Paper No. 1

APPLICATION OF CIRCULATION CONTROL ROTOR TECHNOLOGY TO A STOPPED ROTOR AIRCRAFT DESIGN*

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1. Introduction

This paper presents the application of Circulation Control Rotor (CCR) technology to a revolutionary new aircraft concept—the X-Wing stopped rotor V/STOL. This design affords the potential for major advances in rotary wing aircraft speed, range-payload, productivity and cost through the application of highly innovative aerodynamic and structural design. The technology base for the concept has been derived from almost 6 years of related CCR aerodynamic and structural design studies at the Naval Ship Research and Development Center (NSRDC) and from earlier research in the United Kingdom. Additional design insight has been gained from the experience of various stopped and stowed rotor concepts of the 1960's and also from more recent studies of the NASA "oblique wing" transonic transport concept.

2. Description of Concept

The basic design is illustrated in Figure 1 in an attack-type configuration. Salient features include four highly loaded rotor blades (150 psf wing loading) of moderate aspect ratio (12.0), which are stopped in flight at the 45-degree azimuth position. The rotor/wing is both aerodynamically efficient (hover Figure of Merit ≈0.70, fixed wing lift system equivalent lift-to-drag ratio ≈20.0) and is also structurally ideal (20-percent root thickness ratio, 10-percent tip, and planform taper ratio of 2:1). The high wing sweep, in conjunction with the excellent critical Mach number characteristics of the CC airfoils (Figure 2), permits the wing to have a drag rise Mach number of approximately 0.90. Also, due to a combination of low solidity ratio and the basic symmetry of the wing cross sectional area distribution, the X-Wing aircraft is inherently area-ruled without "coke bottling" (Figure 3). These features permit design of an internal engine configuration with unexcelled transonic drag rise characteristics without the internal space problem, structural difficulties, and added subsonic drag penalty normally associated with area-rule designs. In addition to these more obvious characteristics, the X-Wing possesses several other unique properties which, when taken as a whole, offer a revolutionary improvement in V/STOL capability. These are discussed briefly in the following sections.

3. Aerodynamics

The CCR concept is illustrated schematically in Figure 4. Basically, a thin jet sheet of air is ejected tangentially over the rounded trailing edge of a quasi-elliptical airfoil, suppressing boundary layer separation and moving the rear stagnation streamline toward the lower surface, thereby increasing lift in proportion to the duct pressure.** For a pneumatically controlled rotor application, the azimuthal variation of lift is controlled by a simple nondynamic valve in the hub. At higher speeds and advance ratios, a second duct and leading edge slot are used (Figure 5) so that the rotor can develop significant lift in the region of reverse flow. Two-dimensional airfoil experiments have shown it is

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**For reasons of brevity, it is not possible to discuss the details of the CC section aerodynamics in the paper. The reader is referred to the bibliography contained in reference 1 for more information on these unique airfoils.

possible to develop large lift coefficients by blowing from either slot individually or from both simultaneously. The latter technique is used for advance ratios from 0.5 to 1.0 where the retreating blade experiences "mixed flow" (i.e., locally reversed flow on the inboard sections and forward flow on the outer sections). Test results for this unique airfoil are shown in Figure 6.

The significance of the CCR aerodynamics can be assessed by noting that the critical design parameter for any high speed horizontal rotor concept is, in fact, the maximum lift capability in the intermediate advance ratio range (0.7 to 0.9) where the retreating side of the disc is immersed in mixed flow of low average velocity. Historically, the solution to this problem has been either to add more blade area, to employ a separate wing, or to use a second contra-rotating rotor. Without exception, these approaches have resulted in large and fundamentally limiting weight penalties and usually a hover and/or cruise efficiency penalty. The X-Wing minimizes the transition lift problem by blowing out of both slots in the mixed flow region and by using a cyclic pressure control schedule which shifts the maximum loading to the fore and aft regions of the disc. Figure 7 illustrates the extreme aerodynamic environment which is made tractable by these simple pneumatic techniques in conjunction with the high lift properties of the basic CC airfoil sections. The crucial significance of the transitional lift capability is that it permits the X-Wing to develop blade loadings on the order of three times that of conventional rotors. Figure 8 illustrates the calculated performance through the advance ratio range.*

The design implications of this blade loading capability are far reaching indeed for they permit high aspect ratio blades to be used for efficient hover while also allowing the aircraft to operate in very high speed cruise at the lift coefficient for maximum efficiency. Figure 9 shows the calculated cruise efficiency for one aircraft design (range is proportional to L/D_e) indicating that a peak vehicle L/D_e of 10.0 is achievable at 350 knots (10,000-feet altitude).

