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AN ADVANCED COUNTER ROTATING DISK WING AIRCRAFT CONCEPT

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NIAC

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TECHNICAL ABSTRACT

The need for rapid response in military and civilian rescue and other emergency operations is paramount. Future emergency mission requirements, including rescue and special operations, have shown a critical need for higher cruise speeds than are currently possible with conventional rotorcraft. Helicopters have been the traditional vehicles for these missions because of their VTOL capabilities and ability to hover, but their response times have always been too long. As the U.S. Military is increasingly finding itself pushed into more and more expeditionary operations around the world, there is a great need for an aircraft that will supply both vertical takeoff and landing with efficient long-range cruise; a feature the helicopter does not have. Future rotorcraft systems will, therefore, have requirements for higher cruise speeds than are currently possible with conventional rotor systems. To achieve this, both the VTOL / hover capabilities of the helicopter, coupled with the high speed cruise capabilities of fixed wing aircraft, would be necessary to meet these requirements. One solution is to utilize a large circular hub fairing as a fixed wing with direct propulsion for high speed flight. For low speeds and hover capability, variable pitch blades would be extended and the entire disk rotated. The proposed concept in this study contains the unique combination of efficient vertical takeoff and landing capabilities of a helicopter with that of the high-speed cruise efficiencies of a fixed wing aircraft. The initial sizing chosen for this vehicle design was based on a preliminary vehicle study which was presented at the American Helicopter Society Vertical Lift Aircraft Design Conference, Jan 18-20th , 1995, [1]. Under this NIAC study the initial design of the hybrid rotary and fixed wing aircraft configuration, that includes both single and counter-rotating disks, with variable pitch blades, was studied. Preliminary aerodynamic, aeromechanical and mechanical requirements for the mission, that covered high speed fixed disk flight and rotating disk hover conditions, were studied in order to determine the feasibility of the design for this concept. For this study the preliminary design of the configuration, was sized for a 3500lb GTOW, 300+ knot cruise speed, 600 Nm range, combat search and rescue (CSAR) configuration.

ANTICIPATED BENEFITS

This preliminary design effort will assist in future development of an aircraft which will encompass hover capabilities, lower noise, and efficient high speed cruise. The aim is to produce a vehicle that will have improved cruise aerodynamics over the conventional helicopter whilst maintaining the VTOL capability of the helicopter. Helicopters are used in missions where precise hovering and VTOL capability outweigh the expense and performance limitations. For those missions which involve mainly transporting people, a new vehicle which combines the vertical flight capability of a helicopter with the speed, comfort, and economy of a fixed wing aircraft would extend that market to many more customers. This proposed system will be an efficient, high speed, VTOL aircraft, which is not a direct competitor to the conventional helicopter, but is considered to be a new technology transportation system that will create opportunities for new markets and applications.

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1.0 INTRODUCTION

Future rotorcraft systems have requirements for higher cruise speeds than are currently possible with conventional rotor systems. To achieve this, both the VTOL / hover capabilities of the helicopter, coupled with the high speed cruise capabilities of fixed wing aircraft, would be necessary to meet these requirements. One solution is to utilize a large circular hub fairing as a fixed wing with direct propulsion for high speed flight. For low speeds and hover capability, variable pitch blades would be extended and the entire disk rotated. Combinations of a single disk rotor system with tail rotor or jet, for torque balance, or counter rotating disk rotor system can be utilized depending upon the efficiency requirements.

With the support of LOTC, Inc., and the School of Aerospace Engineering at the Georgia Institute of Technology, Diversitech, Inc., was awarded an NIAC contract, “ An Advanced Counter-Rotating Disk Wing Aircraft Concept”, NIAC/USR Grant No. 07600-028, on June 1st, 1999.

The concept under study is a unique combination of the efficient vertical takeoff and landing capabilities of a helicopter, coupled with the high cruise speed of a fixed wing aircraft. The concept utilizes a solid, co-axial, driven disk of about 60% of the rotor diameter for vertical flight operations. The rotor blades, located on the periphery of the disk, may be retracted after transition to forward flight with the solid disk acting as a fixed wing. This arrangement produces the low disk loading needed for efficient hover, and provides a fixed wing planform for high speed flight. Maximum speed is limited only by the installed power. Under this study the preliminary design of a hybrid rotary and fixed wing aircraft configuration, was sized for a 3500lb GTOW, 300+ knot cruise speed, 600 Nm range, combat search and rescue (CSAR) configuration.

1.1 Background

Since the development of the helicopter, military and commercial aircraft operators have long sought a vehicle which could perform a vertical takeoff and landing with the cruise speed and performance of conventional fixed wing aircraft. The United States has been the most prolific producer of vertical and short takeoff and landing (V/STOL) aircraft configurations in the world. Reference [2], shows a summary of 60 types of V/STOL aircraft that were studied, tested, and flown up to the 1970’s, most of which were US designs. Nearly all were developed to meet military missions as transports or fighter/attack aircraft. Commercial derivatives of some were considered by the manufactures as a secondary market. Aircraft can be lifted and propelled by various combinations of rotors, propellers, fans and jets powered by reciprocating and turbine engines. Vertical flight can be achieved by tilting the entire aircraft from horizontal to vertical, tilting only the thrust producer, vectoring the entire thrust, or using separate systems to produce lift and forward thrust. Nearly every possible combination of these have been investigated or flight tested over the past four decades with only two types, other than pure helicopters, reaching production for military services; the AV-8 vectored jet and the V-22 tilt rotor. For commercial operators, the only current option for VTOL flight is the helicopter. The helicopter has been developed to the point where there are few performance gains to be made in speed, range/payload, and ride comfort, without large expenditures of resources. The helicopter, in its present form, has well served its current users where VTOL and precise hovering control are required to perform the mission. There is, however, an untapped market of users who would like VTOL capability with the speed, range, ride comfort, and operating economy of fixed wing aircraft. The M-85 High-Speed Rotocraft Concept, Ref. [3], explored a configuration that combined the efficient hover of a helicopter with a high speed cruise of Mach 0.85. Other, advanced, high-speed configurations, such as a reaction driven rotor/wing with a cruise speed of 450 kts., have been evaluated for further development, Ref.[4], however, a practical, medium speed vertical takeoff and landing commercial aircraft remains an elusive goal of designers and operators. Commercial derivatives of the V-22 are planned; however, they are several years away from reality.

1.2 Helicopter Operations

A helicopter can be designed for efficient hover by using a large rotor with a low disk loading and a blade twist distribution optimized for low speeds. The low disk loading has the added benefits of reduced noise and low downwash velocity, making it more environmentally acceptable. These elements; however, result in an increased drag at higher speeds thus reducing cruise efficiency. The ability to perform a sustained hover and vertical flight provides a unique capability, but comes at a high price in cruise efficiency. A helicopter is not very efficient in cruise compared to fixed wing aircraft. As a byproduct of low cruise speeds and high fuel consumption, the range capability of helicopters is also lower than fixed wing aircraft.

A long range helicopter could be produced, but due to high cabin noise and vibration levels, passengers may not be comfortable on a long flight. The helicopter users have accepted its limitations, and have found applications where it is still the most efficient method to perform a mission. Expanding the operating envelope of the helicopter to higher speed, more efficient cruise, and longer range, would expand the number of missions such a vehicle could perform.

1.3 Next Generation High-Speed Rotorcraft Design

The vehicle being studied is an option to improving upon the attributes that current VTOL aircraft posses, by merging two proven design concepts together to produce a hybrid of rotary and fixed wing aircraft, using the most efficient features of each for that mode of flight. The innovation in this system is a circular hub fairing as a fixed wing, comprising either co-axial counter rotating disks, or a single disk, with retractable blades arranged around the periphery. This arrangement produces the low disk loading necessary for efficient hover. Combinations of a single disk rotor system with tail rotor or jet, for torque balance, or counter rotating disk rotor system can be utilized depending upon the efficiency requirements. The use of the counter-rotating disks gives the vehicle neutral torque enhancing stability, eliminating the need for a tail rotor and thus the power drain and noise of a tail rotor, however, the complexity and weight of the counter rotating disk system may be prohibitive depending on mission requirements. During cruise flight the rotor blades are unloaded, or the rotor can be stopped and the blades retracted, and the aircraft is supported by a circular wing and propelled directly by an external propeller or ducted fan. Maximum cruise speed would only be limited by the installed power and not by the rotor aerodynamics as in a helicopter. The control, in both vertical and horizontal flight, can be achieved in the conventional manner via the use of collective, with control in hover being provided by the use of cyclic pitch control. During 'fixed-wing' flight, the entire lifting surface is also the control surface. The rotor will be driven with a high speed, low torque, flight weight drive shaft which will be clutched in and out at the power plant. The power shaft will run vertically to a constant velocity (CV) joint located on the center line of the pitch and roll axis. A planetary gear system is contained within the disk system to provide the final gear reduction for the rotor system with an inspection access to the gear box in the center of the top disk. Since the rotor is only powered during takeoff and landing, or less than 5% of the vehicle operating time, the gearbox can be made much lighter than a helicopter transmission which runs 100% of the vehicle operating time.

A key to a successful VTOL vehicle is an efficient hover. While this vehicle concept does allow for a low disk loading, based on total rotor diameter, the inboard portion of the rotor is a solid disk. Using the basic blade lift equation it can be shown that elimination of the inboard 50% of the rotor blade results in only a 12.5% reduction in total lift. Rotor blade twist distribution can be optimized for hover, since the blades are unloaded or retracted during cruise. Reference [3] cited test stand data which showed a rotor with a large centerbody disk had a thrust augmentation in ground effect 10% greater than from a conventional rotor. In addition, the downwash load on the fuselage from the rotor would be negligible since most of the fuselage would be located underneath the disk. This fuselage vertical drag is typically about 2% for well designed single rotor helicopters, according to Reference [5].

1.4 Circular Wing Aerodynamics

During conversion and in horizontal flight, the vehicle will be supported by the circular hub disk/wing. Lift in both VTOL and cruise modes is produced and controlled by the same platform located directly over the center of gravity. Experimental work performed in the 1930's on circular wings gives some insight to the aerodynamic characteristics of the configuration during cruise, “fixed-wing” flight. Reference [6] lists aerodynamic data for a thin, circular disk and various airfoil cross-sections of 12% thickness. The thin disk has a lift curve slope of 0.027 per degree of angle of attack, with a C_L max of 1.2 at an angle of attack of 40 degrees. The airfoil shapes produced C_L max values of 1.5 to 1.9 at an angle of attack of up to 45 degrees with much lower drag than the flat plate. A disk has an aspect ratio of only $4/\pi$, or about 1.27, therefore the drag due to lift or induced drag will be higher than on a typical fixed wing aircraft. The experimental data showed that the most efficient operating point or maximum lift to drag ratio (L/D) of a circular wing occurs at low lift coefficients around 0.20. This produces a wing L/D of about 10 to 1. In high speed cruise, lift coefficients can be low, thus reducing the induced drag, and the profile drag of the fuselage and the rest of the vehicle will dominate the total drag. The experimental data also showed that a circular wing was impossible to spin, greatly increasing the safety of the vehicle.

1.5 Conceptual Design

In order to establish a baseline for future studies and for comparison with existing vehicles, a conceptual design of a vehicle was performed by Vmax Technologies, ref [1]. Since most of the comparisons were made against helicopters, it was decided to design a vehicle similar to current 4/5 seat single engine turbine powered helicopters. The engine chosen for the design study is the Allison 250-C30 which produces 650 shp for takeoff. Various versions of this engine power the majority of the light turbine helicopters produced in the US. Takeoff gross weight (TOGW) ranges from 2500 lb. to 3500 lb., with rotor diameters of 22ft, 26ft and 30ft, fit within the trends of current production helicopters. The conceptual vehicle rotor has 2 to 4 blades in each disk with a rotor system of four to eight blades, depending on the required configuration. Piston powered helicopters tend to have higher empty weight fractions than turbine helicopters due to higher propulsion system weight. To efficiently lift this extra weight, a very low disk loading is required. All of the piston helicopters surveyed had disk loadings of less than 3.6 lb/ft^2. This resulted in a very efficient rotor, capable of lifting more than 10 pounds for each horsepower. The low disk loading also limited cruise speeds to around 100 kts. Turbine helicopters, with lighter engine weights, are able to trade efficient hover for higher cruise speeds. The MD500 series has the highest disk loading (around 5.5 lb/ft^2) and highest cruise speed (135 kts) of any of the single engine helicopters, ref [7]. The conceptual design takes advantage of a lower disk loading for efficient hover since the rotor diameter (with the blades extended) does not impact cruise performance if the blades are retracted.

Rotor lift was calculated using a program developed by Vmax Technologies for propeller blade analysis which utilizes a quasi 3-D lifting line vortex method. The disk lift was sized by the FAA 61 kt. stall speed for single engine fixed wing aircraft, assuming a C_L max of 1.6 .The rotor lift does not begin to seriously degrade until the solid disk reaches 50% to 60% of the rotor diameter. Also, disk lift increases dramatically above 40% of the diameter, resulting in practical vehicles with a solid disk about 50% of the rotor diameter. If any part of the rotor system malfunctions on the ground or in forward flight, the vehicle is capable of performing a safe conventional takeoff and landing as a fixed wing aircraft. The highest cruise efficiency occurs at a disk lift coefficient of about 0.20. Since the conceptual vehicle is unpressurized, cruise altitudes will be limited to below 12,500 ft. For a 200 kt cruise, this would result in a disk diameter of around 14 ft. To achieve a 200 kt cruise speed at a typical cruise altitude for unpressurized aircraft of 8,000 ft **@** 75% engine power would require an equivalent flat plate drag area (A_d) of about 4.0 square feet. Reference [5] gives a trend line for aerodynamically clean helicopters that would give a 3000 lb. vehicle a drag area of 5 ft^2. Calculations performed in reference [8], showed current production single engine fixed wing aircraft in this weight class have drag areas of 3 to 4 ft^2, and composite experimental airplanes have drag areas of 2 to 3 ft^2. A conceptual vehicle in this size class would have an aerodynamically clean fuselage with retractable landing gear and integrated propulsion system driving a pusher propeller. The wing induced drag will be slightly higher, but reference [3] confirmed there is very low interference drag between the wing and fuselage. Therefore, the target A_d of 4.0 ft^2 appears reasonable for this vehicle.

1.6 Circular Wing Efficiencies

Preliminary research by Vmax, Inc, ref [4], has shown that the elimination of the inboard 50% of the rotor blade results in only 12.5% in loss of blade lift. And, the rotor blade twist can be optimized for hover since the blades are retracted for cruise. It was shown, ref.[12],that a rotor with a large center-body disk had a thrust augmentation in ground effect that was 10% greater than that of a conventional rotor. And, the down-wash load on the fuselage is typically around 2% for helicopters. This loss is negligible because the disk shields the fuselage.

Further research by Vmax, Inc has shown that the disk lift does not seriously degrade until the solid disk occupies 50% to 60% of the rotor diameter. Therefore, a practical vehicle can be designed with the solid disk covering 50% of the rotor diameter. In addition, this research indicated that an aircraft with a 31 foot rotor diameter and 2 blades in each disk section (4 blades in the rotor) would support a 2500 lb vehicle with a 4 lb/sq-ft disk loading and a 7 lb/hp thrust load.

From ref. [5], we see that the Disk has a low aspect ratio, and its most efficient operating point, or maximum lift to drag ratio of about 10 to 1 occurs during cruise at low lift coefficients around 0.20. Thus, at high-speed cruise the low lift coefficient results in reduced induced drag, and the profile drag of the fuselage dominates the total drag.

2.0 TECHNICAL PROBLEM DESCRIPTION AND OBJECTIVES

Although a very basic preliminary sizing of this vehicle had previously been performed, ref [1], the most fundamental questions regarding the ability to fly the required mission, aerodynamics of the disk wing, and hover capabilities, had not been addressed. The primary focus of this Phase I study is to address these issues via the investigation of the fixed wing mission for a sized CSAR vehicle.

In order to perform a representative mission analysis a conceptual design of the disk-wing rotor system, with and a nominal vehicle weight was required. An effective way to do this was to establish the size and weight of a two-man concept aircraft that might be assigned a variety of missions including a reconnaissance role or combat search and rescue role. From an experience base the size and weights of such a vehicle can be estimated in order for the drag polars, which are necessary for the mission analysis, to be determined. Included in the vehicle weight estimate are components such as, fuel, engine, disk/rotor system, pilots, avionics, drive shafts, payload etc.

Assuming sufficient fuel to fly a 4 hour mission, this established a baseline vehicle weight and propulsion design to size a solid disk hub, and to determine a nominal blade extension for the required rotor diameter. The mission analysis also determined an initial set of lift and drag profiles for the proposed vehicle design.

Once the required lift coefficients had been determined for the mission profile, an optimum disk plan-form, for use in the analysis of the disk performance, was chosen from readily available airfoil data, [13].

With the disk diameter determined, a blade design for the hover analysis needed to be established. Assuming an estimated GTOW and available horsepower, a hover analysis for the vehicle was performed in order to demonstrate sufficient lifting capacity for the chosen blade design.

Finally, a preliminary aeromechanical analysis of the disk rotor blades for both single and counter-rotating configurations for the entire rotor system was required in order to determine any potential rotor instabilities.

A preliminary mission analysis, for this 3500lb GTOW concept, was performed in order to determined the optimum disc size requirements for the chosen vehicle based on the mission requirements, ref. [1]. The basic configuration for this conception design is illustrated in Figure 1.

Under this study the preliminary design of a hybrid rotary and fixed wing aircraft configuration, was sized for a 3500lb GTOW, 300+ knot cruise speed, 600 Nm range, combat search and rescue (CSAR) configuration. The objectives of this study were as follows:

- From preliminary geometric layout define the basic CSAR mission
- Perform a Fixed wing mission analysis using NASA Langley FLOPS program, [14].
- Determine Required Disk Size from the FLOPS analysis results
- Determine Rotor Blade Sizing for vertical lift
- Perform a Hover Analysis.
- Perform an Aeromechanical Analysis.

- Generate Preliminary model drawings.

In order to achieve the required objectives the study was performed in seven tasks. These tasks were as follows:

TASK 1.0 -- Circular wing Aerodynamics

The initial task in this study included the aerodynamic analysis of a standard disk plan-form including analysis of the disk and fuselage drag profiles for flight regimes from 150 to 500 knots at altitudes from 1000 to 20,000 feet MSL. The aerodynamic analysis conducted under this task will also attempt to evaluate the transition phase from vertical to cruise flight.

This task was performed by Diversitech Inc, utilizing the NASA Langley Flight Optimization System program (FLOPS), to perform a fixed wing analysis of the vehicle concept. The objective of this analysis was to derive the lift and drag characteristics of the vehicle, and to confirm, re-adjust, or modify, the preliminary design, vehicle weight and dimensions of the original concept aircraft, as shown in Figure 2.1.

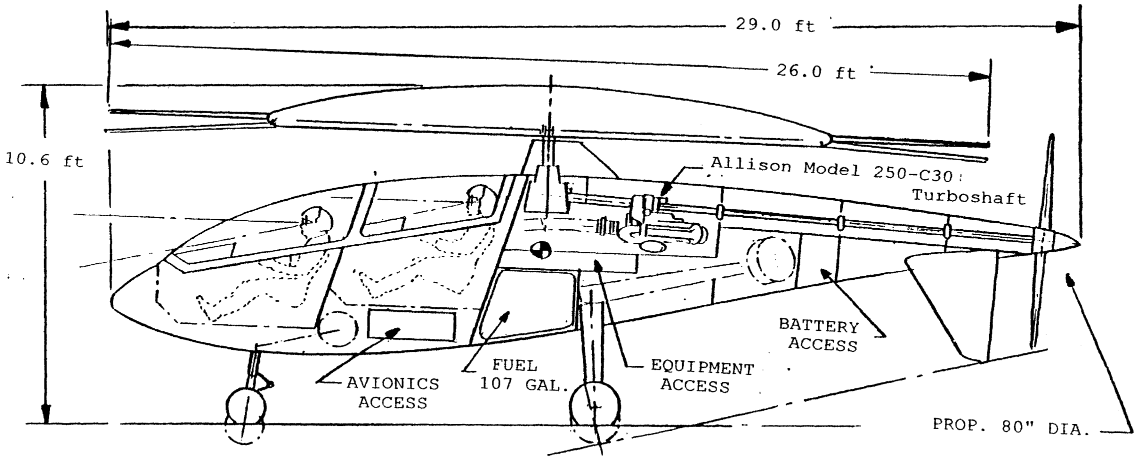


Figure 2.1: Showing the Vmax conceptual rotorcraft design from reference [1].

TASK 2.0 -- Hover and disk blade sizing analysis

This task contained an assessment of previous NASA circular wing study results, ref.[6], on low aspect ratio airfoils and the selection of an optimum plan-form for use in the analysis of vehicle stability and control dynamics. This work was performed by Diversitech, Inc.

After an optimum plan-form is selected the analysis of the disk performance during hover and the transition to horizontal flight was performed. With the disk size having been determined by the fixed wing analysis in Task 1, an initial analysis of the disk/rotor aerodynamic performance in the hover mode was conducted. This effort was conducted by Diversitech, with the support of Hartzell Propeller, Inc. Under this task the investigation of the rotor blade size, and the optimum number of blades required, to support vertical lift for the maximum vehicle gross weight conditions, determined in Task 1, was performed.

TASK 3.0 -- Rotor System Aeromechanical Analysis

In this task a preliminary aeromechanical analysis of the disk rotor blades was performed by Diversitech. In addition to this the Georgia Institute of Technology looked at the entire rotor as a system, for both the single disk and counter-rotating configurations. This effort focused on disk spacing, the number of blades per disk and the mechanical design needed to ensure aeromechanical stability of the disks. The basic aeromechanical analysis for the counter-rotating disk/blade systems was conducted using a high-fidelity multi-body dynamics tool called "DYMORE" which was developed originally by Rensellaer Polytechnic Institute and Sikorsky, ref [15], and was drastically improved in recent years. A comprehensive model was created with counter-rotating discs modeled as rigid bodies and blades modeled as elastic composite beams, with realistic cross-sectional properties obtained by means of detailed cross-sectional analysis code VABS, ref [16]. This approach was expected to provide a superior accuracy as compared to modal frequency analysis which uses traditional 3-D Finite Element Methods.

