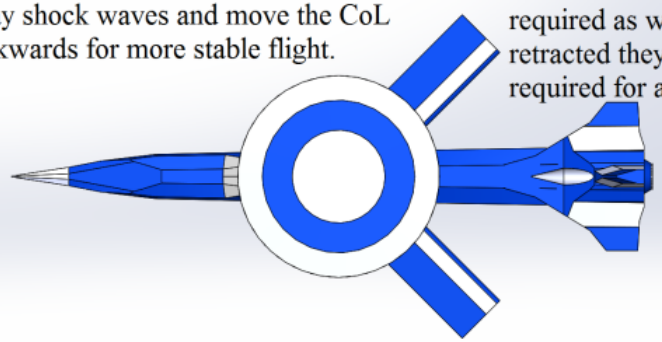
DESIGN AND CAD



Wings are swept back by 45 degrees to delay shock waves and move the CoL backwards for more stable flight.

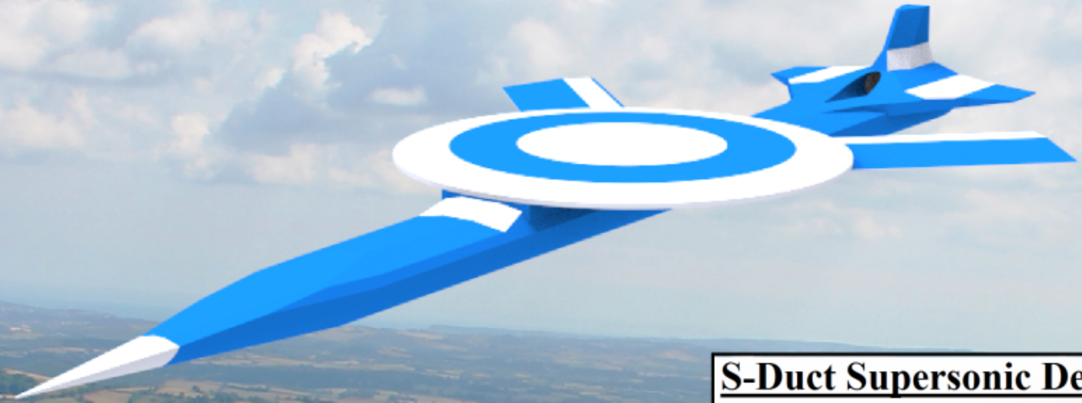
Thick rear stabilisers required as while rotors are retracted they will be required for all roll control

Weight Distribution Design

Centre of Thrust

The Centre of Lift is behind the CoM in an extremely stable position, causing lift induced drag to weathervane the craft and keep the nose out front.

The Centre of Mass is quite far aft and under the diskwing for easy VTOL. When craft is underloaded the difference is compensated for by the SABRE engine. As fuel drains sternwards, this also increases aerial agility.



Frontal Profile Design

Structurally strong but unaerodynamic wedge-shaped vertical stabiliser

Triangular frontal profile helps with airflow around the diskwing and improves supersonic aerodynamic performance

Close tolerances on diskwing and rotors are required to avoid supersonic shocks.

S-Duct Supersonic Design

S-duct allows central positioning of engine without compromising aerodynamic performace. This neccessitates the large longitudinal rudder, but is an unavoidable requirement.