The details of the transitional aerodynamic performance are too lengthy to be described in this paper. Basically, however, the aircraft will accelerate as a thrust compounded helicopter up to the transition advance ratio of 0.7 (approximately 250 knots). Then while maintaining a constant flight velocity, the rotor RPM is rapidly reduced to zero using a rotor brake to decelerate and stop the rotor (approximately 30 seconds total conversion time). A simple arrestment and lock-out system is then used to position the blades during their final revolution. The symmetry of the rotor allows the blades to be stopped in any 45-degree location, thus simplifying the problem of indexing. The aircraft can then either accelerate up to high cruise speeds or it may operate in a fixed wing mode at very low forward speeds (below transition speed). The aircraft would also have the capability for STOL takeoffs and landings in the "blown" fixed wing mode with the large compressor power source used for transition.

Another special aerodynamics problem of high speed rotorcraft is the excessive drag associated with the rotor hub which may account for more than one-half of the total parasite drag. The X-Wing circumvents the problem by eliminating the usual bluff protuberances such as shafting, pitch linkages, control horns, etc., which give rise to flow separation. The rotor blades and hub are designed to be extremely rigid with a 3-degree built-in coning angle. A limited +7-degree blade pitch travel is also included for designs requiring maximum efficient hover operations. The pitch change mechanism is designed to fit within

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*These theoretical results ($C_T/\sigma = 0.16$ at $\mu = 0.7$) have just been experimentally confirmed at this writing by tests on a 7-foot diameter rotor in the NSRDC 8- by 10-foot wind tunnel. An NSRDC report on these tests will be issued in the near future.

the envelope of the root section so that an aerodynamically efficient hub fairing can be employed. Figure 10 shows half-scale model data on several hub-shank designs indicating hub drag values an order of magnitude lower than current helicopter hubs (reference 2). The remainder of the body aerodynamic design is relatively conventional so that with the exception of the hub contribution, the fuselage drag levels are representative of current fixed wing designs.

4. Empty Weight

Notwithstanding its unique aerodynamic capability, possibly the most important characteristic of the X-Wing is its potential for significantly reducing the empty weight penalty of a VTOL. By obviating the historical requirement for separate hover and cruise lifting systems, the X-Wing is capable of achieving rotor blade/wing weight fractions below 6 percent of gross weight by using aluminum construction and below 4 percent by use of high modulus carbon fibre composite. A preliminary rotor/wing structural analysis has been used to design the X-Wing. As indicated in Figure 11, the final structural design must efficiently satisfy the diverse requirements of (1) fixed wing ultimate maneuver loads, (2) aeroelastic divergence of the forward swept blade, (3) rotor frequency placement to avoid resonant amplification, and (4) rotor loads and fatigue life. Figure 12a illustrates the typical structural-aerodynamic design tradeoff encountered for aluminum construction. Minimum weight is achieved at combinations of high disc loading and blade loading. Consideration of the maximum blade loading during transition flight limits the design blade loading to 150 psf. If one then determines for a particular mission (say a range-payload mission) that a high aspect ratio is desirable, then the indicated point would be a good solution. The disc loading value of 15 psf, while somewhat high for Army helicopters, is satisfactory for Navy shipboard use and results in a smaller diameter rotor. Figure 12b indicates that the divergence speed for this particular design is sufficient for the mission chosen.

Figures 13a and 13b indicate a similar tradeoff using graphite composite construction with spanwise and 45-degree cross-ply construction. Significant weight savings relative to the aluminum were found with a considerably reduced dependence on aspect ratio. The divergence characteristics are also markedly superior to the aluminum. It is apparent from these results that while an X-Wing could be fabricated with aluminum, it is actually ideally suited to the high specific stiffness of composite graphite material. The graphite also possesses important advantages in natural frequency placement design for the rotating blade conditions.

The hub and retention system shown in Figure 14 also represents a new area of structural design for the X-Wing. It was found that the use of a titanium "yoke" was a preferred approach to a composite design (at this time) in view of the requirements for high strength, high fatigue stress, ease of fabrication and machining, and most importantly, the need for a high fatigue strength joint with the steel pitch pinion shown in the figure. An additional design feature is the crossed spar layout which permits the root moments and shears to be carried efficiently across the hub, yet permits the blades to be aligned parallel for storage. Collective pitch actuation was accomplished as shown in Figure 14 using a single spur gear and pinion design with redundant actuators and linkages.

Another new area of weight technology was the fan-in-tail installation. This was designed to comply with MIL-8501A specifications using current knowledge from several industry sources. The remaining component designs and their weight calculations were straightforward and used the detailed fixed wing methodology of reference 3 together with state-of-the-art rotary wing methods. Two levels of materials technology were considered: (1) all aluminum and (2) limited use of advanced materials in structural areas which have been demonstrated in current aircraft programs and would be considered as practical for a 1980 prototype aircraft.

Figure 15 illustrates the overall impact of the X-Wing empty weight on rotary wing VTOL historical weight trends. By utilizing the rotor as the sole lifting system and by minimizing the propulsion weight required with efficient aerodynamics, a reversal of the weight trend has been produced.