This improvement in fidelity was crucial since a non-traditional configuration is investigated and no correlation with experimental data was available. The gains in accuracy are achieved by better modeling interactions between the individual blades, discs and the hub. At the same time, computational costs remain reasonable due to an efficient 1-D modeling of the individual blades by VABS, which still provides accuracy that is comparable to detailed 3-D FEM, ref [16]. Modeling of discs as rigid bodies is expected to be adequate at the present stage since discs are designed with the minimum flexibility. Accommodation of shell elements into the DYMORE, which, presently, is underway, will allow one to refine the analysis at the next stage, if necessary. This Task was performed by the School of Aerospace Engineering at the Georgia Institute of Technology.

TASK 4.0 - Design results with evaluation and Final Report

Analysis of the study results of all three tasks is explained in this Final Report, including a summary of conclusions.

TASK 5.0 – Model Scaling for Prototype Development

In preparation for follow-on research, Diversitech, model drawings for the rotor/blade configuration analyzed in this study, were constructed.

3.0 PHASE I SUMMARY

A Phase I program, performed for the NASA Institute for Advanced Concepts, “ AN ADVANCED COUNTER ROTATING DISK WING AIRCRAFT CONCEPT”, NIAC/USR Grant No. 07600-028, which was structured to analytically evaluate an advanced rotorcraft conceptual design, is discussed below.

The conceptual design for the counter rotating disc wing aircraft was presented in a paper given at the American Helicopter Society Vertical Lift Aircraft Design Conference, January 1995. A preliminary design study of this system was performed by Vmax Technologies, and this concept forms the basis for the rotorcraft vehicle analyzed under this study. The main feature of the Vmax vehicle is the counter rotating rotor, which was included to remove the need for a tail rotor to provide torque control during the VTOL phase of the mission.

The objectives of this study were to define a basic rotorcraft mission, based on the preliminary Vmax conceptual geometric layout, perform a fixed wing mission analysis, determine the optimum disk size for the vehicle, determine the rotor blade design and perform a hover analysis, perform a preliminary aeromechanical analysis of the counter rotating and single disk system, and finally generate a set of preliminary engineering drawings for the disk/rotor system.

The main information, that formed the basis for the preliminary design concept was the estimated vehicle drag along with the use of an Allison 250-C30 engine, 650-450 shp, and the vehicle MGTOW of 3300lbs, which includes 700lb of fuel. Because the vehicle was considered to be unpressurized the maximum altitude was set at 12,500ft.

Using this conceptual vehicle design a fixed wing mission analysis was performed using the NASA Langley FLOPS program, ref.[14]. The results of this fixed wing mission helped to determine the basic flight envelope for the vehicle, which encompasses, range & endurance as compared to maximum speed, cruise speed, maximum altitude and disk diameter. Three rotor diameters were considered in the analysis; 22ft, 26ft, and 30ft. It is also important to note that at this stage of the design since the disk wing profile was unknown, an estimate using a Clark-Y airfoil shape, refs. [3] & [6], was used for the FLOPS analysis. The pusher, turbo prop design, cycle was generated from a Hartzell 80”, 5 blade, propeller design, and was generated using the NASA Navy Engine Program, (NNEP).
The FLOPS analysis results indicate that the maximum speed for the study vehicle is M0.5, approximately 300knots. The maximum endurance cruise speed of approximately M0.325 was also calculated. The average mission endurance was determined to be approximately 4hrs, and the maximum range was determined to be approximately 650nm.

The results of the fixed wing analysis were directly applicable for the choice of optimum disk diameter required for the GTOW of the vehicle. An assessment of the results determined that the most appropriate disk diameter to use for this vehicle design was 26ft. This disk diameter comprised a 16ft hub with 5ft blades attached to the periphery of the disk. The preliminary airfoil shape chosen for the disk was a NACA 66_1-012, which was chosen in order to provide sufficient internal volume for mechanisms. For symmetry the LE to 50% chord is used for disk profile. Also included in the sizing of the disk was an FAA stall speed requirement, for light aircraft, of 61 knots. Because of the potential for tail, or propeller, drag the landing AOA was $<15^o$. Assuming the landing weight is 2950 lbs. (i.e. 3300lbs. minus half the

fuel wt), at a 61 knot stall speed, data obtained from the FLOPS analysis indicates that the Clark-Y airfoil has a required C_L<=1.16. For the Clark-Y airfoil this C_L is achievable with a 12^o AOA.
Since the airfoil shape chosen for the disk, 50% LE/LE NACA 66_1-012 airfoil, did not have any aerodynamic data available, an attempt at determining the lift characteristics of this "pseudo airfoil" was made using the USAF DATCOM computer program, ref. [18].
The input to the program used the NACA 66_1-012 pseudo airfoil profile, with the circular planform approximated as a polygon. The gap, that would be present for the counter rotating disk system, was neglected, so in effect the analysis was performed on a solid disk, pseudo airfoil. The results from this analysis indicate that at 12,500ft, if 650 shp is available, the max speed is < 240 knots, determined by thrust versus drag. At 12,500ft, if 450 shp is available, the max speed is < 175 knots.
At 20,000ft, if 650 shp is available, the max speed is < 250 knots, again determined by thrust versus drag. At 20,000ft, if 450 shp is available, there is insufficient thrust is being generated by the pusher propeller to overcome the drag. Therefore, a higher horsepower would be required to overcome the drag at this altitude.

Under a separate study, a standard propeller design, was generated, for Diversitech, by Hartzell Propeller Company, Piqua, OH. The design was based on a 4 bladed rotor with a tip diameter of 26ft, and a hub diameter of 16ft. The available maximum horsepower of 650 shp was assumed with a design tip mach number of 0.9 being used. The design for the blade was supplied as a table indicating the blade section dimensions, and the rotor design was provided in the form of a propeller map. The resulting blade design had a 60" length, and 7" chord.

In order to determine the vertical lift capability a simple hover analysis was performed. With available 650 shp from the Allison 250-C30 engine, and the provided Hartzell rotor design, the requirement was to lift at least 3300 lbs. of "dead weight" vertically. To provide a margin of error 3500 lbs. lift was assumed to be required. The analysis was performed @SL with no ground/fountain effect, which may provide an additional lift, assumed. The results indicate that that with 650shp available, approx. 5000lbs of lift can be generated. With 450shp available, approx. 4000lbs of lift can be generated which would suggest that the 450 shp condition would allow the remaining horsepower to be used for up & away forward flight.

Although not studied in detail, an attempt to demonstrate the ability of the system to transition at 150knots forward speed, and 2,000ft altitude, was made. The results indicated that there was marginally sufficient engine power to both maintain 3500 lb of rotor thrust whilst also maintaining 150knot forward speed, and it was, therefore, concluded that transition was possible. The postulated method for transitioning was to transferring power from the rotor to the propeller, whilst simultaneously changing AOA on the disc. The increased disk lift will need to compensate for the reduced rotor lift due to the decreasing rotor power.

A very preliminary blade aeromechanical analysis, via a vibratory analysis of an individual rotor blade, with a fixed hub, was performed. Using the results of this analysis a Campbell diagram was constructed. The Campbell diagram is used as a graphical interpretation of blade resonance with " per rev" stimuli in order to determine any potentially destructive resonant crossings that may be present in the rotor speed operating range. A typical, experience based, design criteria for a rotor blade requires that blade resonance with a number of known stimuli be avoided in the operation range with specified minimum values of frequency margin. In particular, a standard first flex, 2/rev margin is 15%. The results of this study indicate that there is only a 7% frequency margin between the 1F and 2/rev at the 100% operating speed of 700rpm, which could lead to potential aeroelastic instability associated with rotor interaction.

In order to investigate the potential aeroelastic issues associated with rotor interaction, a preliminary aeromechanic assessment of the rotorcraft concept, in hover, was conducted. Two coaxial counter-rotating discs with rigidly connected elastic blades, two per disc, were modeled in a non-linear multi-body dynamics code called DYMORE. The discs were assumed to be rigid while the blades were modeled as elastic beams. Both a static analysis, with included centrifugal effects, and a stability analysis with aerodynamic effects, modeled by a 2-D blade element analysis based on existing airfoils tables, in conjunction with a finite-wake single rotor wake calculation, were performed. The analysis did not revealed major aeromechanics problems for the designed geometric and material properties of the blades. It is important to emphasize that, while elastic interaction between the two discs is considered to be modeled adequately, the aerodynamics of the wake interaction was not included in the analysis. The wake calculation was conducted independently for each disc. Proper modeling of the wake interaction that would be universally accepted in rotorcraft community is not available at the present time, although various methods, such as the use of different contraction and convection rates for upper an lower discs, have been proposed. Based on experience with coaxial rotors, the impact of the wake interaction on the aeroelastic stability is expected to be less significant as compared to the impact on the performance. Nevertheless, this aspect should not completely be discounted and, in particular, the importance of blade vortex interaction has to be addressed if the concept is to be developed further.

For comparison purposes, a single disc, with four rigidly attached elastic blades with the same properties, was also modeled. Within the precision of the model the aeromechanics characteristic were quite similar to the counter-rotating configuration. The, above mentioned, deficiency of the wake modeling is clearly absent in this case and the fidelity of the analysis is expected to be higher.

The models that were created in the DYMORE system were constructed not only to analyze the hover configuration, but also in order to facilitate further analysis. This would including the investigation of the transition in the forward flight, with controls being properly modeled, for a Phase II follow on program.

4.0 PHASE I STUDY RESULTS

The results associated with the analyses performed under this phase I study are now presented in more detail.

4.1 Preliminary Geometric Layout for the Vmax Conceptual Design

The conceptual design for the Vmax rotorcraft, cited in ref. [1], is shown in Figure 2.1.
A breakdown of the dimensions for this vehicle is given in Table 4.1.1

Table 4.1.1: showing conceptual rotorcraft basic dimensions

Disk Diameter	16ft
Rotor Diameter	26ft
Disk Area	$201ft^2$
Empennage Area	$15ft^2$
Cathedral	45^o
Taper	0.28
Thickness	12%
Frontal Area	$20.54ft^2$
Height	10.6ft
Length	29.4ft
Max Rotation	13^o
Propeller Diameter	80ins
Engine (Allison250-C30)	650-450 shp
MGTOW	3300lbs

Based on standard aircraft preliminary design techniques, ref. [19], estimates for the weights of the associated components for the conceptual design were determined. A breakdown for the weight estimates of this vehicle is given in Table 4.1.2

Table 4.1.2: Weight Breakdown

Structure		
	- Fuselage	240 lbs.
	- Empenage	40 lbs.
	- Main Gear	120 lbs.
	- Nose Gear	30 lbs.
	- Disk	150 lbs.
	- Rotor Blades (x4)	120 lbs.
	SUBTOTAL	**700 lbs.**
Propulsion System		
	- Engine	280 lbs.
	- Shafts	60 lbs.
	- Clutch/G-box	100 lbs.
	- Propeller	60 lbs.
	- Actuators	50 lbs.
	SUBTOTAL	**750 lbs.**
Systems		
	- Electrical	190 lbs.
	- Battery	40 lbs.
	- Seats(2)	80 lbs.
	- Avionics	340 lbs.
	- FLIR	60 lbs.
	- Flight Inst.	40 lbs.
	SUBTOTAL	**750 lbs.**
	TOTAL EMPTY WEIGHT	**2200 lbs.**
Crew		
	- Pilot	200 lbs.
	- Observer	200 lbs.
Fuel		
	- Internal	700 lbs.
Payload		1100 lbs.
	MAXIMUM TAKEOFF GROSS	**3300 lbs.**

In order to perform a mission analysis, using the FLOPS program, it was necessary to determine the vehicle characteristic drag polars. This data was obtained from the preliminary concept vehicle design cited in ref. [1]. A plots showing the characteristic drag polars, used for input to the FLOPS program, are displayed in Figures 4.1.1 and 4.1.2.

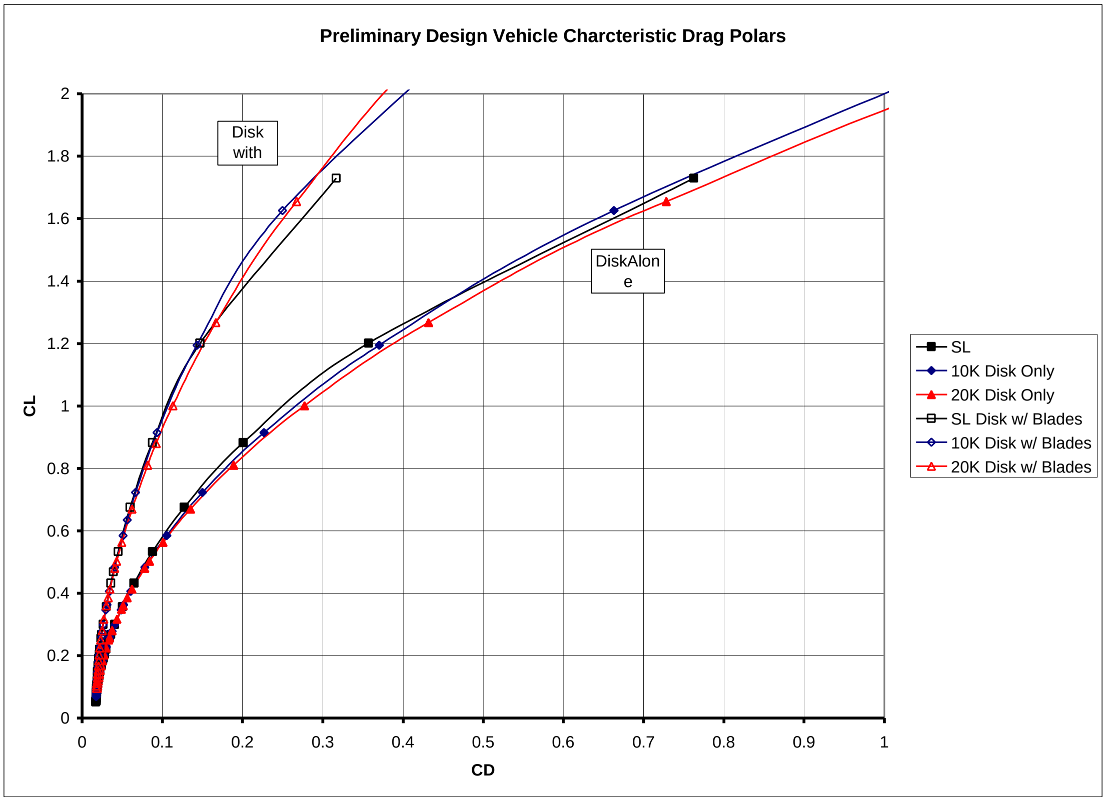


Figure 4.1.1: Preliminary Conceptual Design Vehicle Characteristic Drag Polars

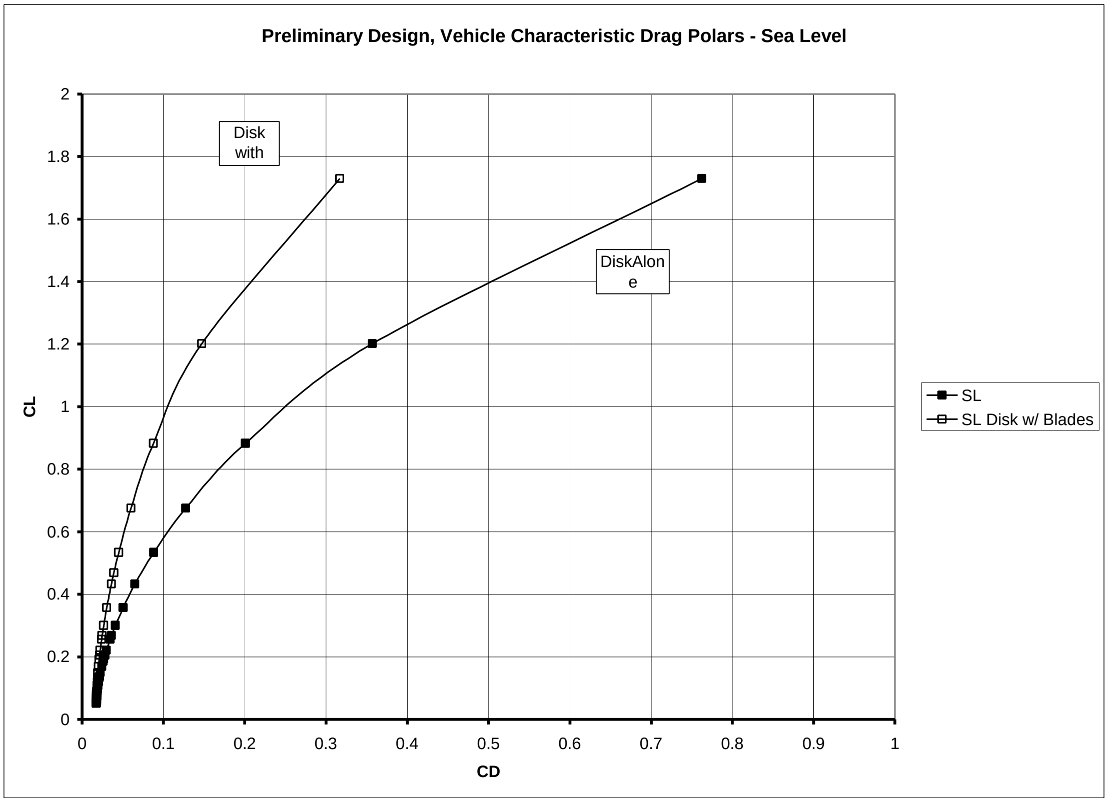


Figure 4.1.2: Vehicle Characteristic Drag Polars – Sea Level

In order to determine the L/D curve for this vehicle the assumed weight was, 2950 lbs., which assumes half of the fuel has been used. From this assumption a C_L was calculated for varying speed, with the C_D being determined from Figure 4.1.1. The L/D data is displayed in Figure 4.1.3.

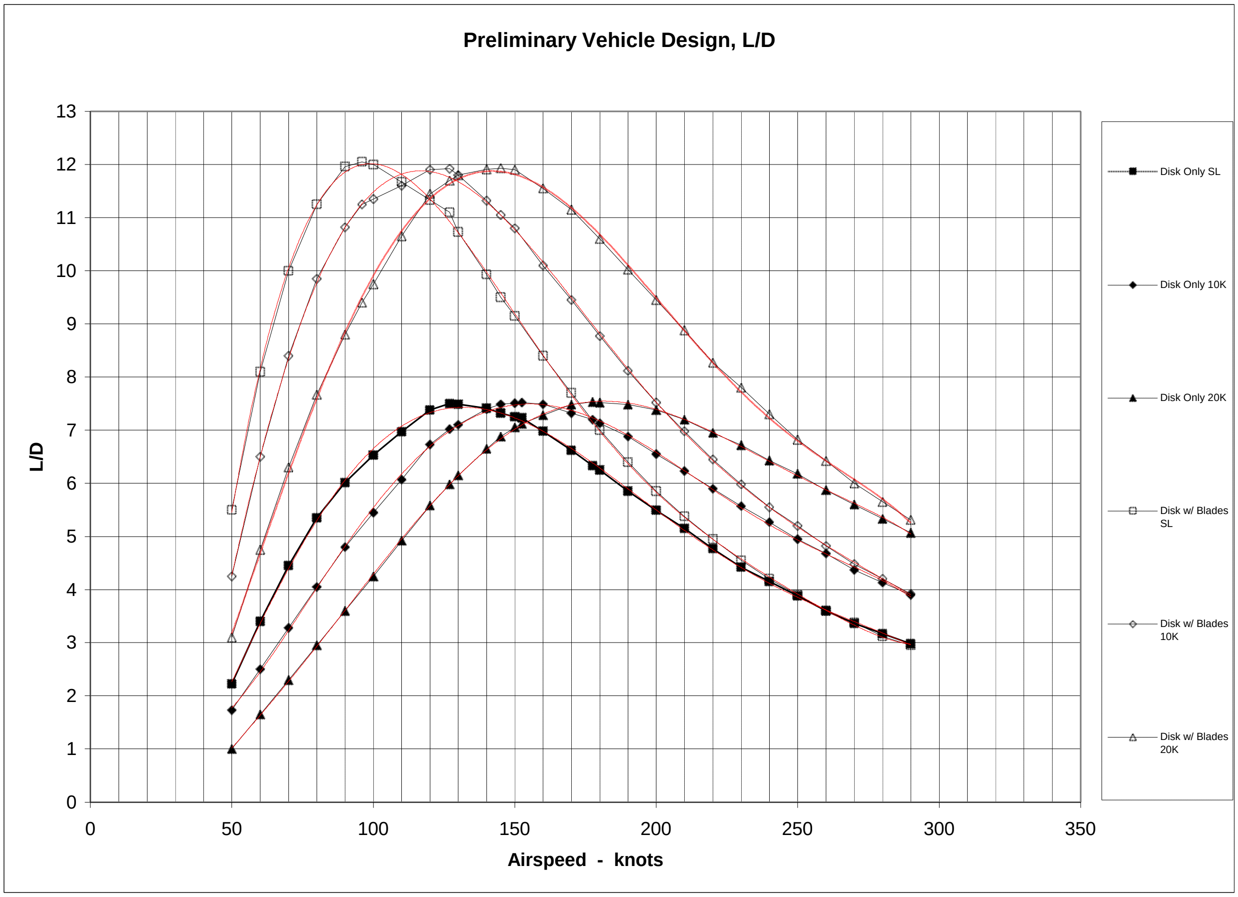


Figure 4.1.3: Preliminary Vehicle Design, Lift/Drag curve for a 2950 lb vehicle weight.

4.2 Fixed wing mission analysis using NASA Langley FLOPS program

Diversitech used FLOPS release 5.94, revised 17 July 1998, to perform the fixed-wing analysis.
The FLOPS program is a NASA Langley Flight Optimization System. The goal of the FLOPS analysis was to verify the ability of the Vmax MODUS design to fly a set mission. The polars used for input to the FLOPS program were generated from the Vmax conceptual design. The analysis assumes a non-oxygen vehicle, i.e. not pressurized with max altitude of 12,500ft. The pusher turbo prop design cycle, which was used as input to the FLOPS program, was generated from a Hartzell 80”, 5 blade, propeller design, and was generated using the NASA Navy Engine Program, (NNEP). For the FLOPS analysis it was assumed that there would be 650 shp for take-off and 450 shp for cruise available from the engine. The required engine power was determined from the engine cycle based on the required speed.
For the analysis the Clark-Y airfoil profile, shown in Figure 4.2.1, was assumed for the disk with a circular planform. Varying disk diameters of 22ft, 26ft, and 30ft, were considered for the analysis.

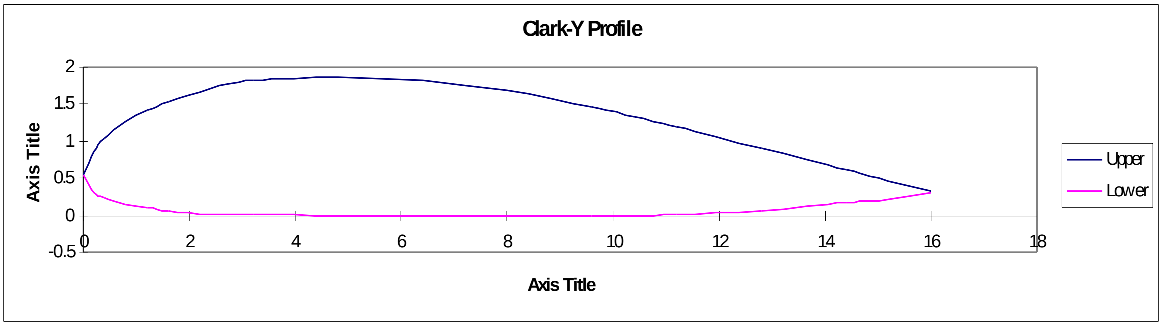


Figure 4.2.1: showing the Clark-Y airfoil profile

The mission that was investigated using the FLOPS program was based on a typical search and rescue mission. Table 4.2.1 details the mission requirements.

Table 4.2.1: showing the rotorcraft mission	
1	Max power takeoff
2	Climb to cruise altitude of 12,500ft
3	1½ hrs OUT
4	descend to loiter altitude 50ft, approx.
5	Hold on station for 1hr
6	Climb back to cruise altitude 12,500ft
7	1½ hrs BACK

Figure 4.2.2 shows the flight envelope, altitude versus speed, as determined by FLOPS. This plot represents the uppermost boundary for operation of this vehicle.

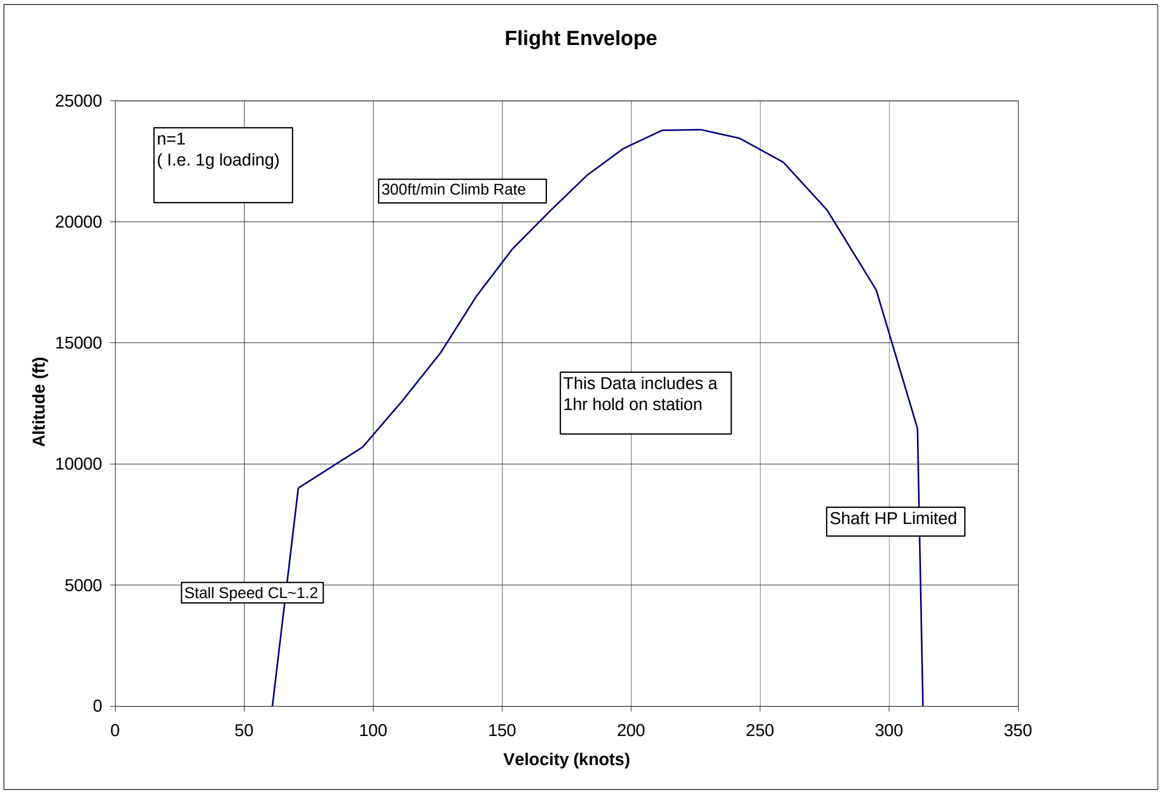


Figure 4.2.2: Showing the flight envelope as a plot of altitude versus velocity.

In order to determine the data displayed in Figure 4.2.2 a maximum1g loading was assumed. The stall speed of 61 knots, with a C_L =1.16, describes the first portion of the curve from 0ft to 900ft. Beyond this point the curve is described by, 900ft & 70 knots to max altitude 23800ft at 227 knots, with a climb rate of 300ft/min. At an altitude 11500ft and 311 knots to SL, the curve is assumed to be shaft horsepower limited, which is why a straight line interpolation is used.

The next plot, Figure 4.2.3, shows the Endurance curve, in hours, versus the various rotor diameters

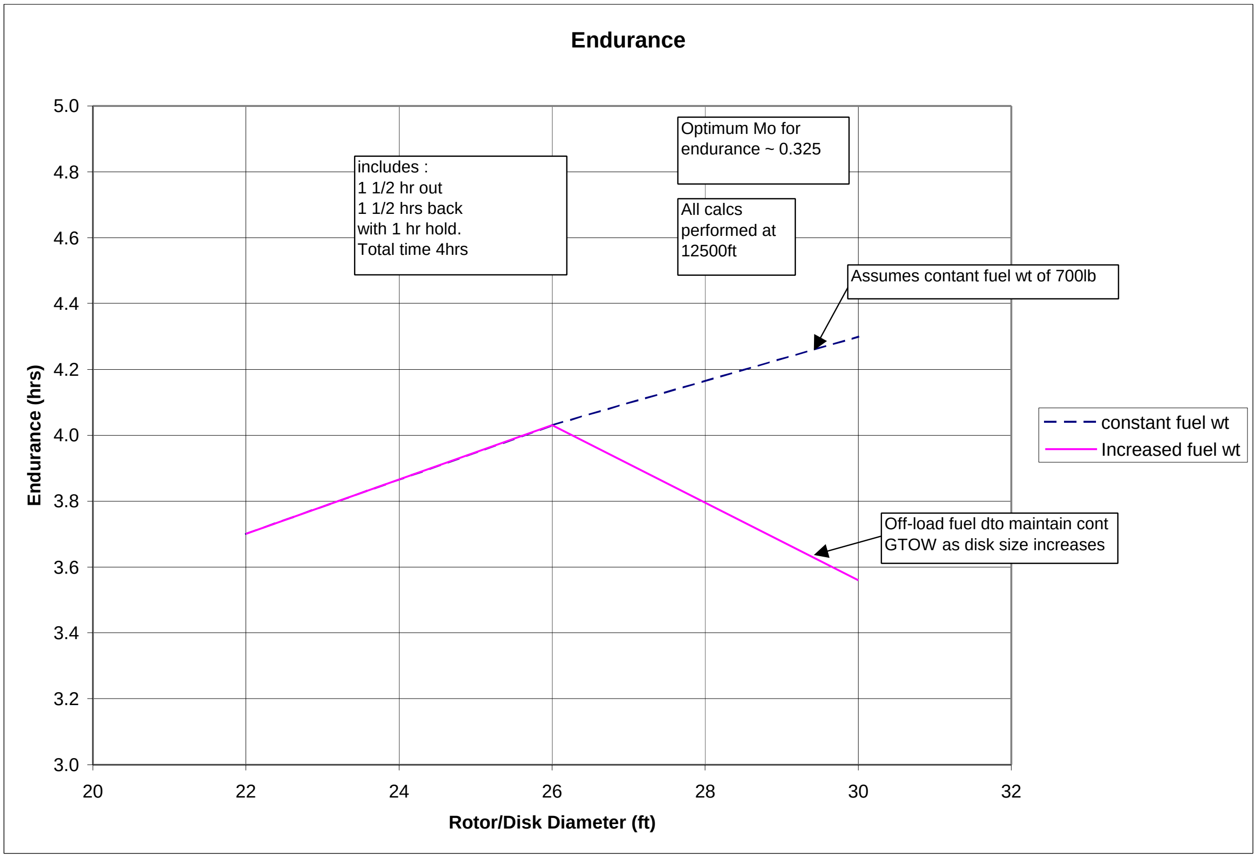


Figure 4.2.3: showing the Endurance curve, in hours, versus the various rotor diameters.

The Endurance plot, Figure 4.2.3, assumes that the flight time is 1½ hrs OUT + 1hr HOLD + 1½ hrs BACK. All data shown is for 12,500 ft. Where the dotted line is plotted, a constant fuel weight is assumed, which accounts for the improved endurance for the 30ft diameter disk. The more correct way to plot this data is to assume that there is a reduced fuel weight due to increased disk weight with GTOW constant. This data is shown by the solid line.

The next set of curves, displayed in Figure 4.2.4, show the maximum range versus rotor diameter for the vehicle. Two curves are shown, one based on the optimum cruise speed and the other based on maximum cruise speed. Also shown on the two curves is data when the fuel weight is held constant, dotted line extensions, and when the vehicle weight is held constant (i.e. reduced fuel weight as disk diameter increases), solid line extensions.

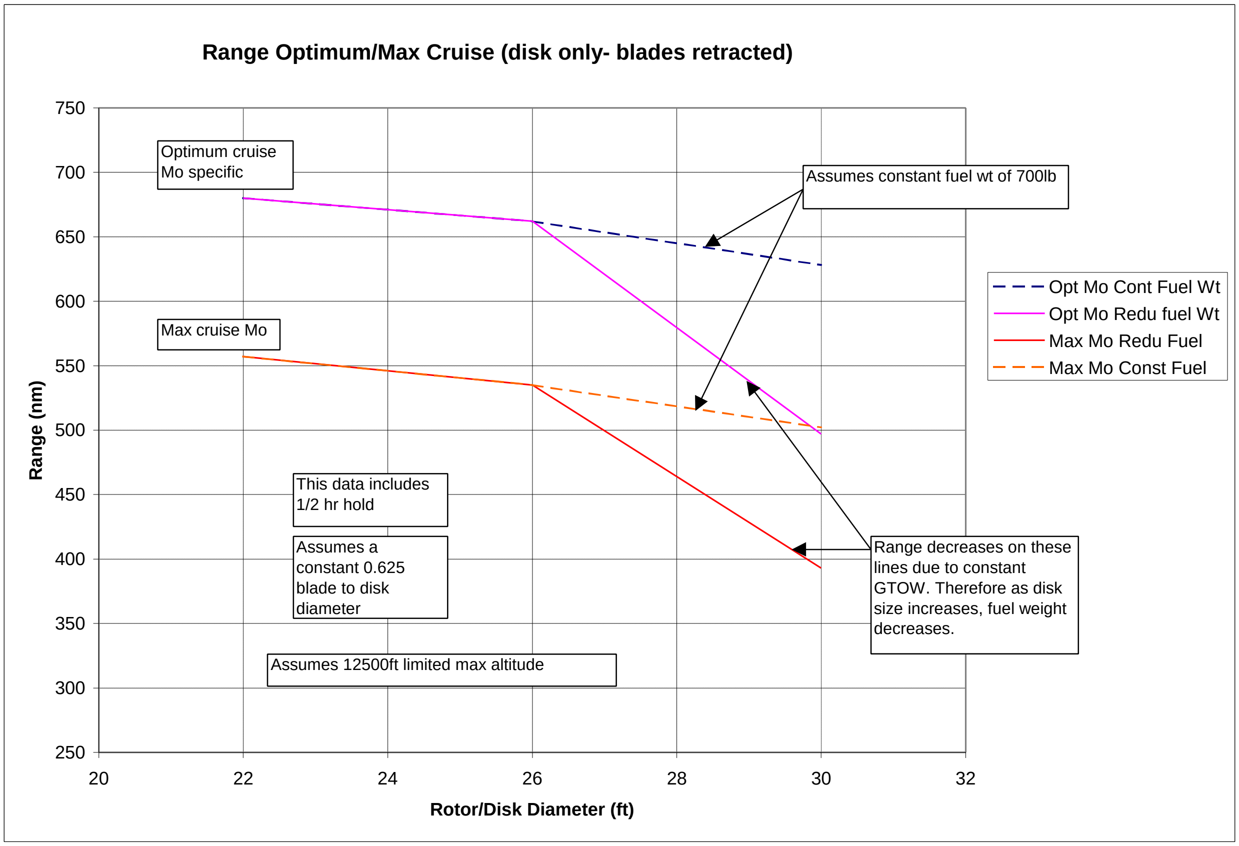


Figure 4.2.4: showing Range, nautical miles, versus rotor diameter.

The data displayed in Figure 4.3.4 assumes lift is generated by only by the disk, i.e. the blades retracted and do not add to the lift capability. Also assumed is a constant 0.625 blade to disk ratio, and assumes a 12500ft limited maximum cruise altitude. The upper curves are for constant fuel weight of 700lbs; the lower curves are for constant GTOW, i.e. when disk size increases, fuel weight decreases to maintain GTOW of 3300lbs.

The next set of curves, displayed in Figure 4.2.5, show plots for range, in nautical miles, versus speed, for varying disk diameters. Also shown is a range curve for a 30ft diameter disk with the fuel weight held constant.

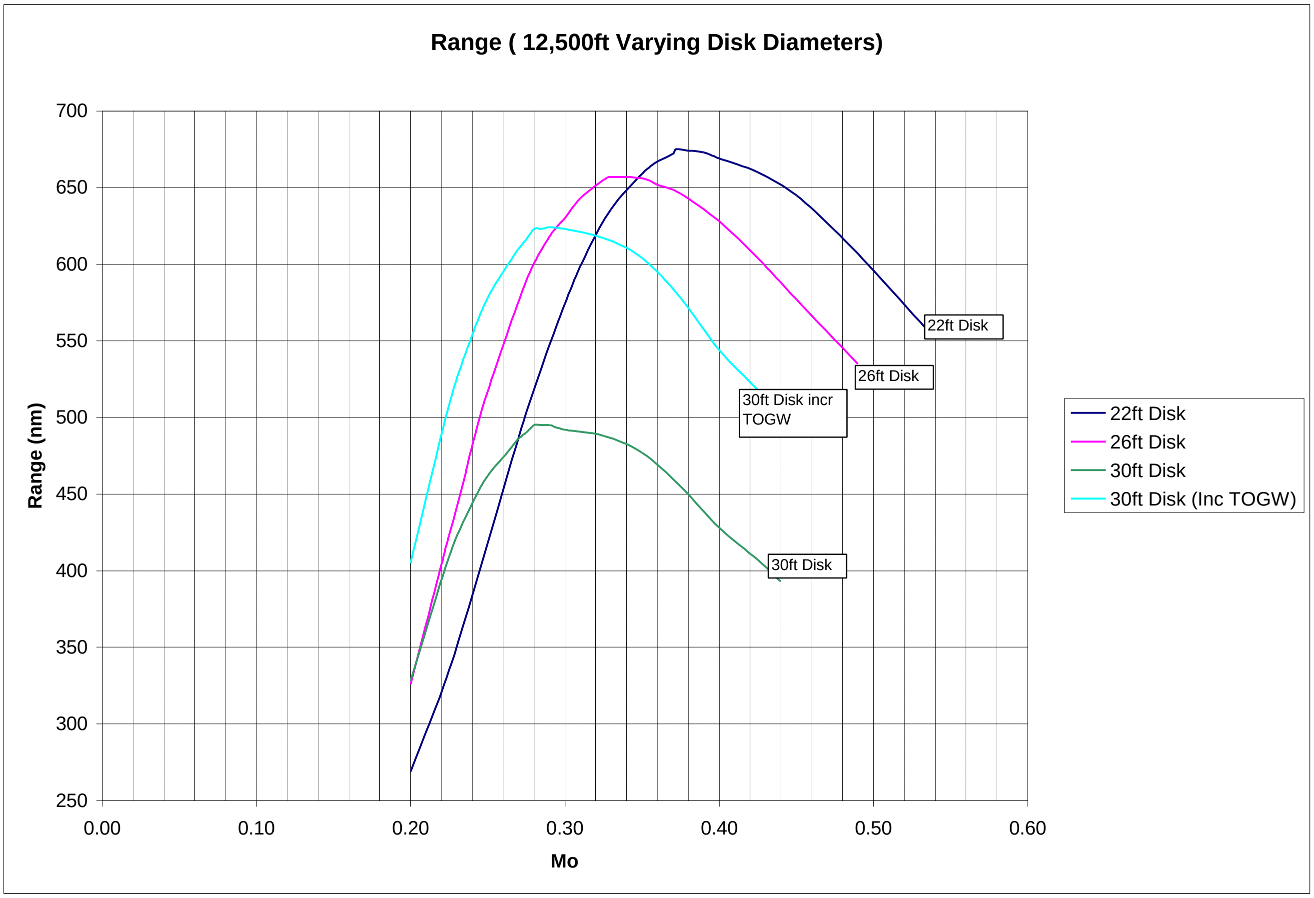


Figure 4.2.5: showing plots for range, in nautical miles, versus speed, for varying disk diameters.

The displayed data, in Figure 4.2.5, shows the variation in range based on changes in disk diameter. This assumes a constant vehicle GTOW. As disk diameter increases, fuel weight decreased to maintain 3300 lbs. GTOW. A curve for a 30ft diameter disk, with constant fuel weight of 700 lbs., is also shown. All data shown is at 12500ft altitude.

Note: at 12,500ft M0.5 is approximately 300 knots

The next set of data, dsplayed in Figure 4.2.6, shows the range, in nautical miles, versus speed, for a constant diameter disk of 26ft at altitudes varying from 2000ft up to 12500ft.

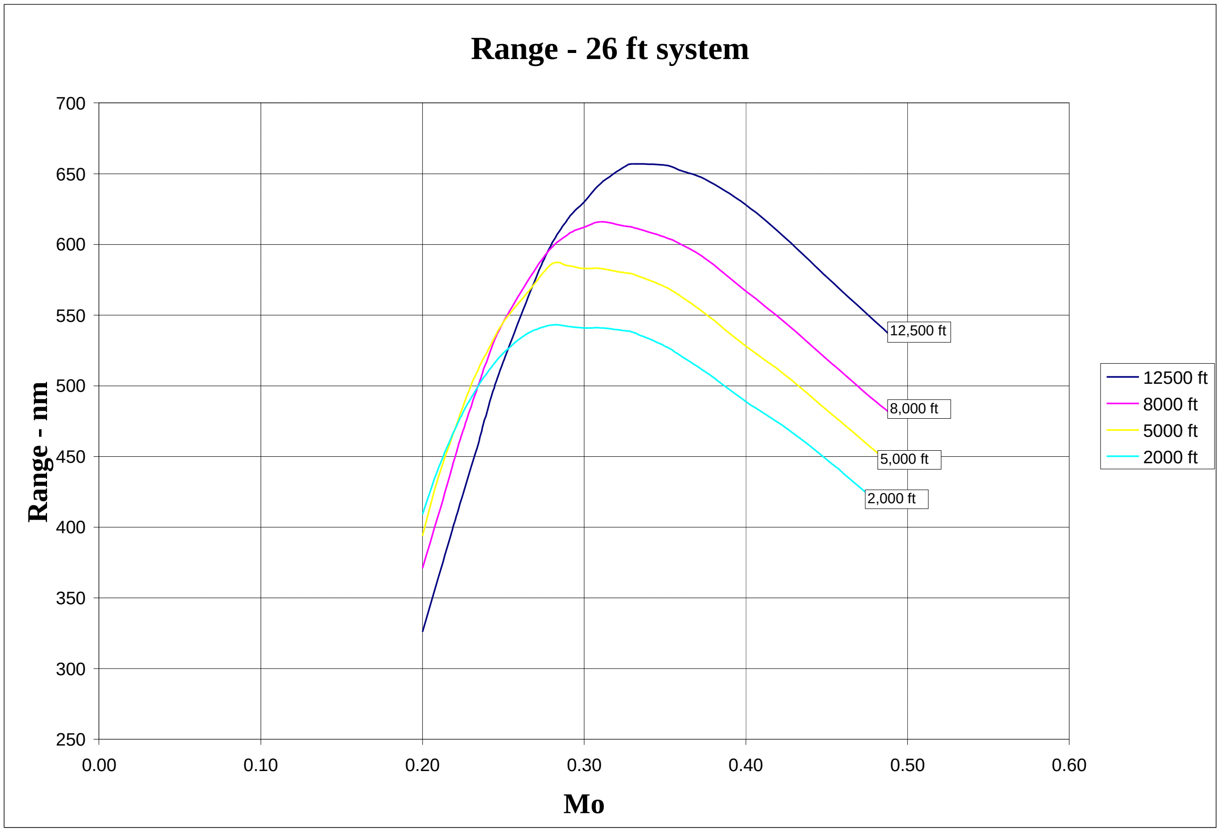


Figure 4.2.6: showing a plot of range, in nautical miles, versus speed, for a constant diameter disk of 26ft at altitudes varying from 2000ft up to 12500ft

The data shown is for "fixed wing" operation with blades retracted for varying altitudes, with the upper limit being 12500ft. The 26ft diameter disk assumes a 16ft diameter disk hub with 5ft long blades This data indicates that the range decrease as altitude decreases.