5. Mission Analysis

The results of the weight and aerodynamic studies were combined with a propulsion/drive system study to provide inputs for a mission analysis. The optimum propulsion arrangement from a weight and performance standpoint appeared to be a single fan engine for thrust and dual shaft engines for rotor drive and compressor power. A detailed mission calculation which illustrates the potential benefits of the X-Wing for such diverse applications as ASW and civilian transport is shown in Figure 16. It indicates the potential payload improvements of the X-Wing, relative to other rotary wing VTOL's, may be greater than 100 percent for a typical medium range mission.

6. Rotor Aeroelasticity and Dynamics

The critical aeroelastic and dynamic aspects of the design are (1) aeroelastic bending divergence in the stopped wing mode, (2) resonant amplification of blade vibratory bending stresses during rotor slowing and stopping, and (3) potential high frequency coupled instabilities of isolated blades, multi-blades, and the rotor/body combination. The divergence design has been alluded to previously. In general, for blade aspect ratios below approximately 13.0, it is not found to impact the blade weight fraction. The mode of divergence is dominantly a clamped root pure bending condition and, as such, is straightforward to analyze. Resonant amplification of blade airloads is a potentially serious problem for any variable RPM rotor. Although the problem was not found to be severe with an unloaded rotor (reference 4), it will be of much greater significance for the highly loaded X-Wing. The major excitation will occur with the lower blade modes at tip speeds near maximum. For example, a stress buildup was known to occur on previous unloaded, slowed and stopped rotors when the first flatwise bending crossed the 2 per rev excitation near 60-percent RPM. This was partially due to the frequency coalescence and also partially due to a significant second harmonic airload content at the high advance ratio range. The solution for this problem with X-Wing has been twofold: (1) the rotor is decelerated rapidly using a mechanical brake so that only a limited number of high fatigue cycles will occur, and (2) the first flatwise blade frequency has been placed above 2 per rev. The latter condition is quite unusual for rotor design as it implies extremely high stiffness. However, the constraint is compatible with good divergence design so that for composite construction, a value of approximately 2.2 per rev is obtained without varying either mass or stiffness distributions from the values needed for the basic wing design. Figure 17 indicates the frequency characteristics of a 30,000-pound design.

The potentially high frequency instabilities are currently being analyzed for X-Wing. The design philosophy has been to use high stiffness in all modes so as to avoid strong coupling effects. However, the nature of the section design requires the elastic axis and mass center to be coincident at mid-chord. It thus remains to be seen if the rotor system can be designed to be flutter free at very high speeds.

7. Stability and Control

The stability and control characteristics of X-Wing are very specialized. The most critical stability and control problem of stopped/stowed rotors has historically been coupled rotor/body low frequency dynamics during transition. A promising solution to the problem (shown in Figure 18 from reference 5) is made possible by employing four blades and transitioning around zero angle of attack using the blowing to obtain the lift and control required. In this manner, the oscillatory rolling and pitching moments on the X-Wing should be very substantially reduced even when allowing for gust effects.

8. Summary

A new aircraft concept has been presented which employs Circulation Control Rotor Aerodynamics technology to achieve an efficient compromise of hover and cruise performance using only a single lifting system. The concept also offers a speed potential approaching Mach 1.0 with excellent fixed wing maneuver capability. A low empty weight fraction appears possible using the efficient structure of the rotor blades. Certain potential dynamic and stability and control problems are currently being studied both analytically and in the wind tunnel. At the present time, there do not appear to be any fundamentally limiting technical problems which will prevent the timely development of this unique aircraft.

9. References

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2. Rotorcraft Parasite Drag, special report presented to the 31st Annual National Forum by the Ad Hoc Committee on Rotorcraft Drag, Washington, D.C., May 1975.

3. W.H. Ahl, Hypersonic Aerospace-Vehicle Structures Program. Volume II - Generalized Mass Properties Analysis, Martin-Marietta Corporation, Technical Report AFFDL-TR-68-129, Vol. II, Part I, Jan 1969.

4. E.A. Fradenburgh, R.J. Murrill and E.F. Kiely, Dynamic Model Wind Tunnel Tests of a Variable-Diameter, Telescoping-Blade Rotor System (Trac Rotor), USAAMRDL Technical Report 73-32, U.S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, Virginia, July 1973.

5. J.P. Shivers, Wind-Tunnel Investigation of Various Small-Scale Rotor/Wing Configurations for VTOL Composite Aircraft in the Cruise Mode, NASA Technical Note D-5945, Langley Research Center, Hampton, Virginia, Oct 1970.

6. E.O. Rogers, Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods, ASED Technical Note AL-273, Naval Ship Research and Development Center, Bethesda, Maryland, Aug 1972.