4.3 Determining the Required Disk Size

From the results of the FLOPS analysis the optimum disk size was determined.
The disk size chosen for the 3300 lbs. GTOW vehicle was 26ft. This is based on a 16ft diameter disk with 5ft rotor blades. The disk size chosen is partially based on an FAA stall speed requirement, for light aircraft, of 61 knots. On landing, because of the potential for tail, or propeller, drag the landing AOA for the Vmax conceptual vehicle is <15°. Assuming the landing weight is 2950 lbs. (i.e. 3300lbs. minus half the fuel wt), at 61 knot stall speed data, obtained from the FLOPS analysis, indicates that the Clark-Y airfoil has a required C_L <=1.16, which is achievable with a 12° AOA.
Although the polars used for the FLOPS analysis were developed from the available data for the Clark-Y airfoil, ref. [6], because the rotor needs to be symmetrical, this data is not entirely correct. The Clark-Y airfoil data is for a circular wing planform, however, it assumes that the circular wing is fixed, and is, therefore, always facing in one direction which allows for the profile to have clearly defined leading and trailing edges. Clearly for a symmetric rotating disk the leading edge will become the trailing edge, and vise-versa. In order to investigate the potential lift/drag characteristics produced by a symmetric airfoil profile, an airfoil profile that was considered to be a reasonable substitution for the circular planform Clark-Y airfoil was chosen. The preliminary airfoil shape chosen for the disk was a NACA 66_1-012. From ref. [13], at the correct Reynolds number for a sea level 61knot landing, and at a 12° AOA, the section C_L is 1.2. This is approximately equivalent to the Clark-Y. Also the NACA 66_1-012 profile provides sufficient internal volume that may be required for mechanisms. For symmetry the LE to 50% chord is used for disk profile. A plot of the NACA 66_1-012 airfoil profile is given in Figure 4.3.1. A plot showing the pseudo, LE to 50% chord, airfoil profile is given in Figure 4.3.2.

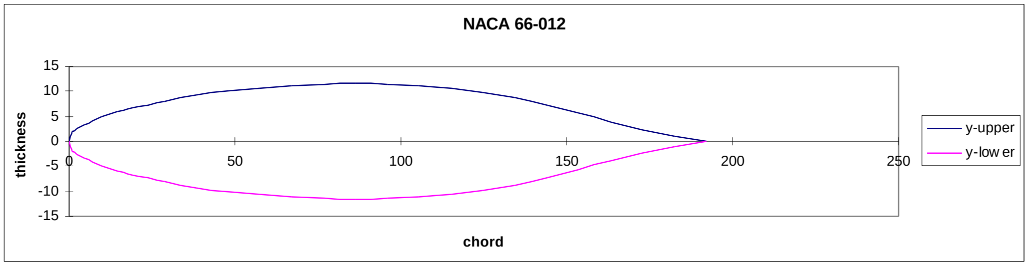


Figure 4.3.1: showing the NACA 66_1-012 airfoil profile.

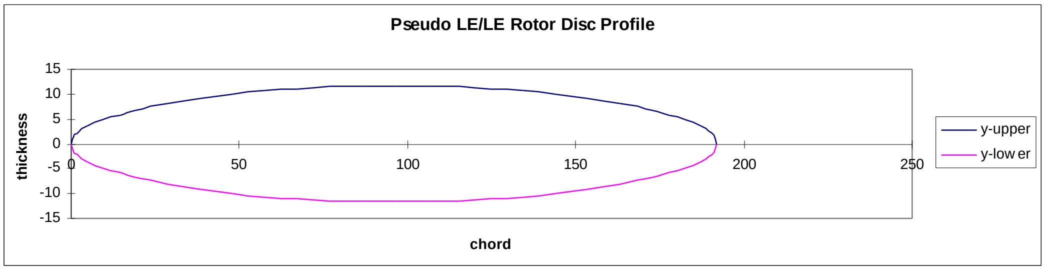


Figure 4.3.2: showing the pseudo LE/LE, NACA 66_1-012, airfoil profile.

Using the NACA 66_1-012 pseudo airfoil a preliminary analysis was performed,to determine the lift characteristics using the US Airforce Digital DATCOM program, ref.[18].
The airfoil profile for the NACA 66_1-012 pseudo airfoil, that was used in this analysis, is shown in Figure, 4.3.2. The circular planform of the 16ft diameter wing/rotor hub was approximated with a polygon, see Figure 4.3.3. The gap between counter-rotating disks could not be accounted for in this analysis, and was, therefore, neglected.

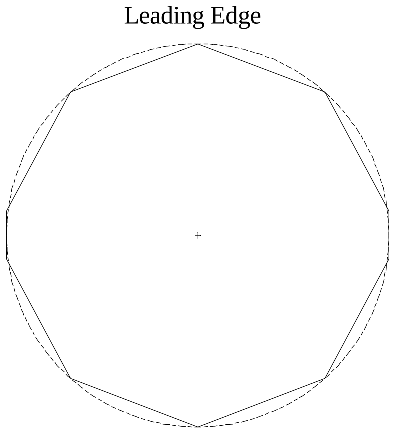


Figure 4.3.3: showing the NACA 66_1-012 pseudo airfoil polygonal planform

The digital DATCOM analysis was performed for both 12500ft and 20000ft altitude. In each case a number of wing lifts(similar to vehicle weights), from 0 to 3500 lbs, were studied and plots of vehicle drag versus speed were created. Superimposed on these plots are curves of engine thrust versus speed for various engine power settings from 100 to 800 horsepower. For each of the cases, since the chosen engine was assumed to have 650hp available at takeoff and 450hp available for cruise, these curves were condensed to only show 650 and 450hp thrust versus speed curves and a drag versus speed curve for the 3500lb wing lift. Figure 4.3.4 displays the 12500ft data, with the condensed data being displayed in Figure 4.3.5. Figure 4.3.6 displays the 20000ft data, with the condensed data being displayed in Figure 4.3.7.

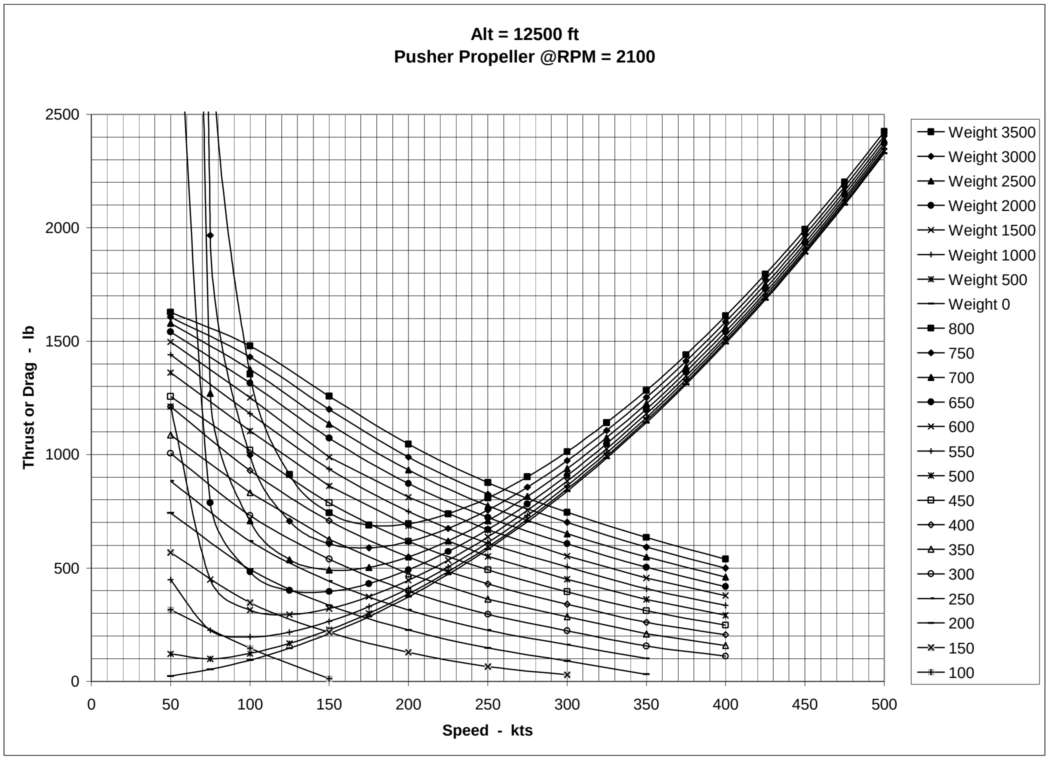


Figure 4.3.4: showing the full NACA 66_1-012 pseudo airfoil DATCOM results for 12500ft

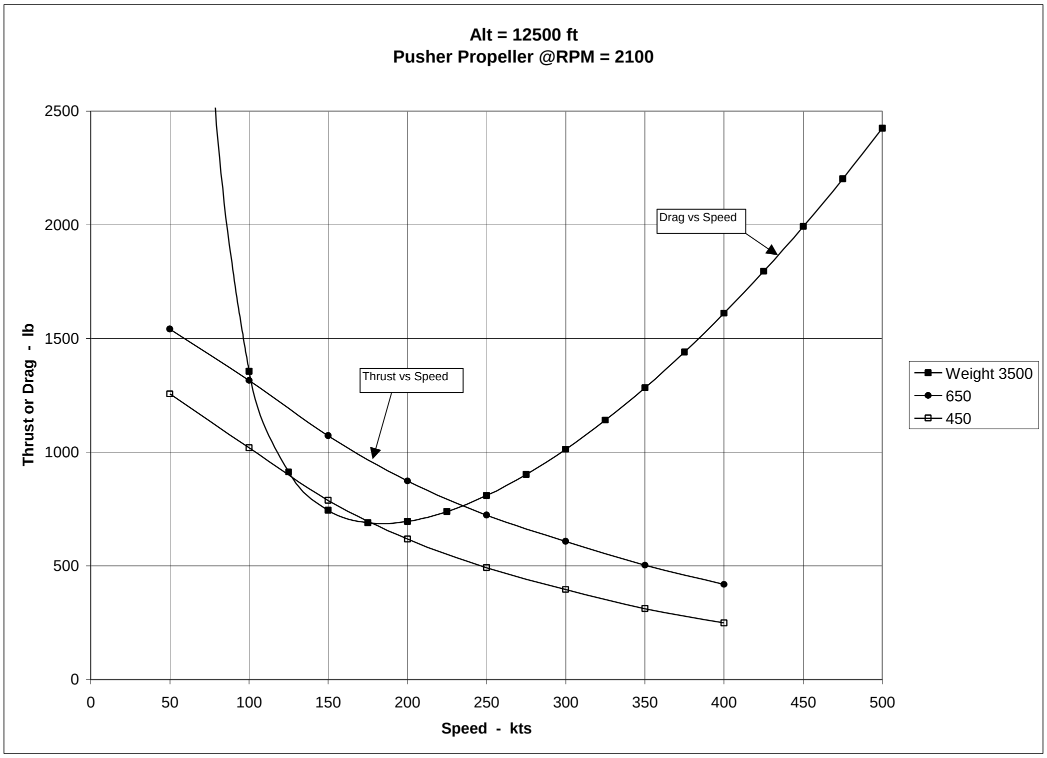


Figure 4.3.5: showing the condensed NACA 66_1-012 pseudo airfoil DATCOM results for 12500ft.

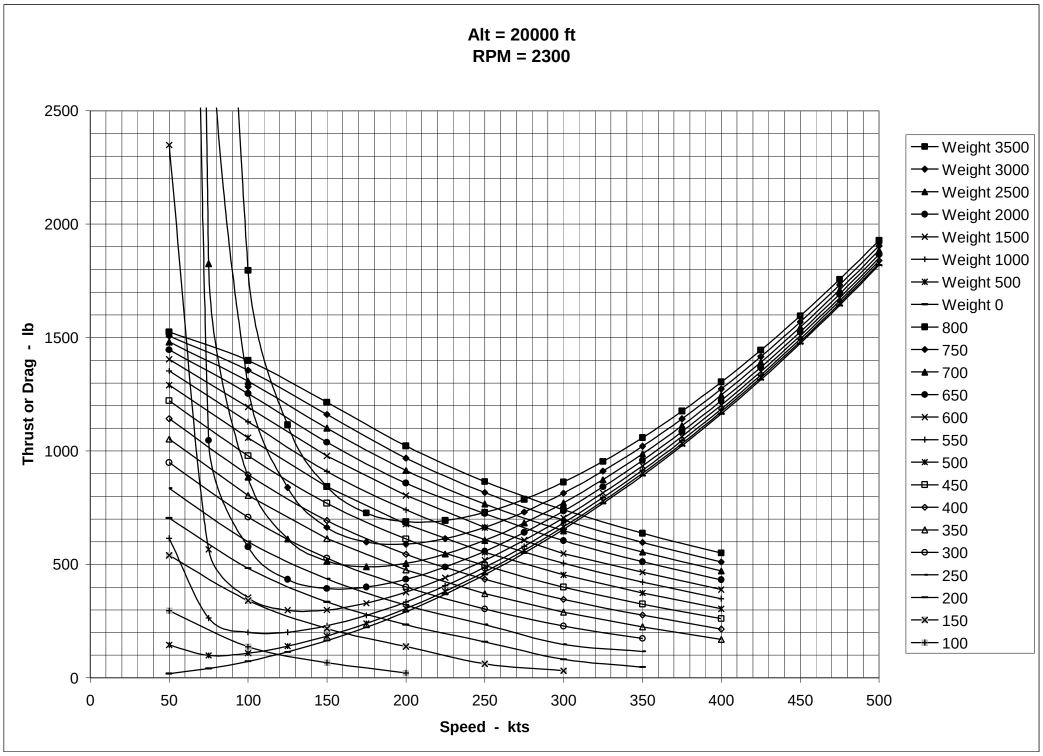


Figure 4.3.6: showing the condensed NACA 66_1-012 pseudo airfoil DATCOM results for 20000ft.

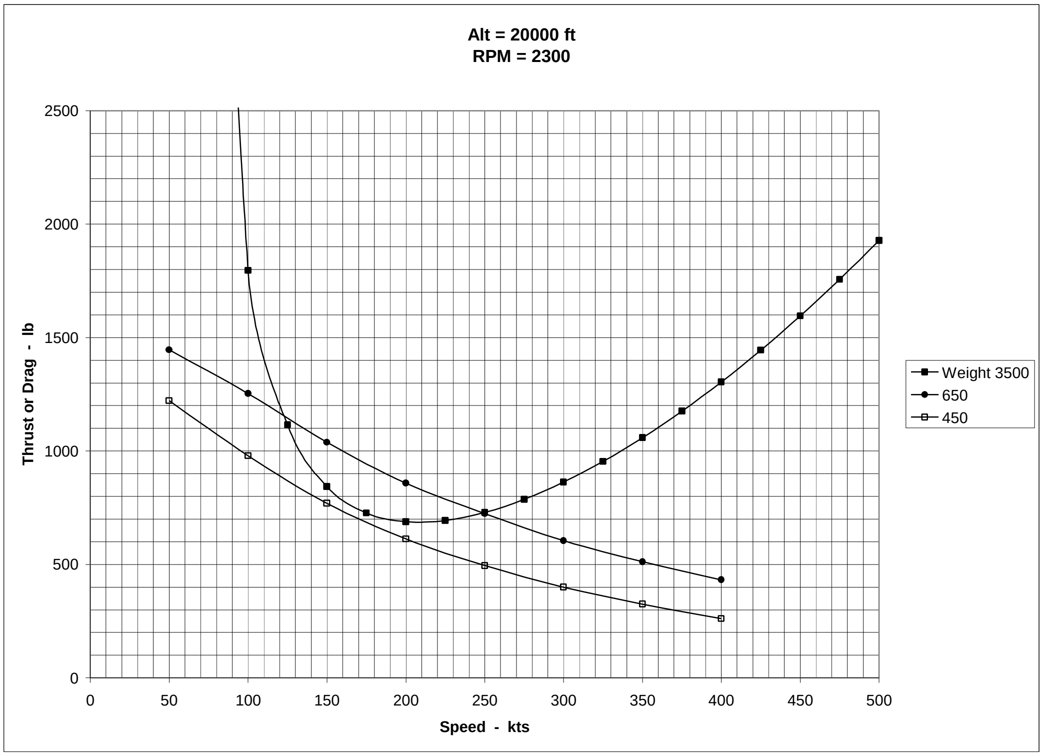


Figure 4.3.7: showing the condensed NACA 66_1-012 pseudo airfoil DATCOM results for 20000ft.

A number of important results were obtained from this study. Because the airfoil shape used for the circular wing did not have a standard trailing edge, but rather a leading edge reversed, the drag was expected to substantially increase. It was therefore necessary to investigate the ability of the installed power to overcome the vehicle drag whilst producing sufficient lift required for a 3500lb GTOW vehicle. The results indicate that at 12,500ft, if 650 shp is available, the max speed, as determined by thrust versus drag is < 240 knots. At 12,500ft, if 450 shp is available, the max speed is < 175 knots. At the higher altitude of 20,000ft, if 650 shp is available, the max speed, as determined by thrust versus drag is also < 240 knots. At 20,000ft, if 450 shp is available, insufficient thrust is being generated by the pusher propeller to overcome the drag. Therefore, a higher horsepower would be required to overcome the drag at this altitude.

In order to better understand the lift characteristics of the disk wing, and its effect on the vehicle performance, it is suggested that, for each new disk wing profile, the correct polars need to be determined and a new FLOPS analysis performed. In order to highlight this issue a comparison of the lift coefficient, $C_{L,}$ versus angle of attack, AOA, between the Clark-Y airfoil data, ref. [6], and the NACA 66_1-012 pseudo airfoil DATCOM results is made in Figure 4.3.8. Also, in Figure 4.3.9, a comparison is made of lift coefficient, C_L, versus drag coefficient, C_D, between the same two wing profiles.

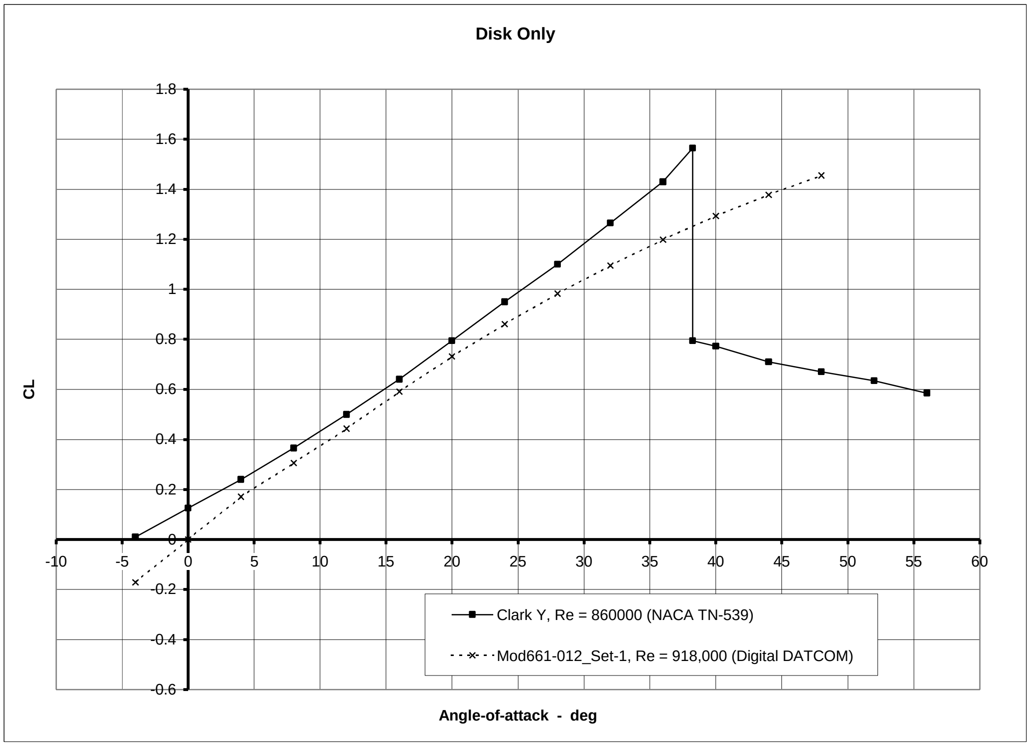


Figure 4.3.8: showing C_L versus AOA, Clark-Y and NACA 66_1-012 pseudo airfoil

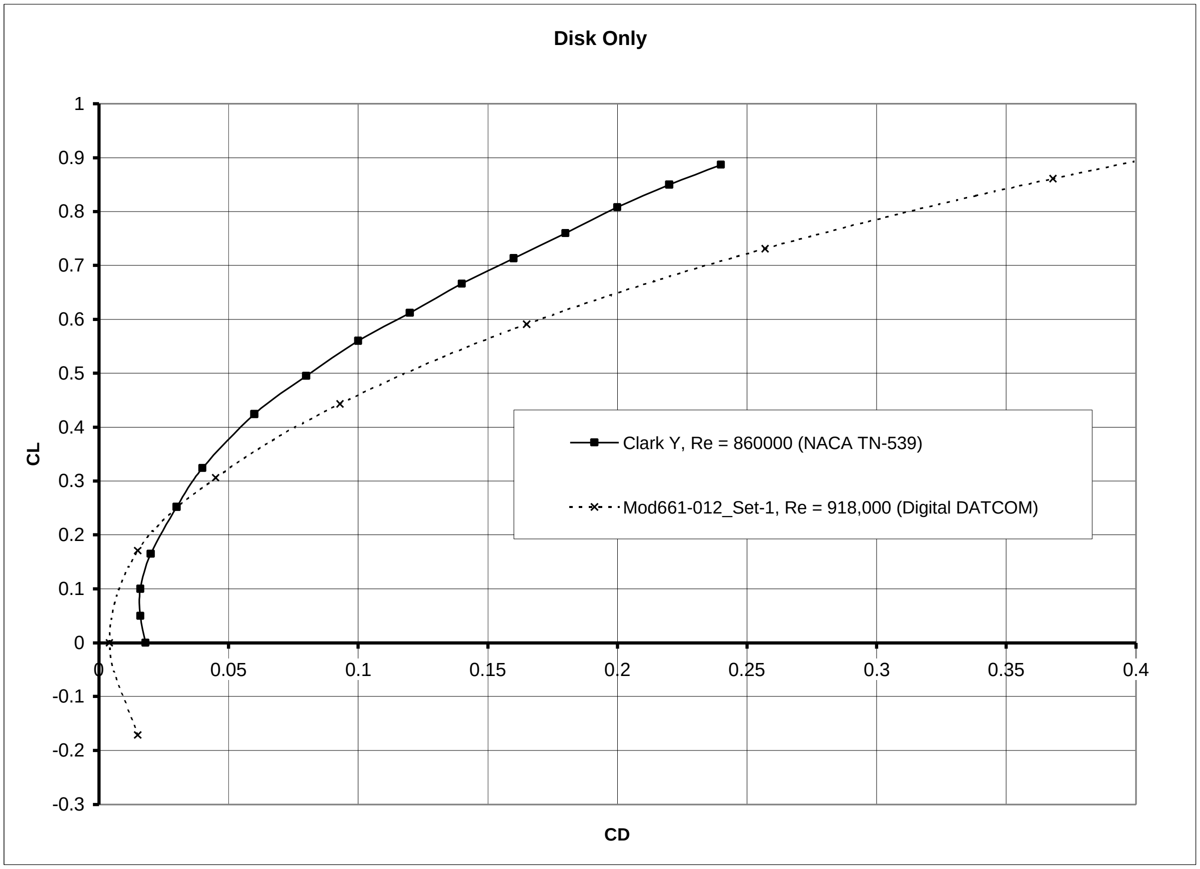


Figure 4.3.9: showing C_L versus C_D, Clark-Y and NACA 66_1-012 pseudo airfoil

As can be seen from the data displayed in Figures 4.3.8 and 4.3.9, there is a sufficient difference between the Clark-Y and NACA 66_1-012 pseudo airfoil, to indicate that a new FLOPS analysis, which includes the polars for the NACA 66_1-012 pseudo airfoil, may be necessary.