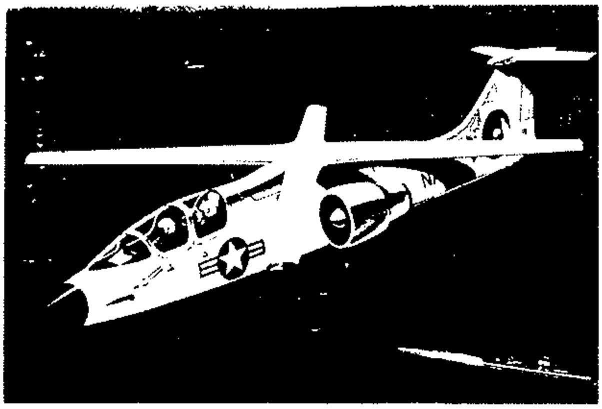

Figure 1 – Circulation Control X-Wing V/STOL Aircraft Concept

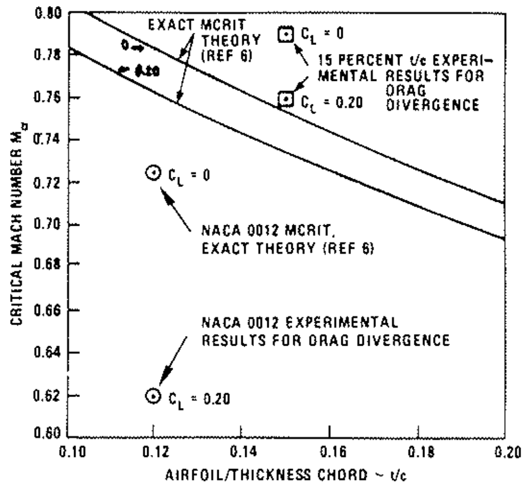

Figure 2 – Compressibility Characteristics of Two Dimensional C.C. Airfoils at Zero Angle of Attack

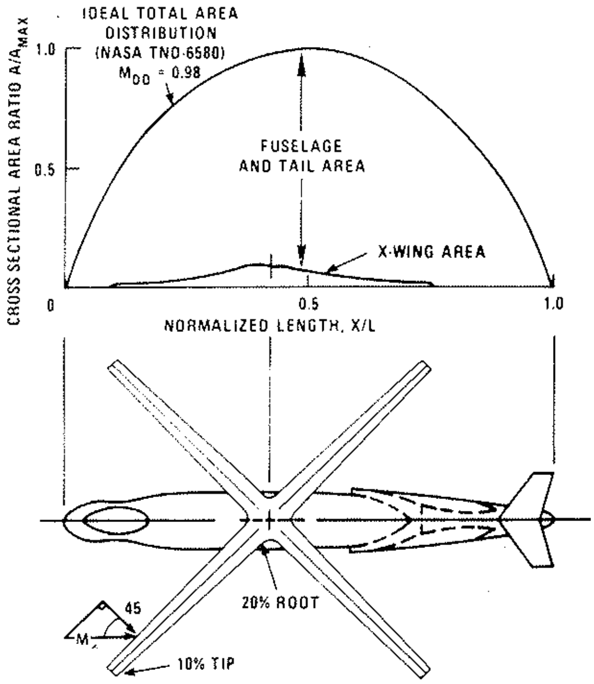

Figure 3 – X-Wing Transonic Design Features (Approximate Drag Divergence Mach = 0.89)

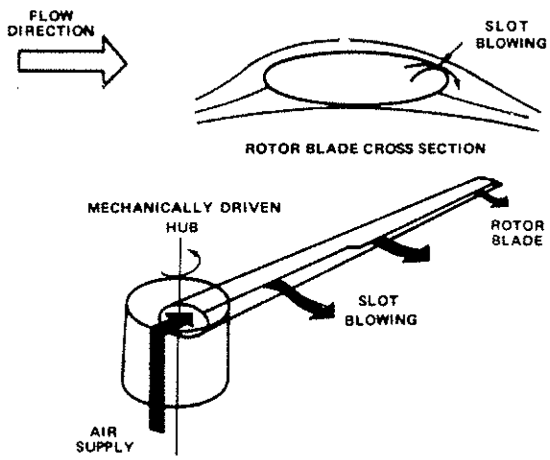

Figure 4 – Circulation Control Rotor–Basic Concept

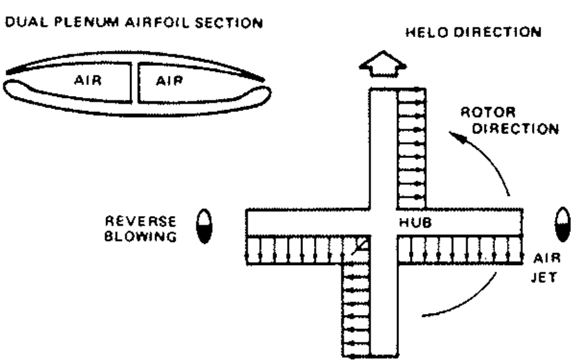

Figure 5 – Dual Blowing Concept for Transition Through High Advance Ratios

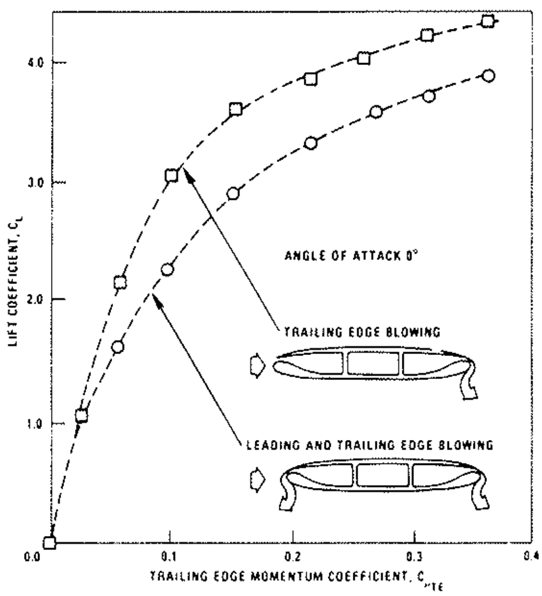

Figure 6 – Effect of Simultaneous Leading and Trailing Edge Blowing

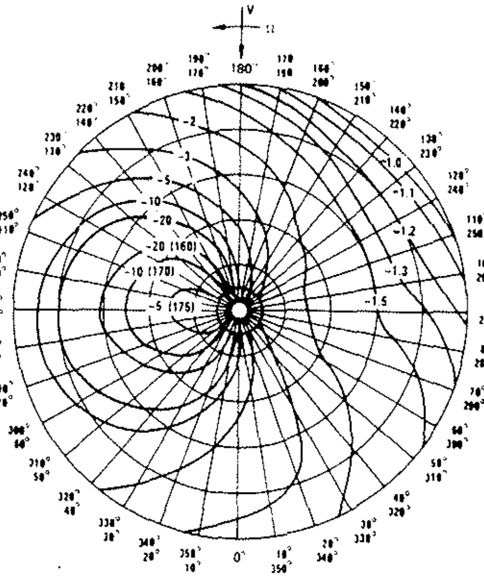

Figure 7a – Angle of Attack Distribution, Degrees

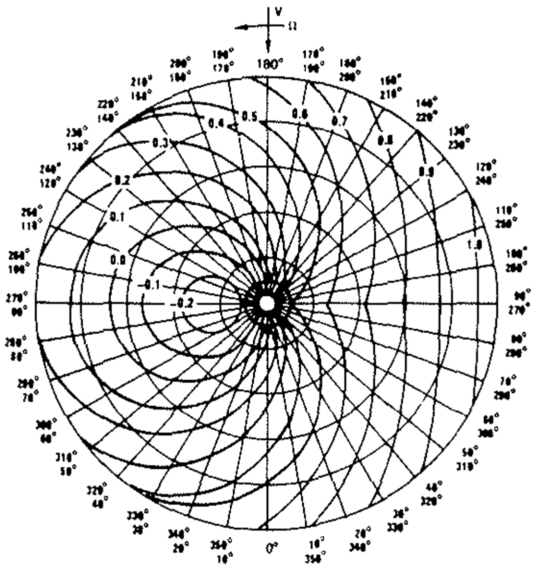

Figure 7b – Mach Number Distribution

Figure 7 – Rotor Aerodynamic Environment During Transition Flight ($\mu = 0.7$, $\alpha_s = 0$, $C_{T/\sigma} = 0.129$)

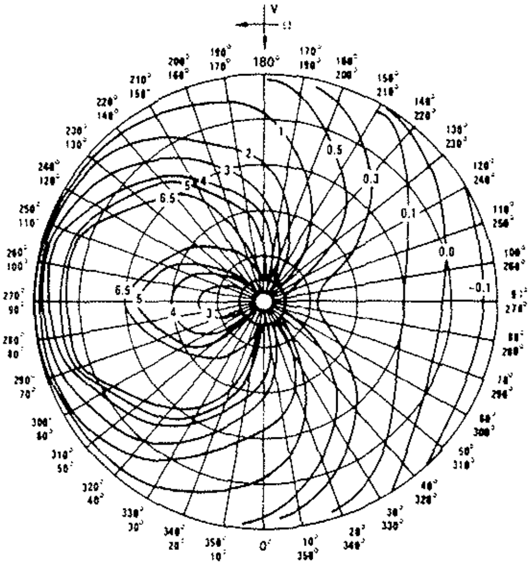

Figure 7c – Lift Coefficient Distribution, C_L

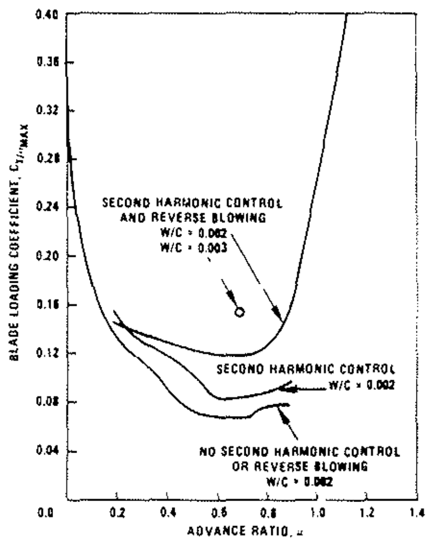

Figure 8 – Maximum X-Wing/Rotor Thrust Capability
(w/c is slot height to chord ratio)