4.4 Determine Rotor Blade Sizing for vertical lift

From the results of the FLOPS analysis the required disk diameter was determined to be 26ft. The next design analysis performed was to determine the rotor blade size for a 26ft diameter rotor, with a 16ft hub, based on the required GTOW of 3300lbs.Hartzell Propeller Company, Piqua, OH, performed the design, and provided the propeller map. The design was based on 4 rotor blades with a tip diameter of 26ft attached to a single disk hub of 16ft in diameter. The blades were, therefore, 5ft in length, i.e. 60ins. The effect of the 16ft diameter hub was included in the rotor blade analysis. The available takeoff power for vertical lift was assumed to be 650 shp. A blade design tip Mach number of 0.9 was used.

The blade design, determined by Hartzell, had a 60” length and a 7” chord. The section data provided by Hartzell is displayed in Table 4.4.1.

Table 4.4.1: section data for the Hartzell blade design

Radius (in)	Width (in)	Thick (in)	Twist (deg)	C_L design	NACA Airfoil
95	7.0	1.5	32.0	.50	16-5-21
105	7.0	1.0	30	.70	16-7-14.3
115	7.0	.70	28.5	.65	65-6.5-10
125	7.0	.55	27.5	.53	65-6.5-10
135	7.0	.40	26.7	.41	65-6.5-10
145	7.0	.30	25.8	.30	65-3-04
150	6.0	.24	25.3	.25	65-3-04
156	4.0	.20	24.9	.20	64-2-04

A picture of the finite element model (FEM) of the Hartzell Rotor Blade is displayed in Figure 4.4.1.

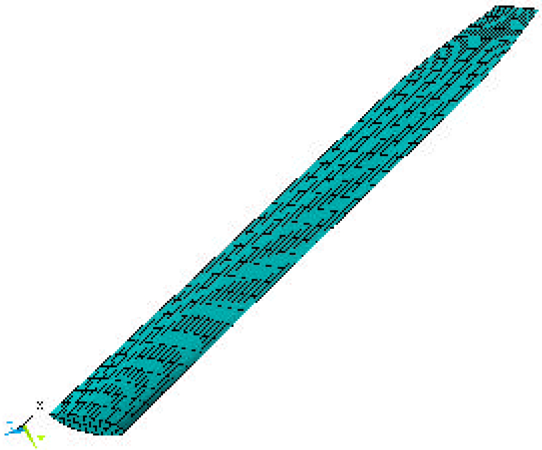


Figure 4.4.1: showing the FEM of the Hartzell Rotor Blade

4.5 Hover Analysis

In order to determine the vertical lift capability a simple hover analysis was performed. With available 650 shp from the Allison 250-C30 engine, and the provided Hartzell rotor design, the requirement was to lift at least 3300 lbs. of “dead weight” vertically. To provide a margin of error 3500 lbs. lift was assumed to be required. The analysis was performed @SL with NO ground/fountain effect, which may provide an additional lift, assumed.

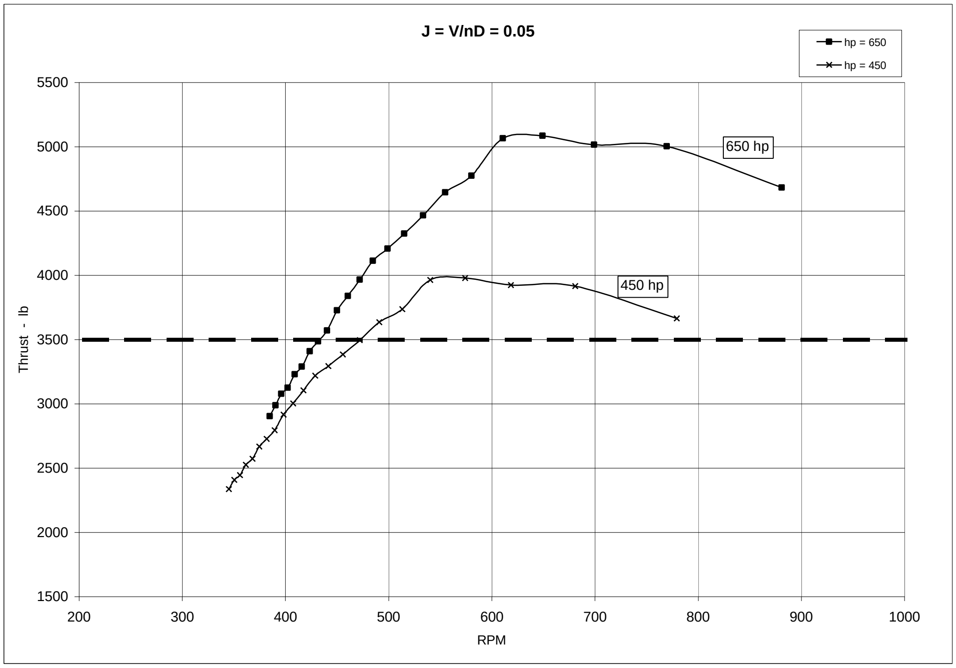


Figure 4.5.1: showing the preliminary hover analysis results.

The results indicate that that with 650 shp available, approx. 5000lbs of lift can be generated. With 450 shp available, approx. 4000lbs of lift can be generated which would suggest that the 450 shp condition would allow the remaining horsepower to be used for up & away forward flight.

4.6 Potential for Transition

At this stage of the program a full transition analysis is not feasible, however, it is recognized that the ability for transition to occur, between hover and fixed wing flight needs to be demonstrated.
In order to do this a number of “snap shots” of the vehicle mission were analysed.
As the rotorcraft transitions to forward flight it is assumed that the amount of lift being generated by the rotor blades will decrease.
In order to transition, a constant forward velocity is chosen such that there is sufficient horsepower to

(1) drive the vehicle forward at the chosen velocity
(2) provide sufficient horsepower to the rotor in order to generate 3500 lbs. of vertical lift

The analysis performed assumes a 0^{o} AOA for the disk, and does not account for blades extended drag.
An altitude of 2000ft was chosen, and assumed to be reasonable for rotorcraft transition.
The ability to transition is divided into two sets of curves. The first set of curves, Figure 4.6.1, shows both lift versus speed and thrust versus speed on the same plot. All the data displayed in Figure 4.6.1 is at an altitude of 2000 ft.

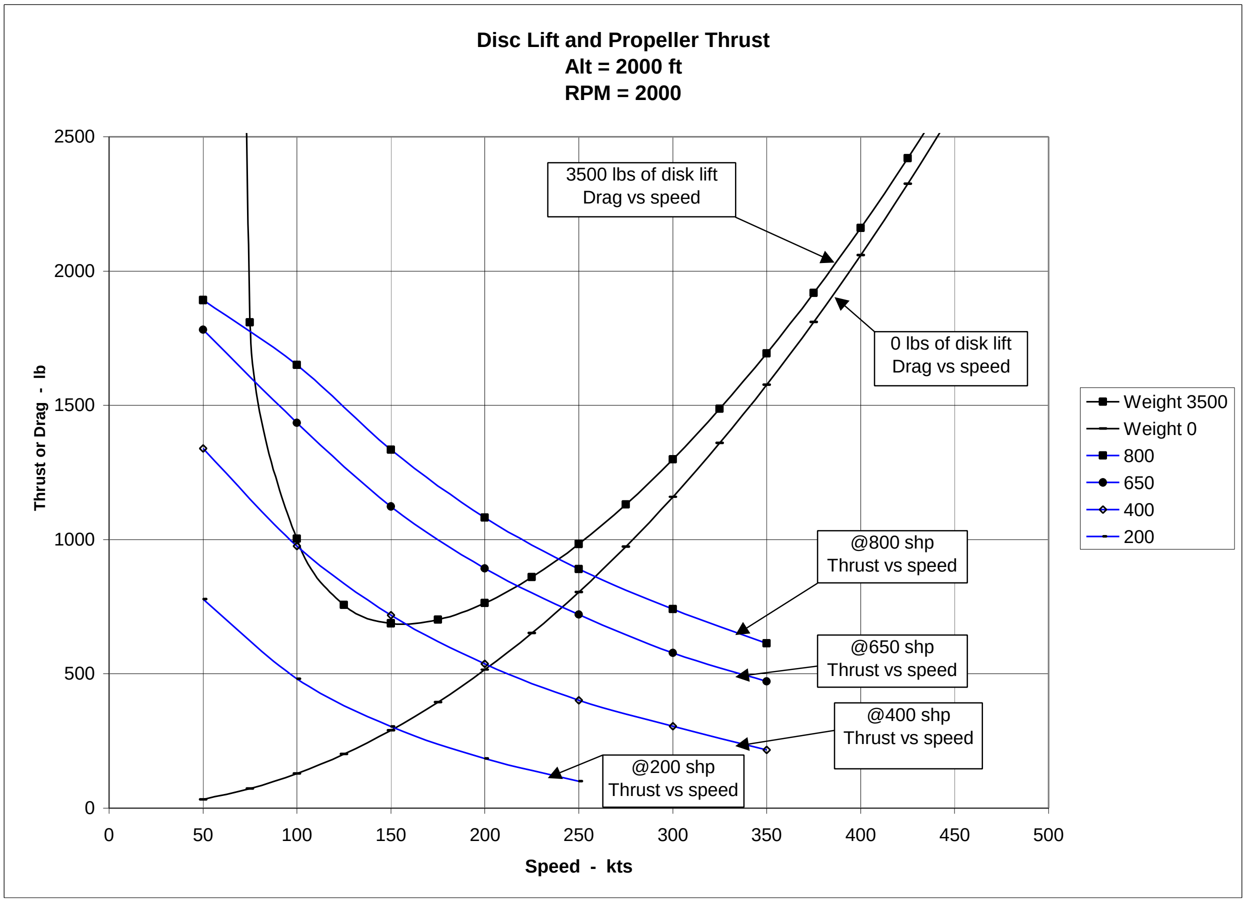


Figure 4.6.1: showing Thrust/Drag versus speed for the NACA 66_1-012 pseudo airfoil, DATCOM results at an altitude of 2000 ft.

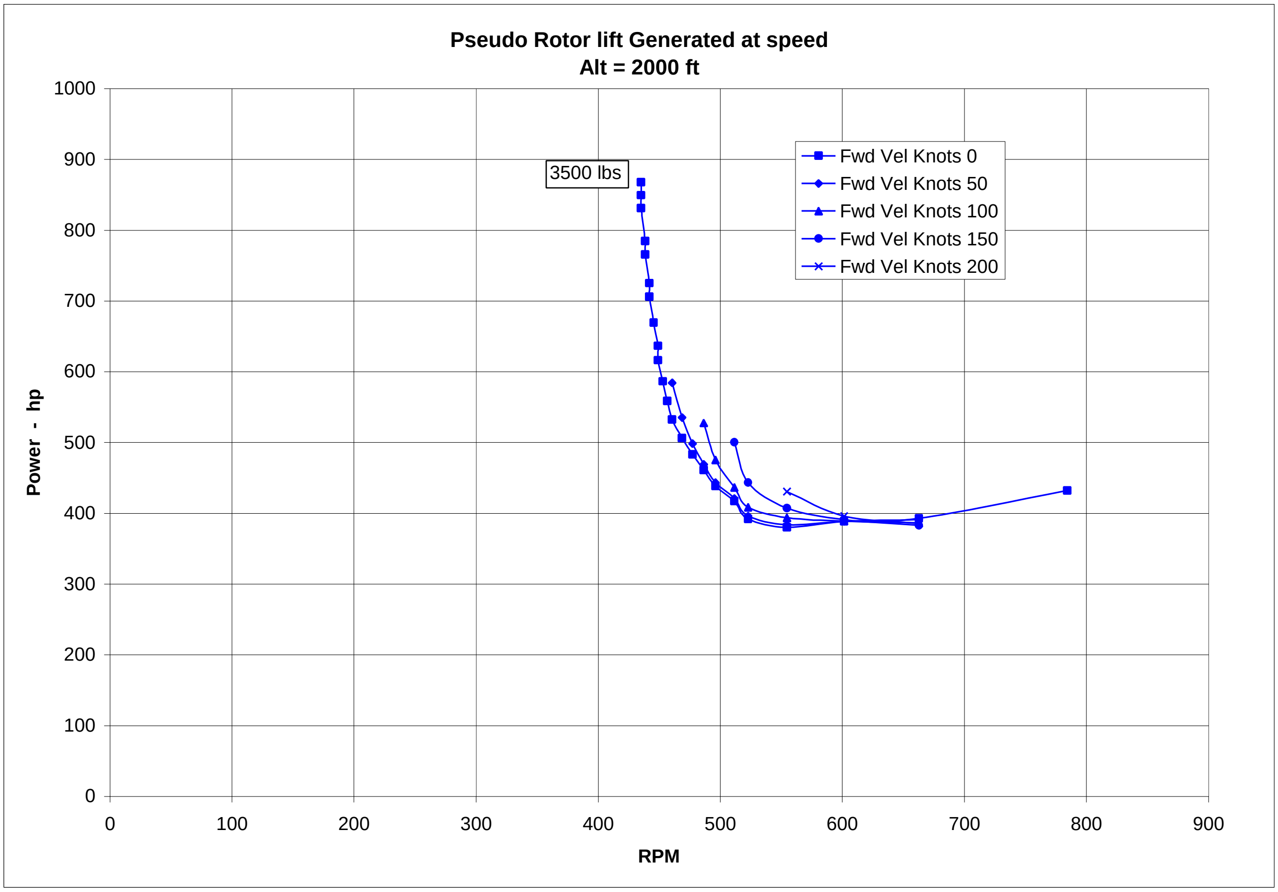


Figure 4.6.2: showing required rotor power versus rotor rpm for a 3500 lb weight at 2000ft altitude.

The second set of curves, Figure 4.6.2, shows the required rotor power versus rotor rpm for a 3500 lb weight at 2000ft altitude. The data calculated shows the variation in lifting thrust with forward velocity.

The data displayed in Figure 4.6.2 is a first approximation of the forward flight characteristics. In order to calculate this data a number of assumptions were made.

(1) When the rotor blade is aligned spanwise to the direction of flight the rotor sees only rotational velocity.

(2) When the rotor is aligned chordwise to the direction of flight the rotor sees (a) rotational velocity plus forward velocity, or (b) rotational velocity minus forward velocity. Downwash effect and disk lift are neglected.

(3) For equilibrium the lift on each rotor blade must equal (vehicle weight)/4 , for a four blades system.

Transition is postulated to occur by transferring power from the rotor to the propeller, whilst simultaneously changing AOA on the disc. The increased disk lift, due to increased forward velocity and AOA, will need to compensate for the reduced rotor lift due to the decreasing rotor power. The control schedule required to perform this maneuver is not discussed here, however, the ability to maintain both forward velocity, and vertical lift, with the provided installed engine power is studied.

By using a combination of the data displayed in Figures 4.6.1 and 4.6.2, the following is concluded.

For 0lbs lift on disk, 200 shp is required to maintain a 150 knot forward speed. At 150 knots a pseudo rotor lift of 3500 lbs. requires 400 shp. Therefore, there is sufficient engine power, 650 shp, to maintain this condition at 2000 ft altitude, however, at 150 knots, in order to generate 3500 lbs. of lift from the disk, an AOA will need to be set, and a minimum 400 shp is required. While it is noted that this approach is, at best, crude it does illustrate the potential limitations in transitioning from vertical to forward flight, in particular, as the disk AOA is increased the drag on the vehicle, which is not accounted for in Figure 4.6.1, will increase. It is, therefore, recommended that a more detailed transition analysis, that will account for all of these effects simultaneously, be performed in future studies.

4.7 Preliminary Blade Aeromechanical Analysis.

A very preliminary blade aeromechanical analysis, via a vibratory analysis of an individual rotor blade, with a fixed hub, was performed. A finite element model was constructed, using ANSYS 5.5, Figure 4.7.1. The blade model was run with a fixed root, at a maximum speed of 700rpm, with blade stiffening and spin softening applied, and with no gas loading. In order to apply stress stiffening a steady state stress analysis is initially run. The results of this analysis are displayed in Figures 4.7.2 and 4.7.3. Using the results of this analysis a Campbell diagram, Figure 4.7.4, was constructed. A 0% speed case was not run under the assumption that the percentage change in frequency, between 0% and 100% speed, would be minimal. The Campbell diagram is used as a graphical interpretation of blade resonance with “ per rev” stimuli in order to determine any potentially destructive resonant crossings that may be present in the rotor speed operating range. A typical, experience based, design criteria for a rotor blade requires that blade resonance with a number of known stimuli be avoided in the operation range with specified minimum values of frequency margin. In particular, a standard first flex, 2/rev margin is 15%.