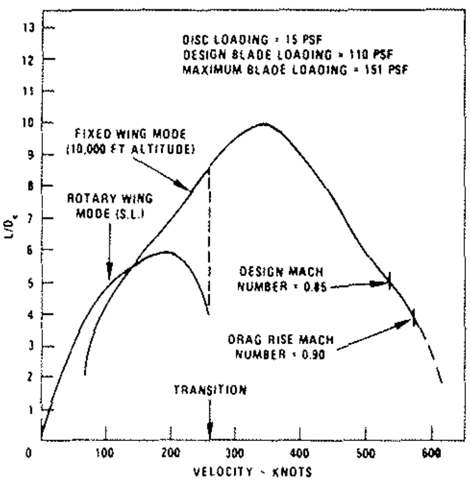

Figure 9 – X-Wing Aircraft Equivalent Lift-to-Drag Ratio

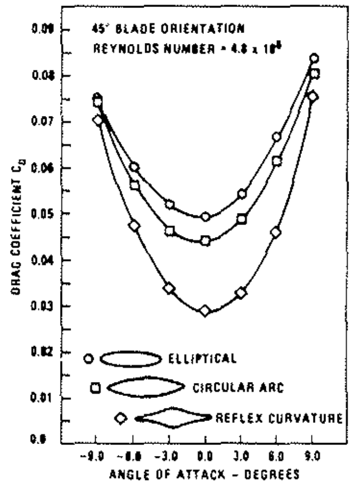

Figure 10 – Drag Coefficient (Based on Hub Planform Area) for Three Hubs with Shanks

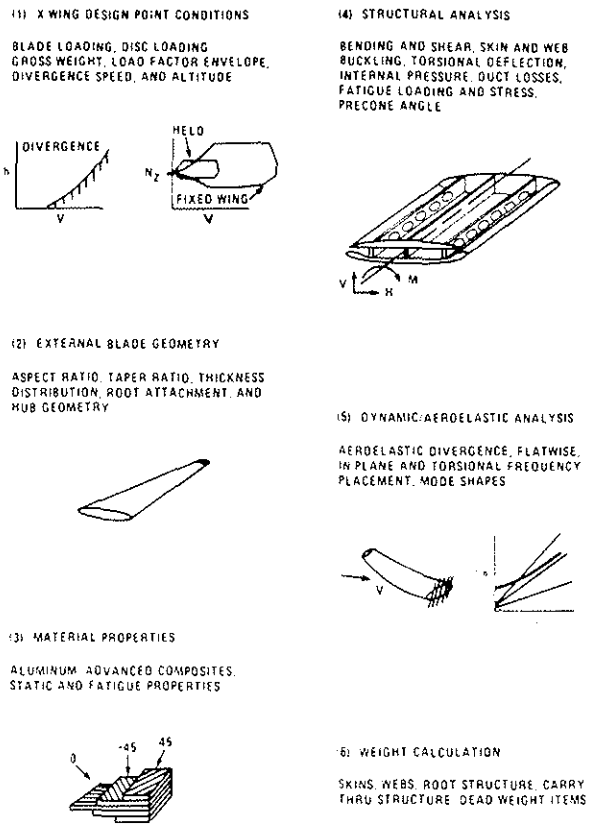

Figure 11 – Wing/Rotor Design and Weight Analysis Approach

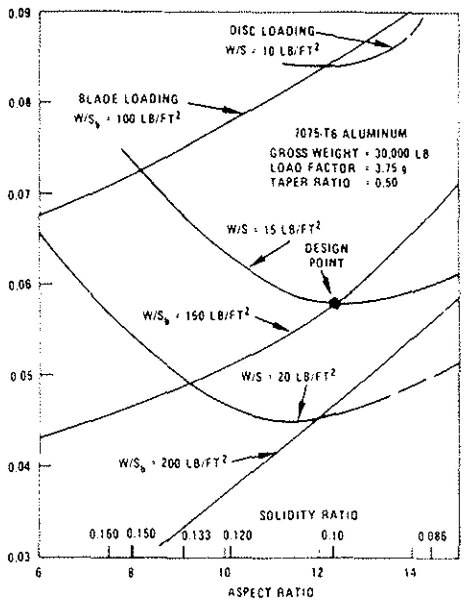

Figure 12a – Blade Weight/Gross Weight Ratio

Figure 12 – Aluminum Blade Construction: Effect of Design Parameters

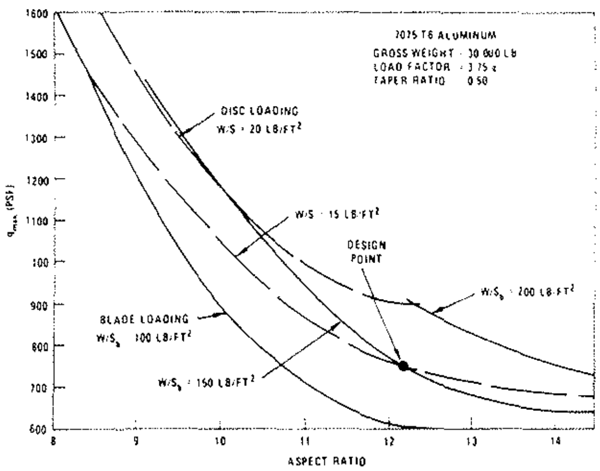

Figure 12b – Divergence Dynamic Pressure

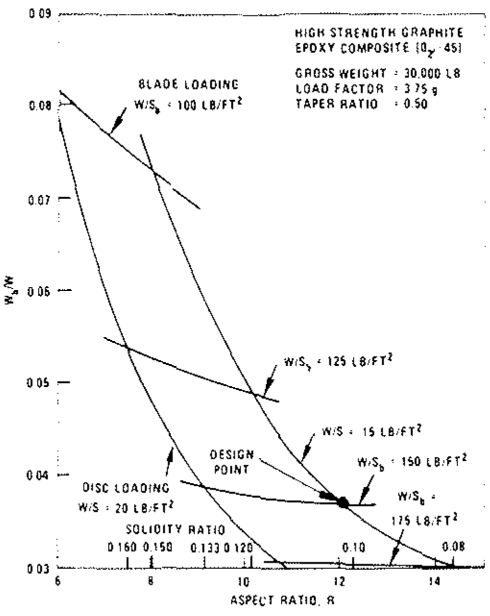

Figure 13a – Blade Weight/Gross Weight Ratio

Figure 13 – Graphite Composite Construction: Effect of Blade Design Parameters

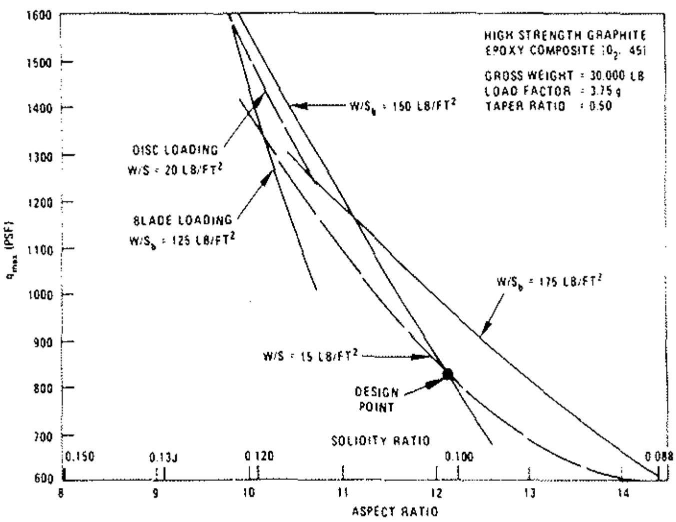

Figure 13b – Divergence Dynamic Pressure

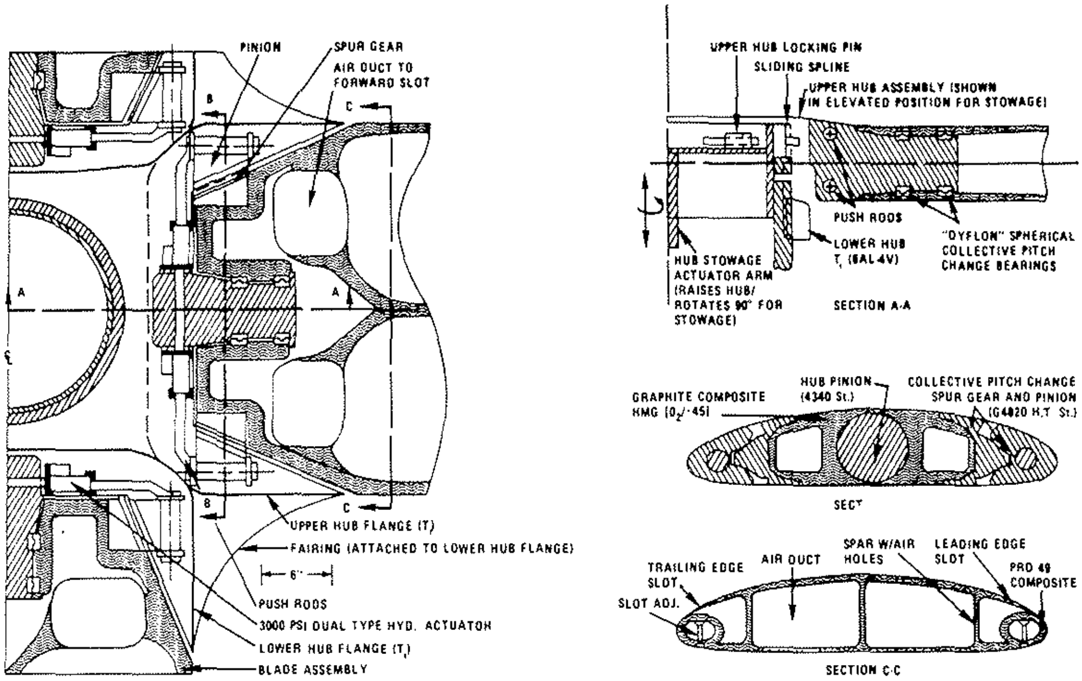