The results of the steady state stress analysis indicate that the maximum von Mises stress is 3.2 ksi, with a maximum tip deflection of 0.1497 in. The results of the modal analysis study on the Hartzell rotor blade indicate that there is only a 7% frequency margin between the 1F and 2/rev at the 100% operating speed of 700rpm. Table 4.6.1 lists the calculated modes and associated modal frequencies. Mode plots, used to identify each mode, were produced for the first 10 modal frequencies. These plots are displayed in Figures 4.6.5 through 4.6.15

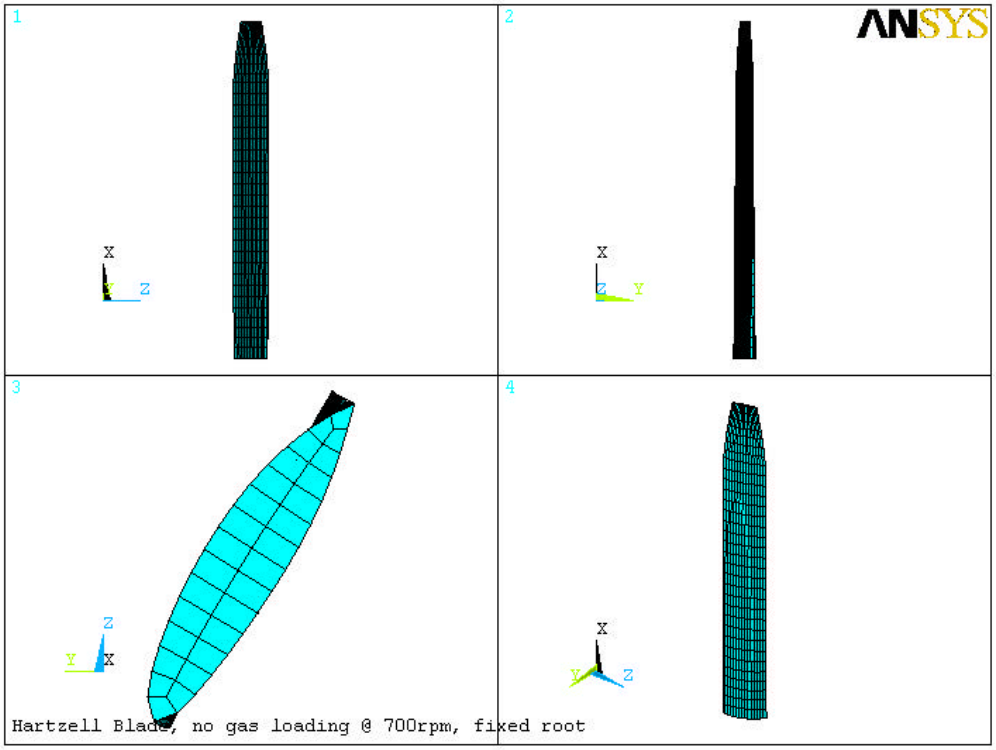


Figure 4.7.1: Hartzell rotor blade finite element model

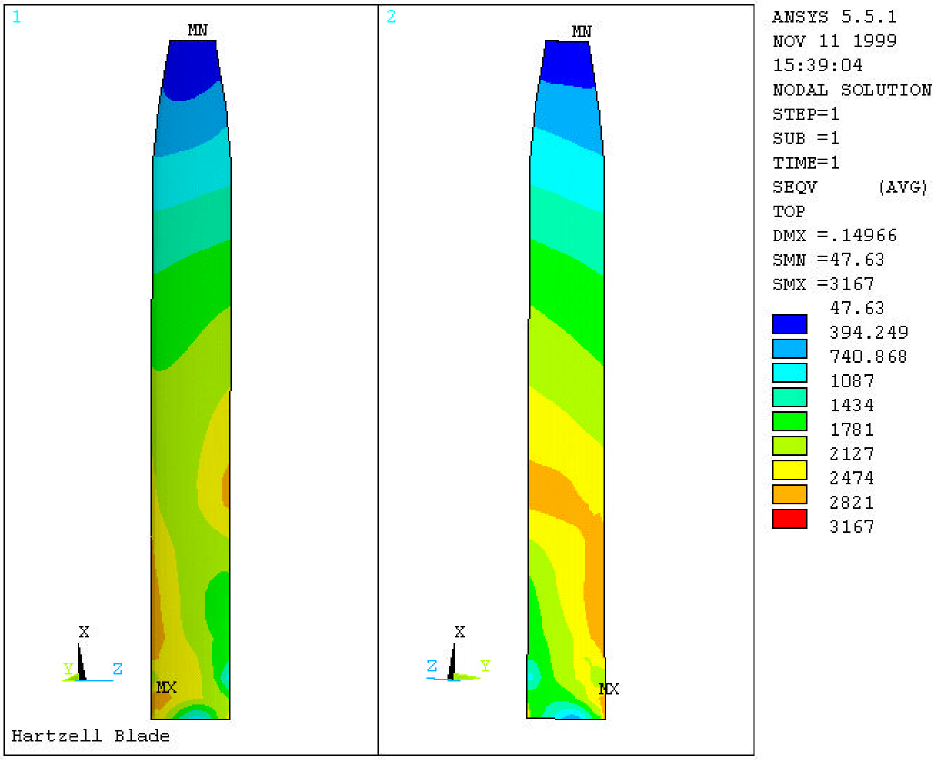


Figure 4.7.2: Hartzell rotor blade steady state stress results

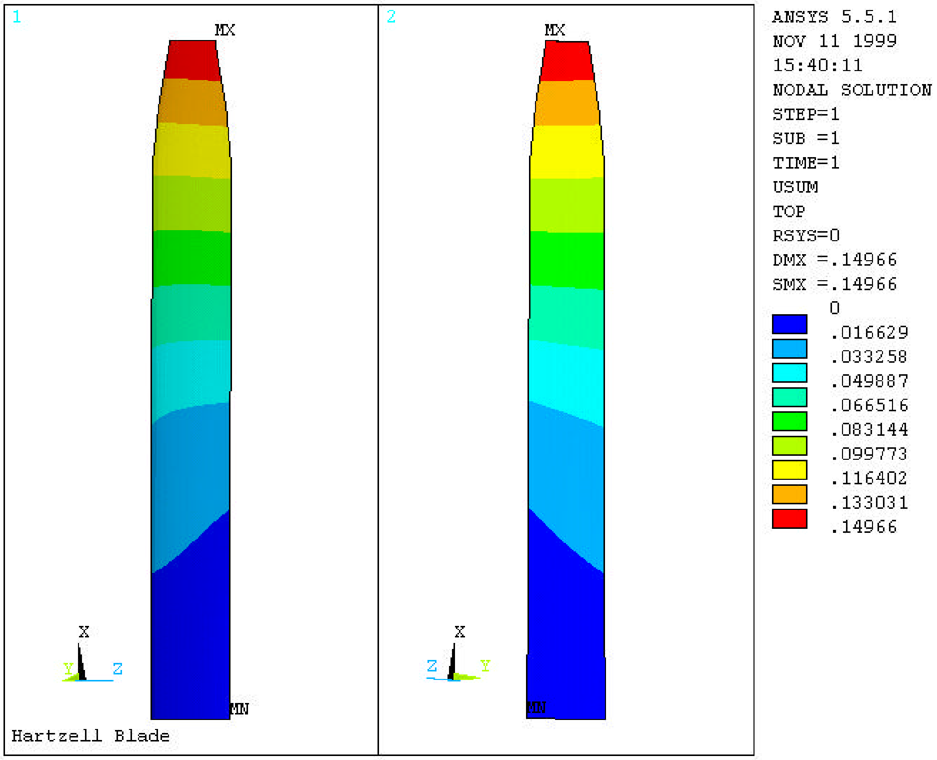


Figure 4.7.3: Hartzell rotor blade steady state displacement results.

Table 4.7.1: Hartzell Blade Modal Frequencies

Mode	Frequency (Hz) 0%	Frequency (Hz) 100%
1F	7.8	25.2
2F	28.2	55.1
1A	60.2	64.2
3F	65.0	96.5
4F	117.1	151.7
5F	188.8	225.1
1T	224.7	226.5
2A	253.9	257.5
6F	281.6	318.8
7F	394.8	432.7

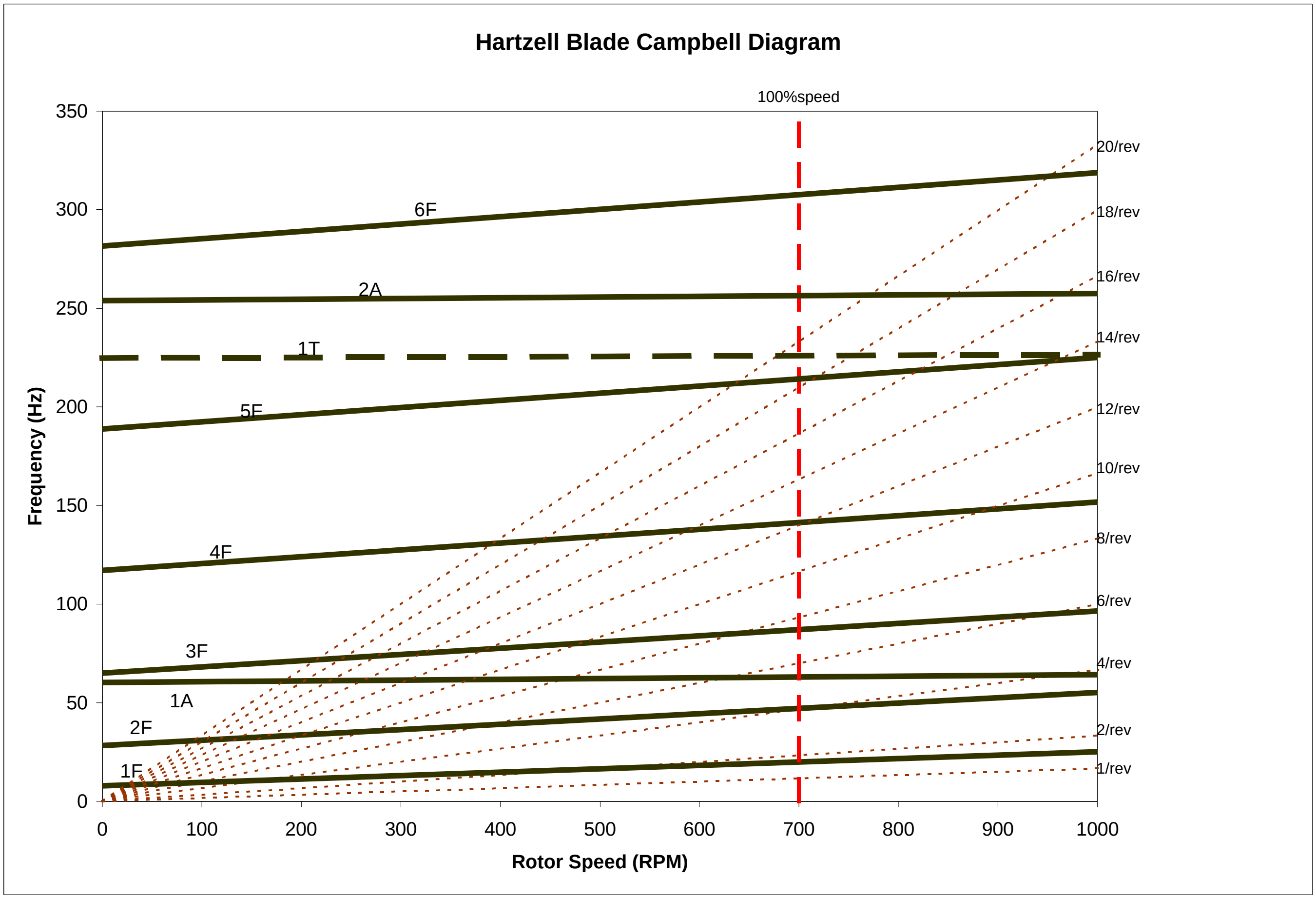


Figure 4.7.4: Hartzell Blade Campbell Diagram

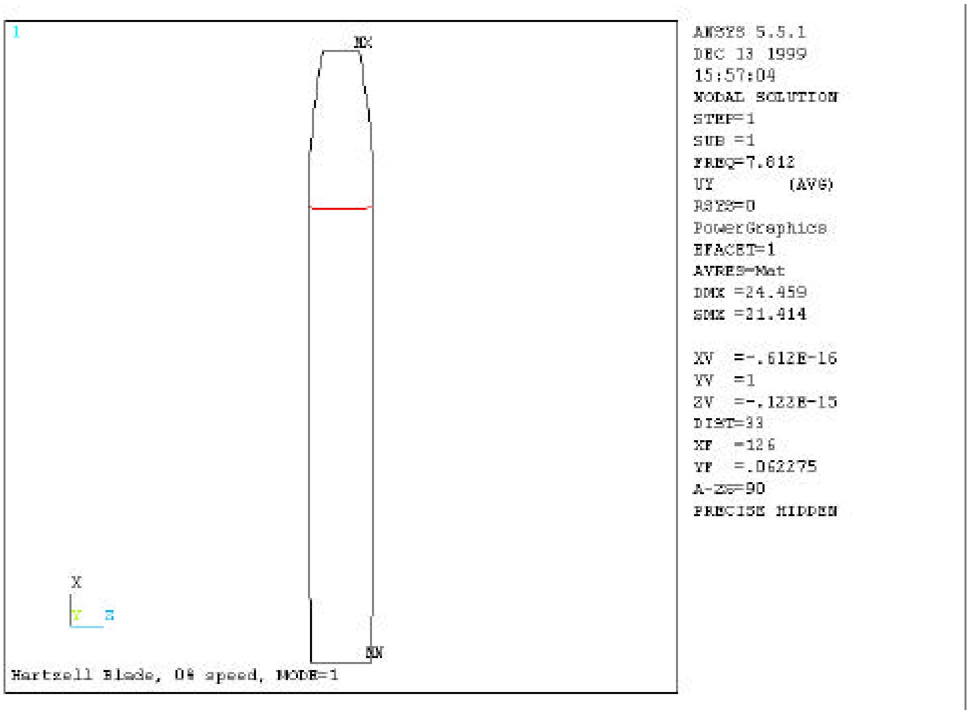


Figure 4.7.5a: Hartzell rotor blade, 0% speed, Mode=1, 1F

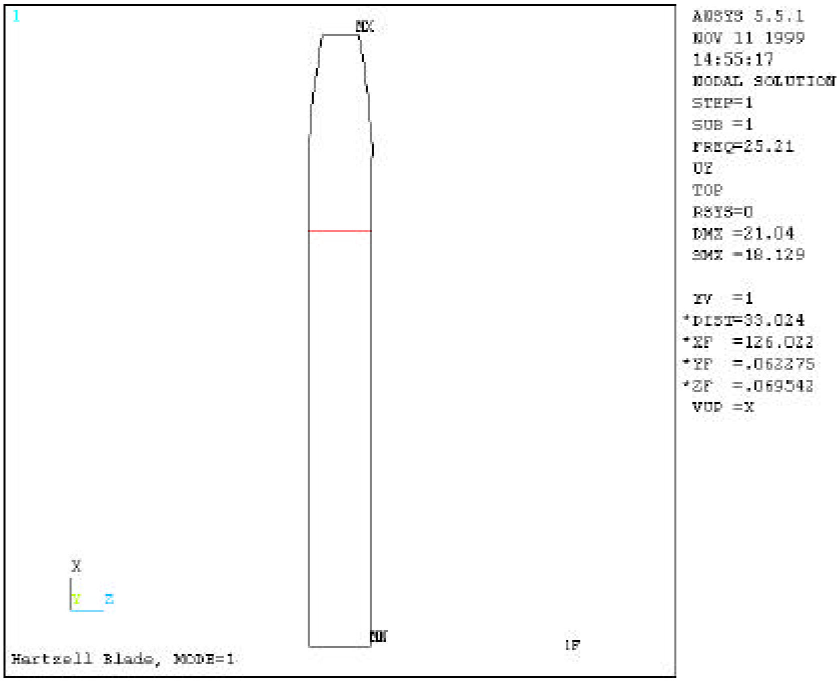


Figure 4.7.5b: Hartzell rotor blade, 100% speed, Mode=1, 1F

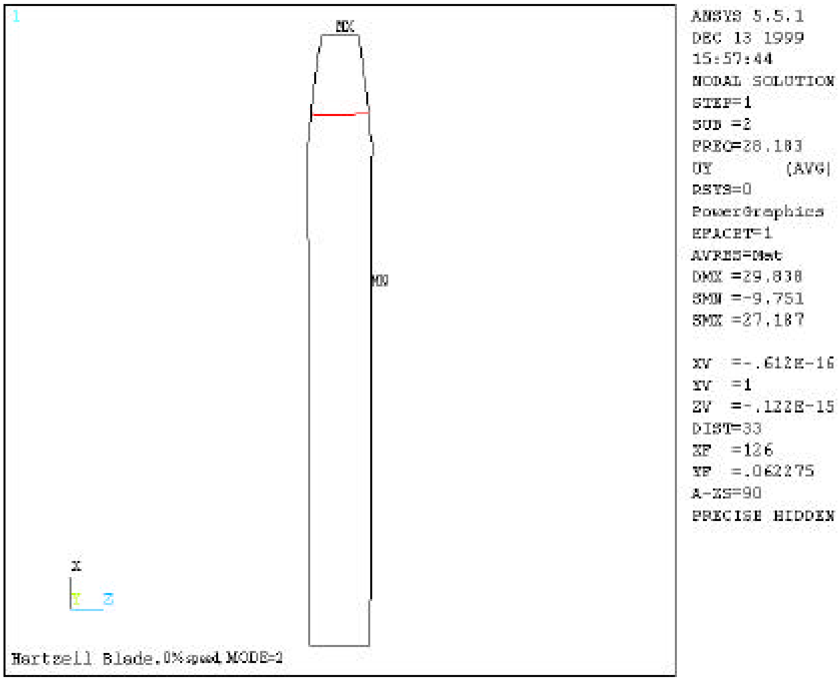


Figure 4.7.6a: Hartzell rotor blade, 0% speed, Mode=2, 2F

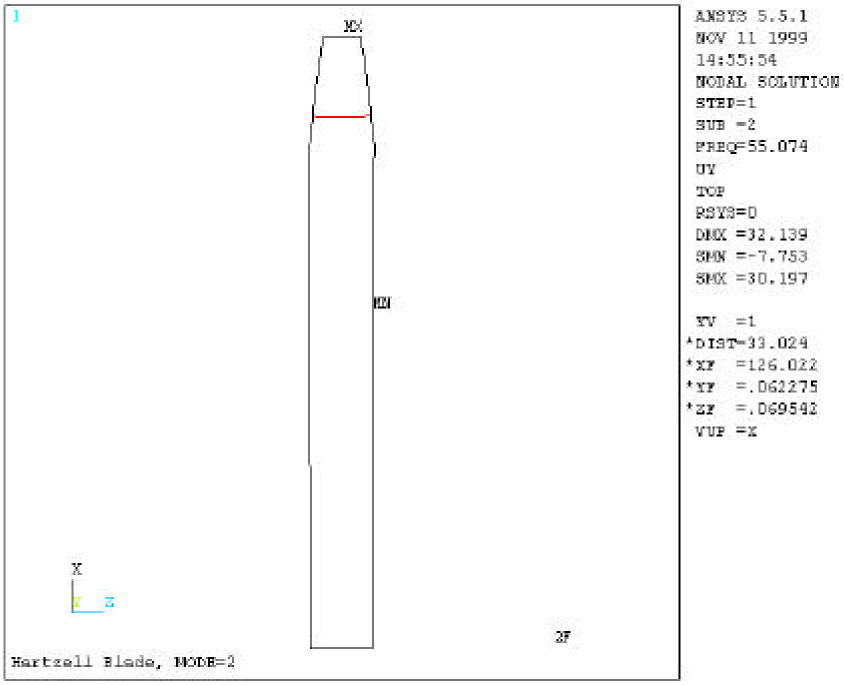


Figure 4.7.6b: Hartzell rotor blade, 100% speed, Mode=2, 2F

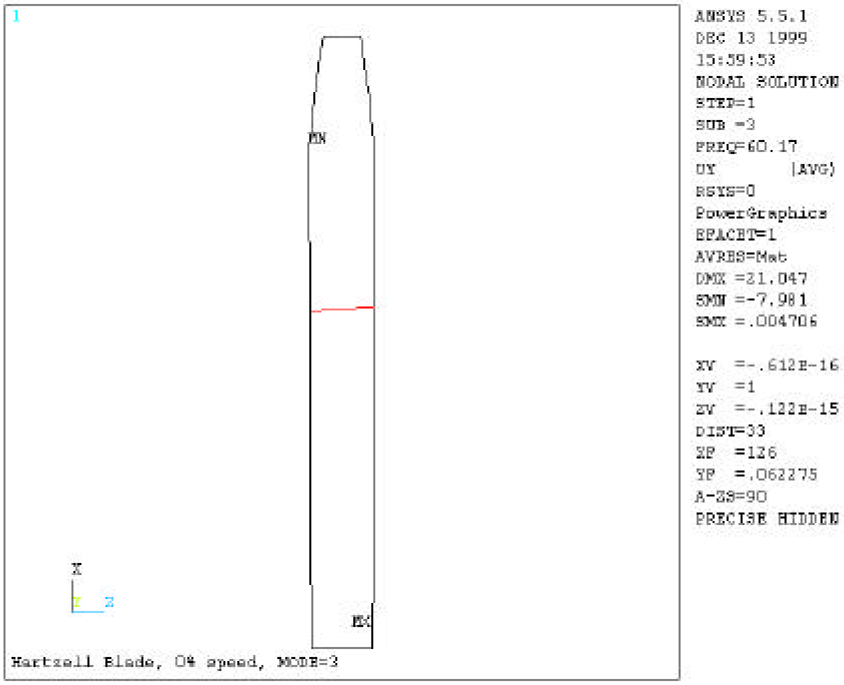


Figure 4.7.7a: Hartzell rotor blade, 0% speed, Mode=3, 1A

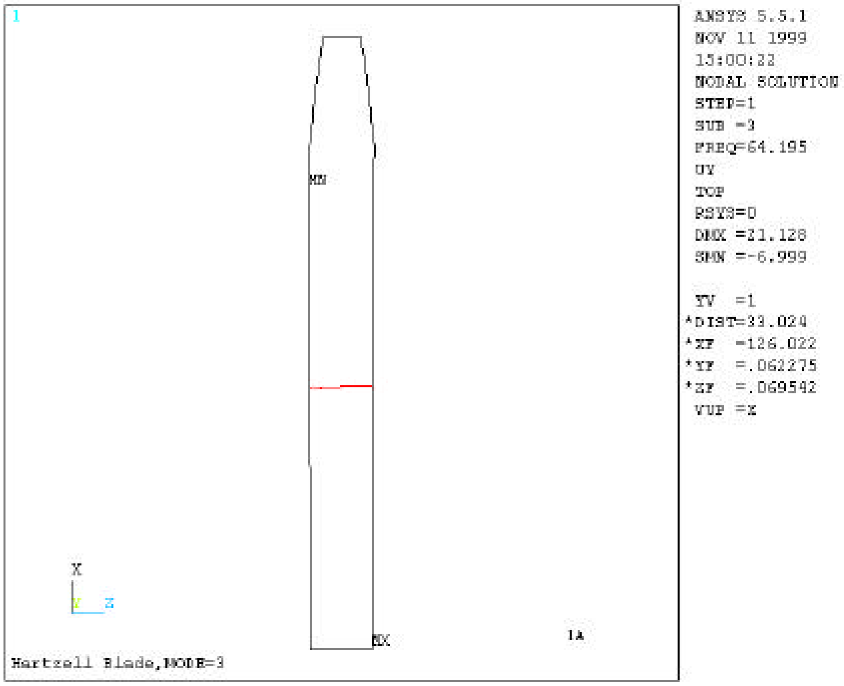
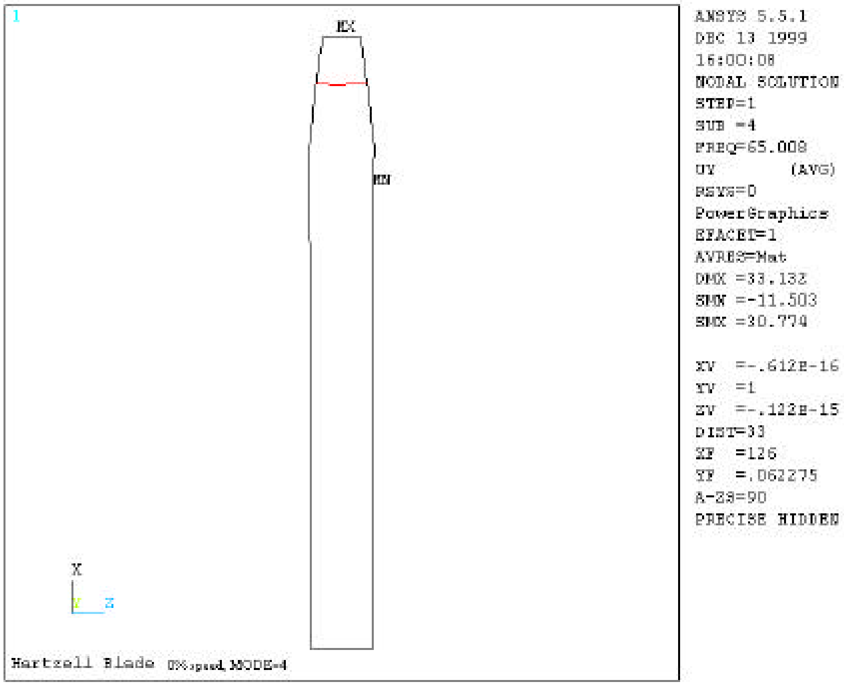


Figure 4.7.7b: Hartzell rotor blade, 100% speed, Mode=3, 1A



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ANSYS 5.5.1
DEC 13 1999
16:00:08
NODAL SOLUTION
STEP=1
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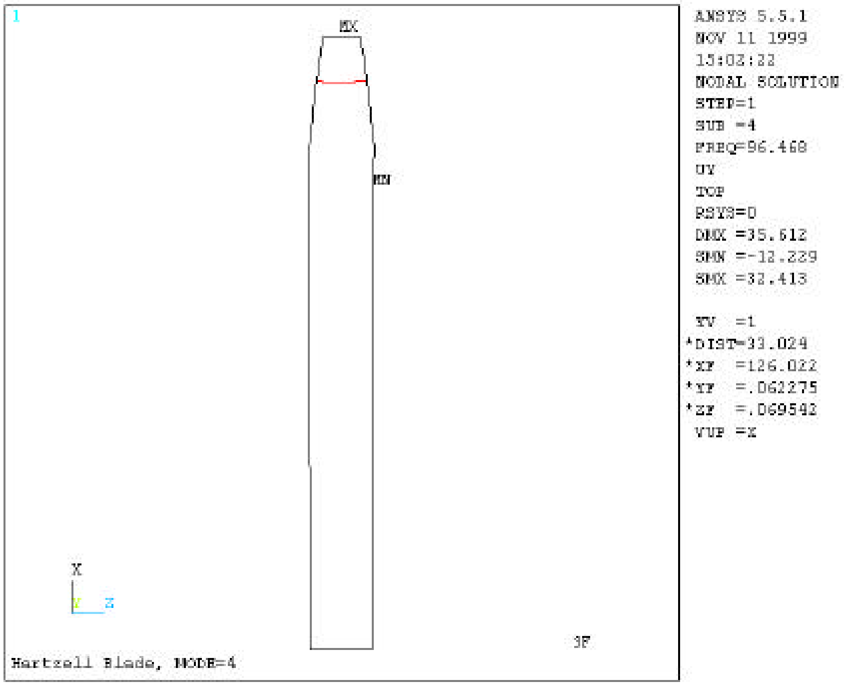
FREQ=65.008
UY        (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =33.132
SMN =-11.503
SMX =30.774

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```

Figure 4.7.8a: Hartzell rotor blade, 0% speed, Mode=4, 3F



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15:02:22
NODAL SOLUTION
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FREQ=96.468
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TOP
RSYS=0
DMX =35.612
SMN =-12.229
SMX =32.413

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```
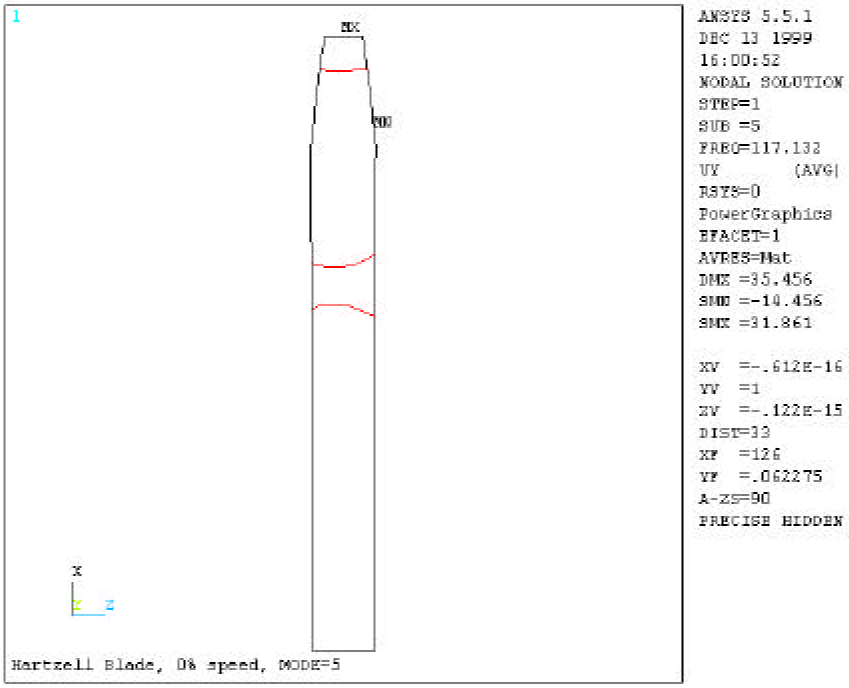

Figure 4.7.8b: Hartzell rotor blade, 100% speed, Mode=4, 3F



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16:00:52
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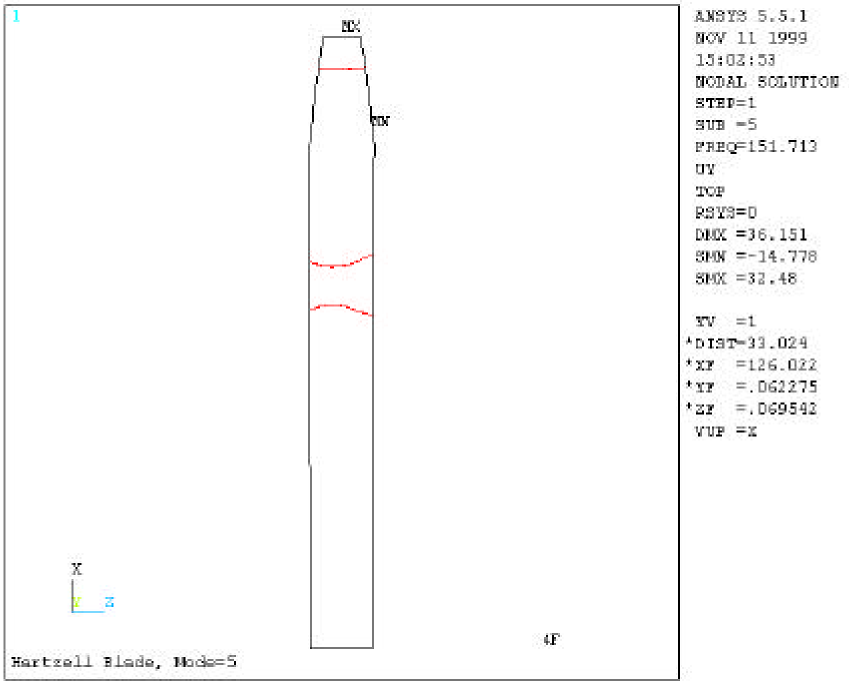
SMX =31.861

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```

Figure 4.7.9a: Hartzell rotor blade, 0% speed, Mode=5, 4F



```
ANSYS 5.5.1
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15:02:53
NODAL SOLUTION
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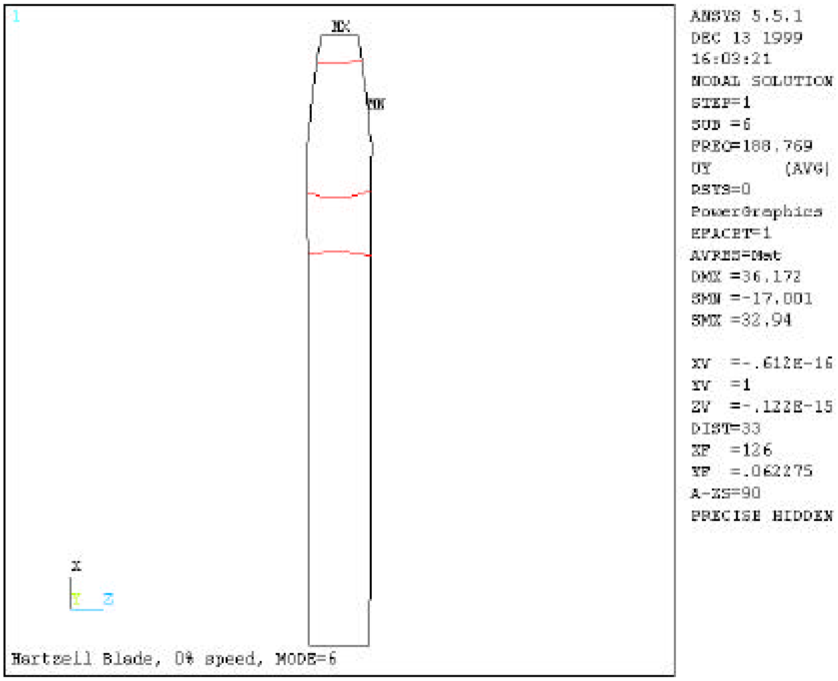
TOP
RSYS=0
DMX =36.151
SMN =-14.778
SMX =32.48

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```

Figure 4.7.9b: Hartzell rotor blade, 100% speed, Mode=5, 4F



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ANSYS 5.5.1
DEC 13 1999
16:03:21
NODAL SOLUTION
STEP=1
SUB =6
FREQ=188.769
UY        (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =36.172
SMN =-17.001
SMX =32.94

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```
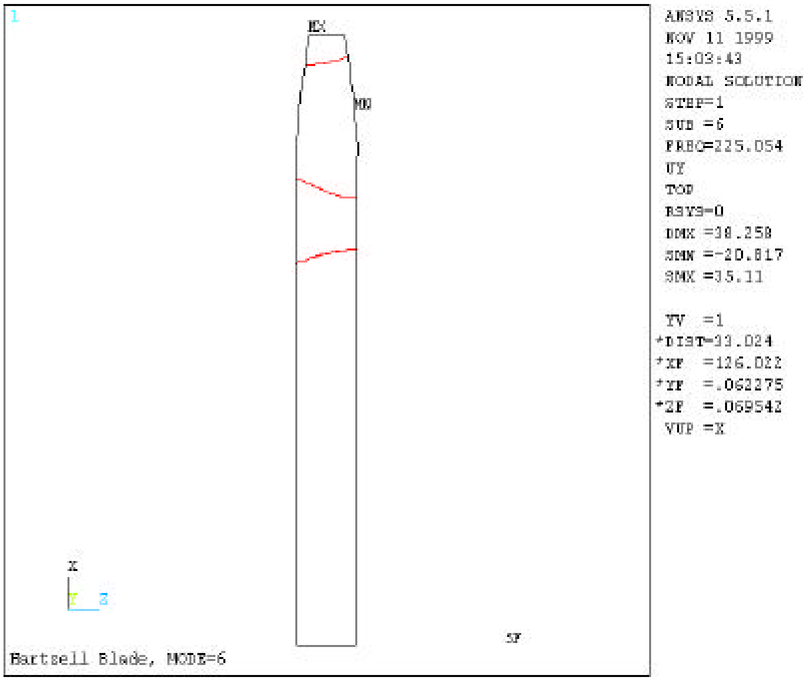

```
Hartzell Blade, 0% speed, MODE=6
```

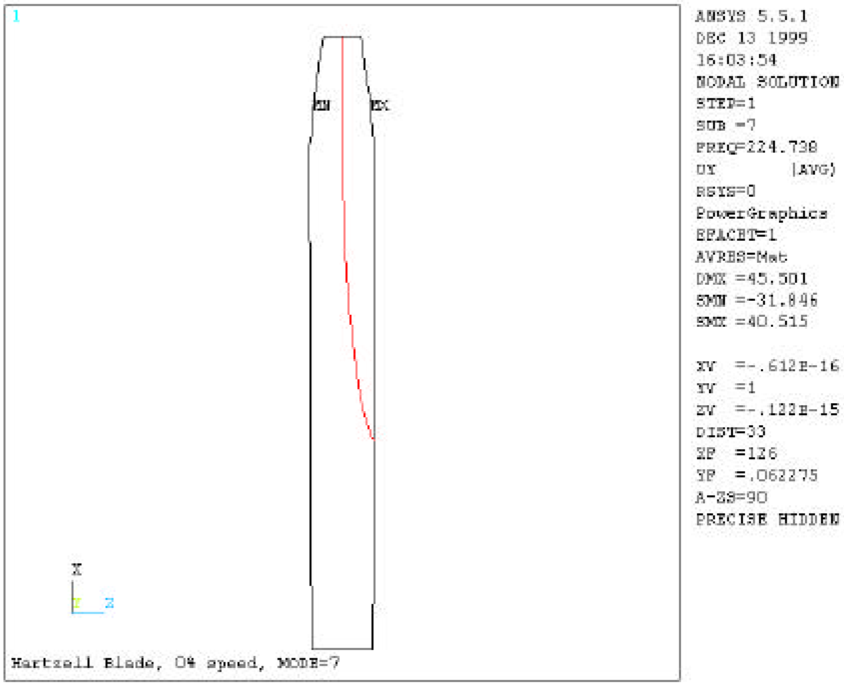
Figure 4.7.10a: Hartzell rotor blade, 0% speed, Mode=6, 5F



```
ANSYS 5.5.1
NOV 11 1999
15:03:43
NODAL SOLUTION
STEP=1
SUB =6
FREQ=225.054
UY
TOP
RSYS=0
DMX =38.258
SMN =-20.817
SMX =35.11

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```

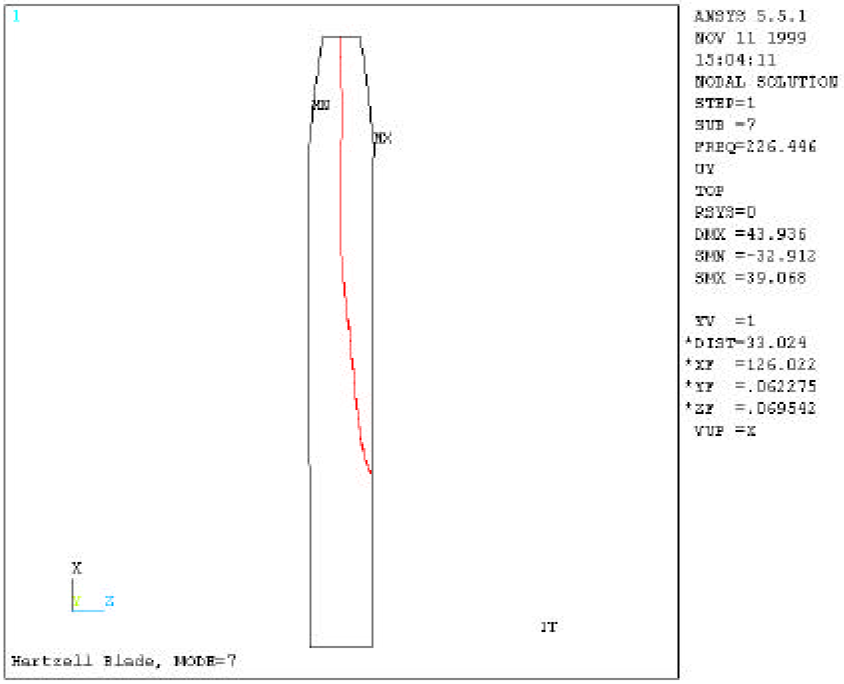
```
Hartzell Blade, MODE=6
```

Figure 4.7.10b: Hartzell rotor blade,100% speed, Mode=6, 5F



```
ANSYS 5.5.1
DEC 13 1999
16:03:54
NODAL SOLUTION
STEP=1
SUB =7
FREQ=224.738
UY        (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =45.501
SMN =-31.846
SMX =40.515

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```

Figure 4.7.11a: Hartzell rotor blade, 0% speed, Mode=7, 1T



```
 ANSYS 5.5.1
 NOV 11 1999
 15:04:11
 NODAL SOLUTION
 STEP=1
 SUB =7
 FREQ=226.446
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 TOP
 RSYS=0
 DMX =43.936
 SMN =-32.912
 SMX =39.068

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```

Figure 4.7.11b: Hartzell rotor blade, 100% speed, Mode=7, 1T

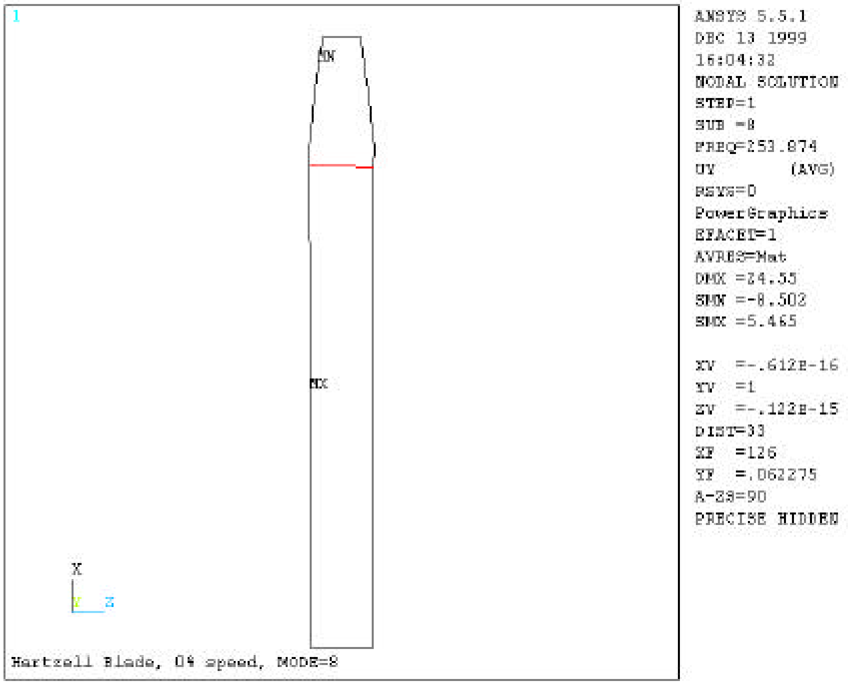


Figure 4.7.12a: Hartzell rotor blade, 0% speed, Mode=8, 2A

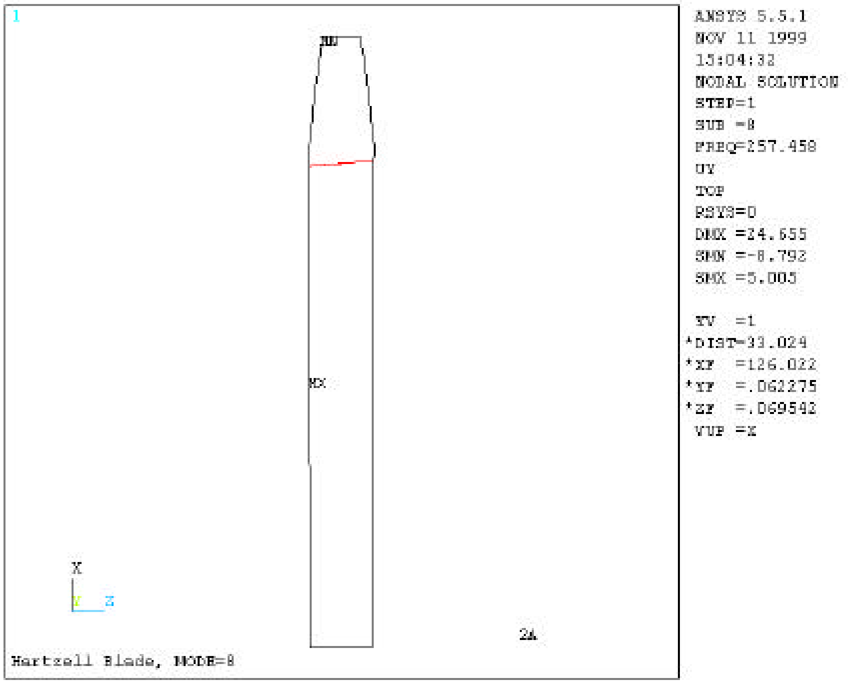
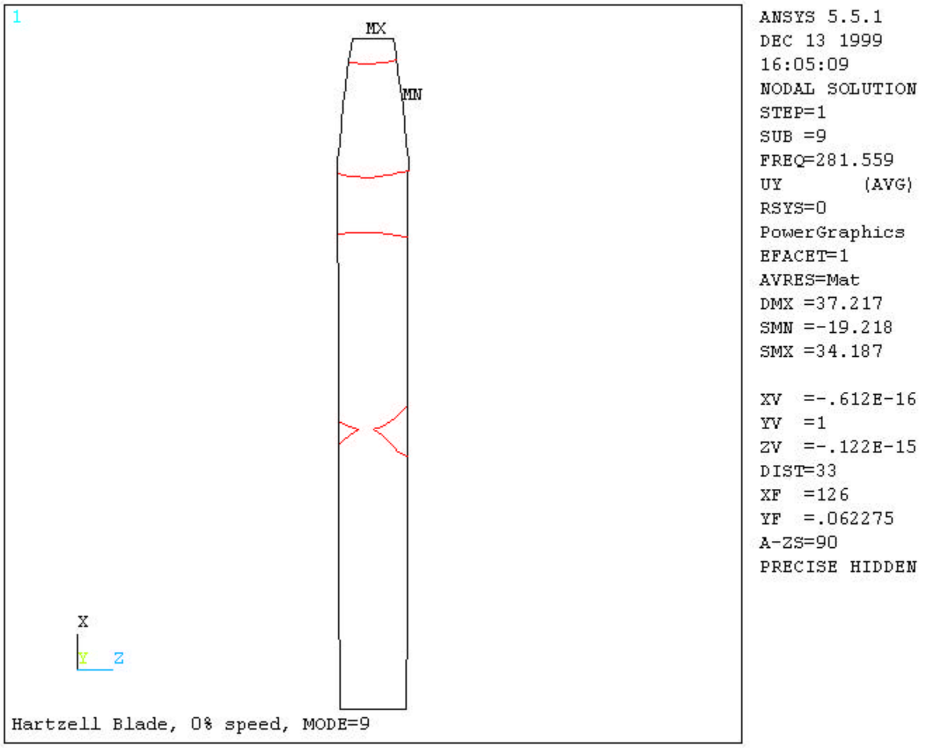