Figure 14 – X-Wing Dual Cross-Spar Rotor Hub Structural Design

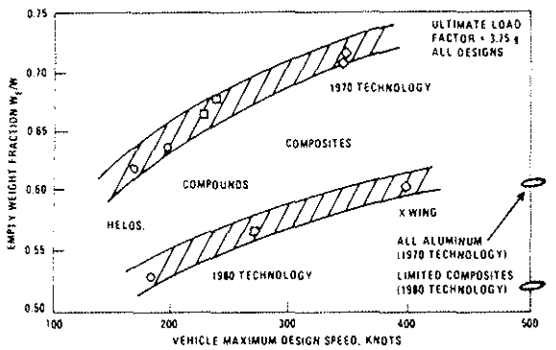

Figure 15 – Impact of the X-Wing Design on Rotary Wing VTOL Empty Weight Trends

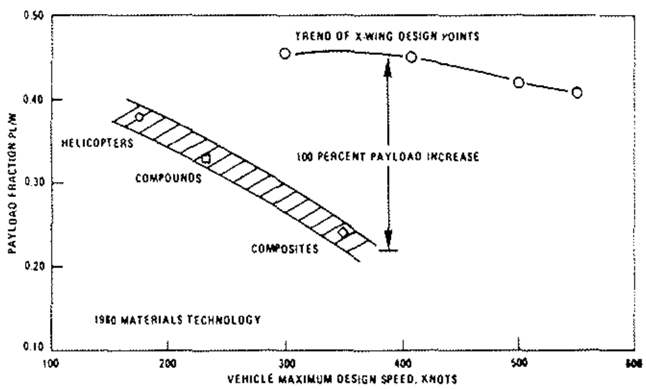

Figure 16 – Comparison of X-Wing Payload Capability with Other Rotary Wing VTOL Aircraft
(200 nautical mile mission)

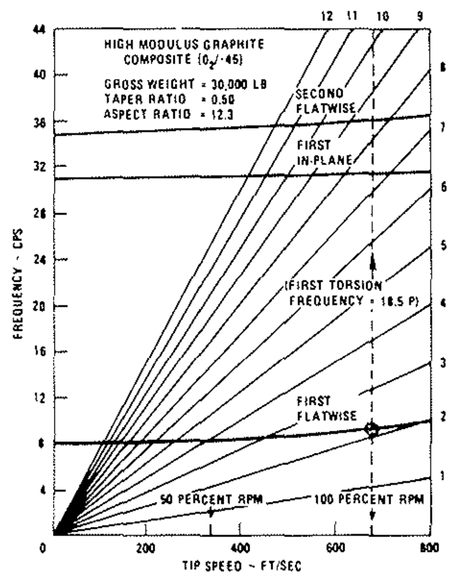

Figure 17 – X-Wing Rotor Blade Frequency Characteristics

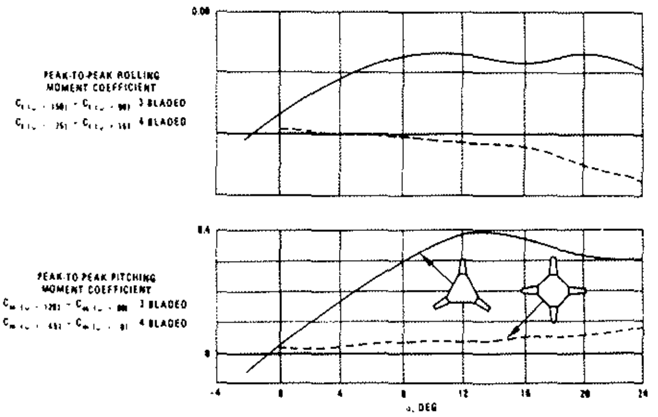

Figure 18 – Effect of Four Blades on the Reduction of Peak-to-Peak Moments during the Rotor Revolution (Reference 5)