Figure 4.7.12b: Hartzell rotor blade, 100% speed, Mode=8, 2A



```
ANSYS 5.5.1
DEC 13 1999
16:05:09
NODAL SOLUTION
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RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =37.217
SMN =-19.218
SMX =34.187

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```
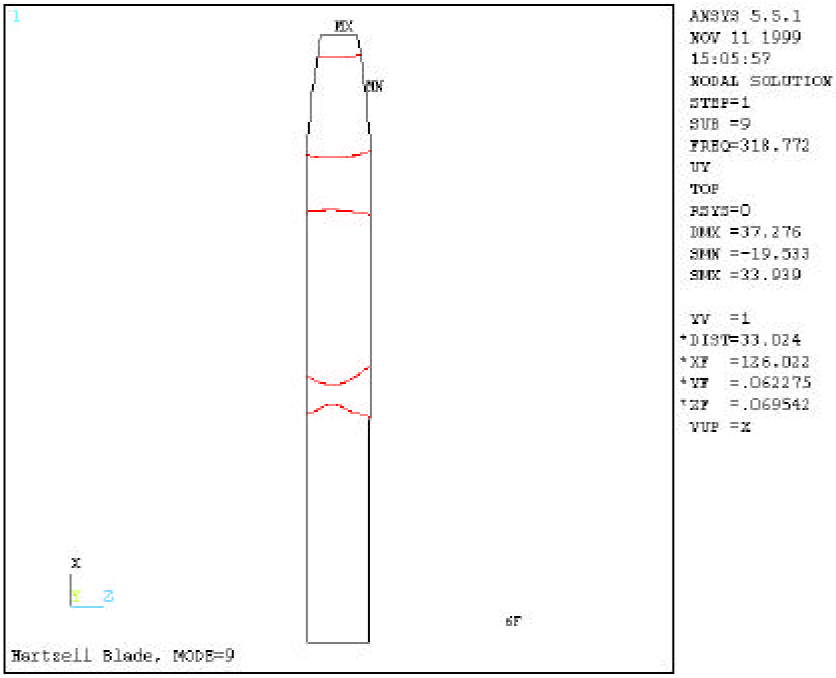

Figure 4.7.13a: Hartzell rotor blade, 0% speed, Mode=9, 6F



```
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 TOP
 RSYS=0
 DMX =37.276
 SMN =-19.533
 SMX =33.939

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```
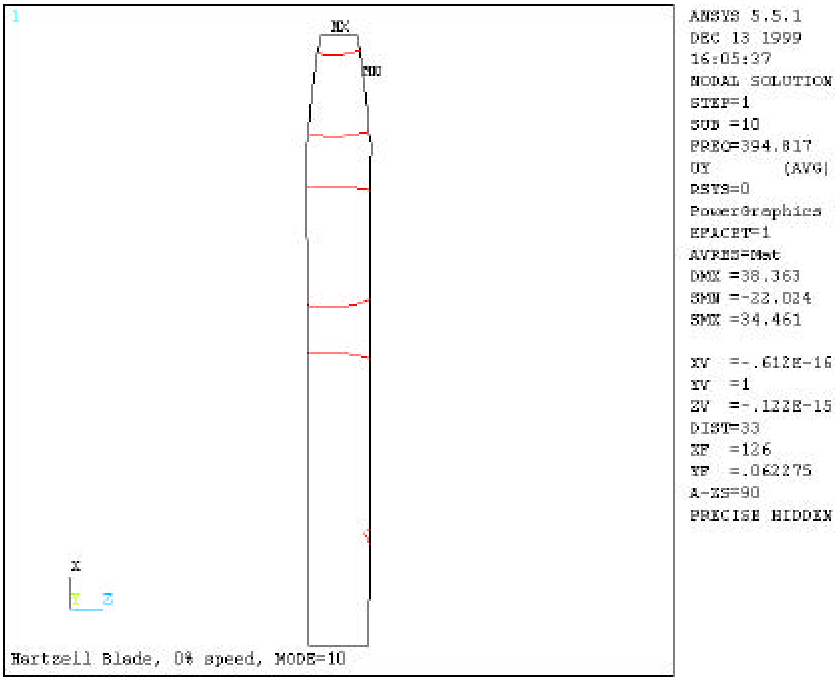

Figure 4.7.13b: Hartzell rotor blade, 100% speed, Mode=9, 6F



```
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DEC 13 1999
16:05:37
NODAL SOLUTION
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FREQ=394.817
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RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =38.363
SMN =-22.024
SMX =34.461

XV  =-.612E-16
YV  =1
ZV  =-.122E-15
DIST=33
XF  =126
YF  =.062275
A-ZS=90
PRECISE HIDDEN
```
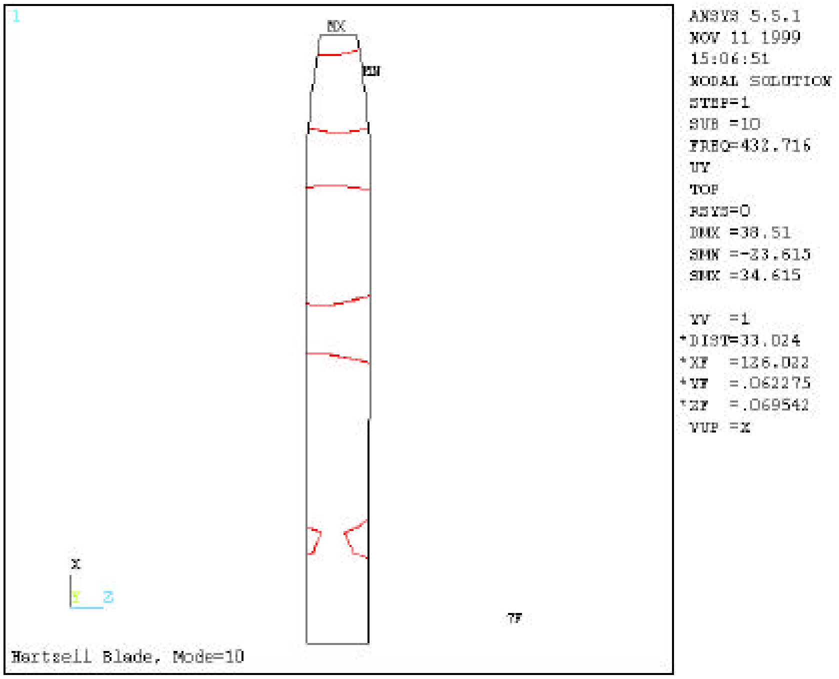

Figure 4.7.14a: Hartzell rotor blade, 0% speed, Mode=10, 7F



```
 ANSYS 5.5.1
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 15:06:51
 NODAL SOLUTION
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 FREQ=432.716
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 TOP
 RSYS=0
 DMX =38.51
 SMN =-23.615
 SMX =34.615

 YV  =1
*DIST=33.024
*XF  =126.022
*YF  =.062275
*ZF  =.069542
 VUP =X
```

Figure 4.7.14b: Hartzell rotor blade, 100% speed, Mode=10, 7F

4.8 Aeromechanics Multi-Body Non-Linear Dynamics Analysis

A preliminary aeromechanics model of the Vmax concept rotor was constructed in DYMORE, which is a state of the art multi-body non-linear dynamics code [20]. The model allows addressing various concerns such as structural integrity, magnitude of elastic deflections, aeroelastic stability, aerodynamics loads, etc. DYMORE provides a unique balance between high fidelity of the analysis with sophisticated, yet frugal use of computational means. In such a multi-disciplinary area as aeromechanics, in spite of the remarkable and continuos progress in computers, this remains an important issue for some years to come; so formidable are the computational challenges. Among the cutting edge theories that were incorporated in DYMORE, two that are particularly innovative have to be mentioned; cross-sectional beam analysis [21] and the implicit Floquet analysis [22]. The former compresses the information about the elastic deformation of both composite or isotropic beams into compact 6 by 6 matrix of stiffnesses (which include all possible elastic couplings) while retaining the fidelity of a finite element model with tens of thousands degrees of freedom. This proves to be vital in the multi-body environment, since it naturally resolves the problem of interface between elastic bodies. The latter extracts the dominant eigenvalues of the transition matrix using the Arnoldi algorithm, without the explicit computation of this matrix (as a requirement for the classical Floquet analysis for stability of periodic systems – which effectively puts out of reach systems with more than 100 degrees of freedom). As a result, the proposed method yields stability information at a far lower computational cost than that of the classical Floquet analysis, and is ideally suited for stability computations of systems involving a large number of degrees of freedom. In addition a unique versatility of DYMORE modeling has to be commended. Models in the DYMORE can be built from the ground up and the complexity of the model can be increased step-by-step, as the amount of knowledge about the designed vehicle accumulates.

Description of the model

As the first step of creating such a comprehensive model, hover conditions have been modeled with the counter-rotating discs clamped to shafts at the zero angle of attack. It is recognized that the information that can be obtained from such a simplified model might be of a limited value. However, it is a necessary foundation on which the further refinements should be based in order to address most urgent problems pertaining to aeromechanics. Such problems are discussed below along with the corresponding refinements that could address those problems. A single disc configuration, with four elastic blades rigidly attached to the disc, was also modeled for comparison purposes.

Two discs are attached to the coaxial counter-rotating shafts by means of revolute joints. Both discs were assumed to be rigid while blades were modeled as elastic beams. Based on the preliminary configuration, a rigid disc with a 16 feet diameter was assumed. Hartzell blades were modeled as close as possible with respect to their elastic and aerodynamic specifications. Lifting lines were attached to each blade and their influence was included in the dynamic analysis. The aerodynamic effects are modeled by 2-D blade element analysis (based on the existing airfoil tables) in conjunction with finite-wake single rotor wake calculation [23,24].

First, a static analysis with included centrifugal effects due to the rotation was performed. See the lowest frequency mode Fig. 4.8.8. The resulting solution was used as an initial condition for the subsequent dynamic analysis. Two types of dynamic analysis can be conducted with the DYMORE. The first one was a direct time integration to study evolution of the structure in time (see the results of the simulation

Figs. 4.8.3 - 4.8.7). The second (more computationally expensive) was the mentioned above implicit Floquet stability analysis. In the latter procedure the perturbation was introduced to the trimmed state of the system. Next, an iterative procedure was invoked and the integration was conducted for exactly one period at each iteration step. Finally, Floquet analysis was employed to extract sufficient information about the transfer matrix to recover its dominant eigenvalues by employing Arnoldi method (which is an unconditionally stable method for recovering eigenvalues of large sparse matrices).

Results and discussion

“Nearly hover” condition had been modeled with the far field flow velocity components chosen as 1ft/sec forward velocity, 0.645 ft/sec vertical velocity, and no sideways velocity. This choice was basically the result of trial and error, since the pure hover condition results in matrix singularities, and the ill conditioning has to be avoided.
Vertical spacing between the discs for modeling was chosen to be 1ft which gives the 0.2 ratio to the radius of the blades (cf. the ABC (Advanced Blade Design) where this ratio was 0.138).

For a single disc (Fig. 4.8.2) it took 52 steps to converge with 128 steps of Arnoldi algorithm and about 2 hours of Pentium II 400 computer (8 eigenvalues were searched). Here 128 steps correspond to the period of the system. This configuration has been found stable with the least dumped mode having the damping ratio –0.083524 and the next one –0.08976. As with any Floquet method, the frequency of a given mode is not defined uniquely. For the counter-rotating system (Fig. 4.8.1) when 8 eigenvalues were searched, convergence was achieved already at the 29 step, but all the eigenvalues were spurious and the search had to be extended to 16 eigenvalues. For 16 eigenvalues the iteration procedure blows up at the 53 step with four dominant eigenvectors having big negative damping ratios, the largest being unrealistically huge (this takes about 4 hours of PC time). Similar phenomenon occurred for 12 eigenvalues. It is not clear whether this indicates that the system with counter-rotating is indeed unstable, or it is the calculation scheme that blows up due to bad convergence of the inflow model. It has to be noted that, based on the traditional frequency Campbell diagram method (see fan diagram, Fig. 4.7.4), the close proximity of the first flapping mode to the 2 per rev frequency is the subject of some concern. It implies that the system is susceptible to the 2 per rev excitation, which is bound to occur in a two-blade per disc system. Conducted analysis might indicate that for near hover condition there is not a sufficient amount of damping in the system to keep it stable.
It is felt that while obtained values for the damping can not be trusted, the situation does not seem to be as trouble-free as it is with the single disc configuration. Therefore, further investigation of the counter rotating configuration is advised which should include some extensive study of various near-hover points with several inflow models. In fast forward flight the situation can be different altogether, and in any case the vibration levels in such regimes are likely to be high, so the redesign of the blade in order to change the flapping frequency might be suggested. In the process of choosing the bending stiffness in flapping, the following trade off has to be also taken into consideration: The high stiffness of the tips is needed in order to allow the clearance. On the other hand, this also results in high bending moments at the root with the possible detrimental effects on the fatigue life - as was the case with ABC see [25,26]. Minimal vertical spacing is considered to be beneficial from the performance point of view, and therefore the clearance between the tips of the flapping blades has to be observed [27]. DYMORE has convenient means to calculate the magnitude of flapping (by tracking down the displacements of the blade tips). Clearly, the most adverse situation is not encountered in the hover flight, but rather expected to occur during/immediately prior to the transition, when the forward flight speed is at its maximum.

Ground/air resonance, which is usually associated with the in-plane motion of the blades, should not provide a reason for concern in the studied configuration. The absence of the lead lag hinges and relatively stiff in-plane bending of the blades eliminates this problem altogether, as was the case with the ABC configuration (there the lag motion was almost purely in plane and practically no coupling with flapping and pitching was observed [25]).

Recommended other refinements/issues to be addressed

The net rolling moment in forward flight is passed on the hub, which alleviates the retreating stall and this is clearly one of the best selling point of coaxial configuration, but at the same time it created significant bending moments. Also, the shaft has to be carefully designed (in ABC shaft stresses exceeded endurance in the descent because of the hub moment needed to balance the horizontal tail moment). In the present model the shafts were considered to be rigid, and modeling of the flexible shafts is clearly desirable (and not difficult to implement).

As was mentioned above, even if the system is stable, the flapping frequency of the blades might cause severe 2 per rev vibration. It is interesting to note that vibration is highly dependent on rotor phasing - for a designed blade crossover at 90-degree azimuth the symmetric hub forces tend to cancel (including vertical, longitudinal) and pitch moment). On the other hand, for 0-degree azimuth, the antisymmetric hub forces (lateral force, roll moment, yaw moment) tended to cancel. If the dominant excitation of the airframe is attributed to pitch or roll moment (which would be the case for the high flap stiffness), then blade crossover at 0-degree azimuth is expected to result in much lower vibration levels. Although prediction of vibration level is notoriously difficult, primarily due to sensitivity to various parameters that seem to be impossible to take into consideration, some trends clearly can be established based on the constructed model. Again, the most adverse situation is expected to be in the transition/ before the transition, where the forward flight velocity is high.

Flexibility of the discs also should be included in the analysis: although the discs are presently designed fairly stiff and their flexibility influence is unlikely to have a significant impact on stability, this refinement is mandatory for addressing vibration problem. Any degrees of freedom present in the hub mechanism should to be also included in the analysis and this should not present a technical difficulty as far as modeling in DYMORE is concerned.

The aerodynamics of the wake interaction was not included in the analysis: The wake calculation was conducted independently for each disc. In reality the wake from the upper rotor should contract inward and convect downward faster than an isolated rotor would. For the lower rotor the faster axial rate is also apparent, but the radial contraction is almost absent. More sophisticated modeling of the wakes interaction might also shed some light on the present uncertainty with the stability (although the problem most likely lays somewhere else), but it will definitely affect the level of vibrations, and the importance of BVI (blade vortex interaction) has to be assessed.

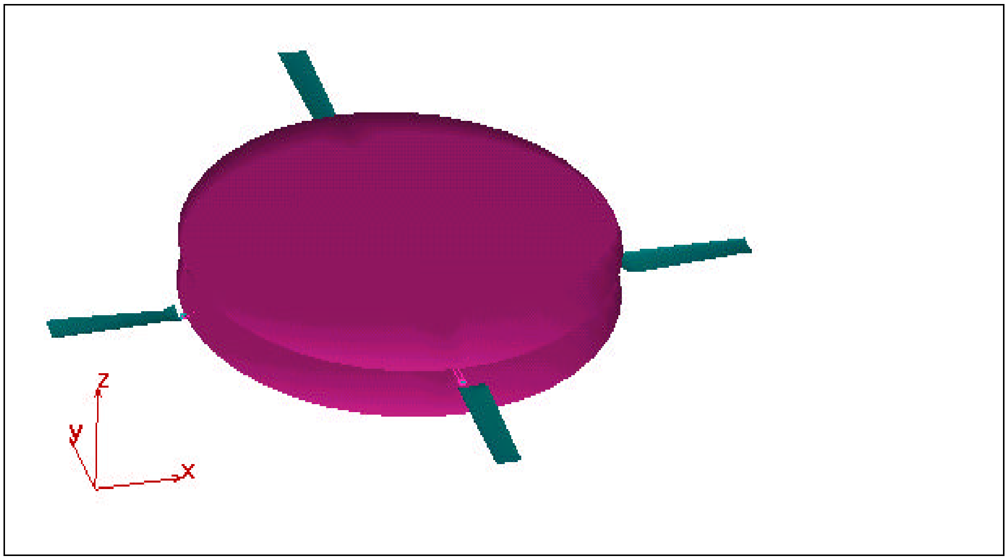

Figure 4.8.1 General layout of the counter-rotating double disc configuration

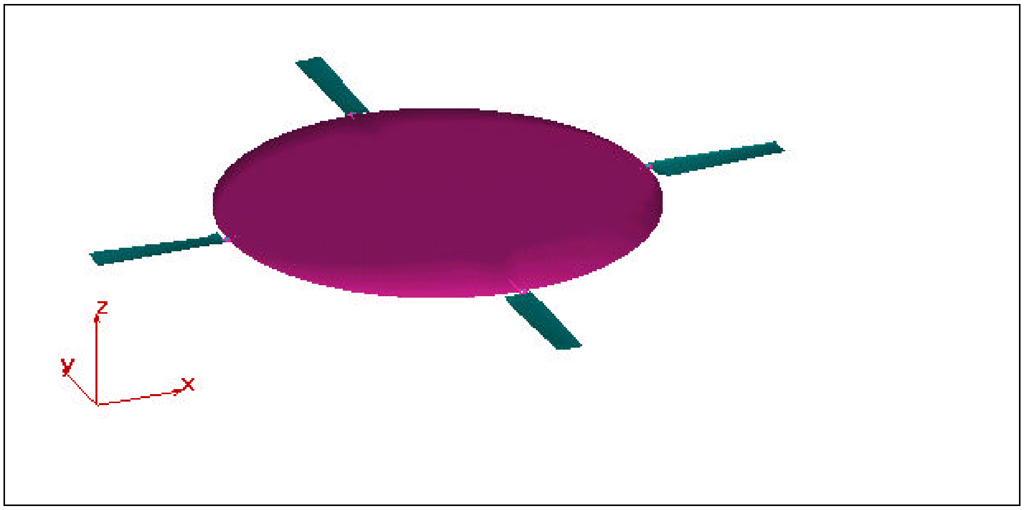

Figure 4.8.2 General layout of the single disc configuration

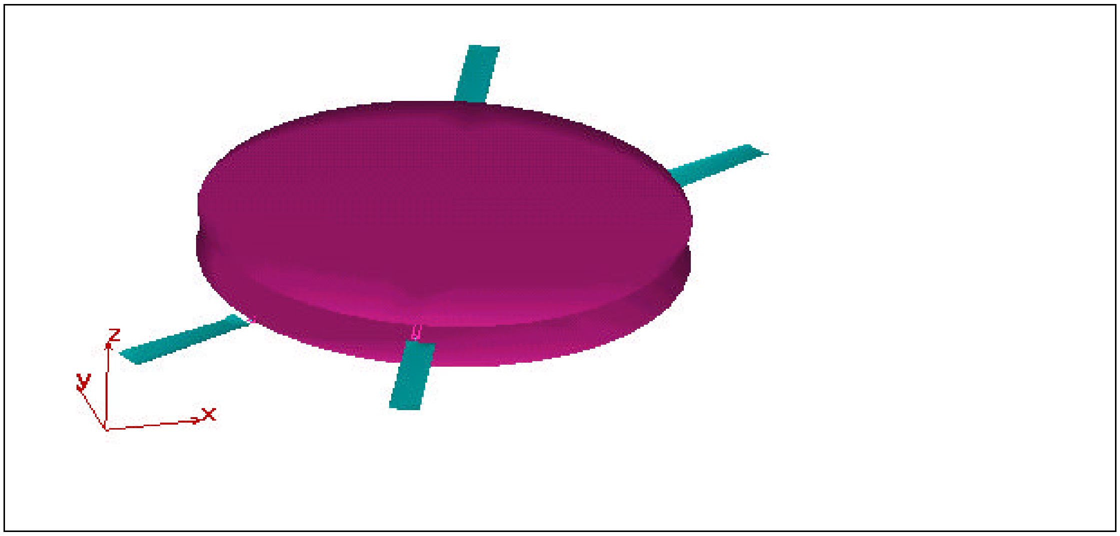

Figure 4.8.3 Results of dynamic simulation. Step 33 (time 2.06 E-2 sec)
(Time step 6.25E-4;angular velocity 78.5 rad/sec, tip speed 1020.5 ft/sec)

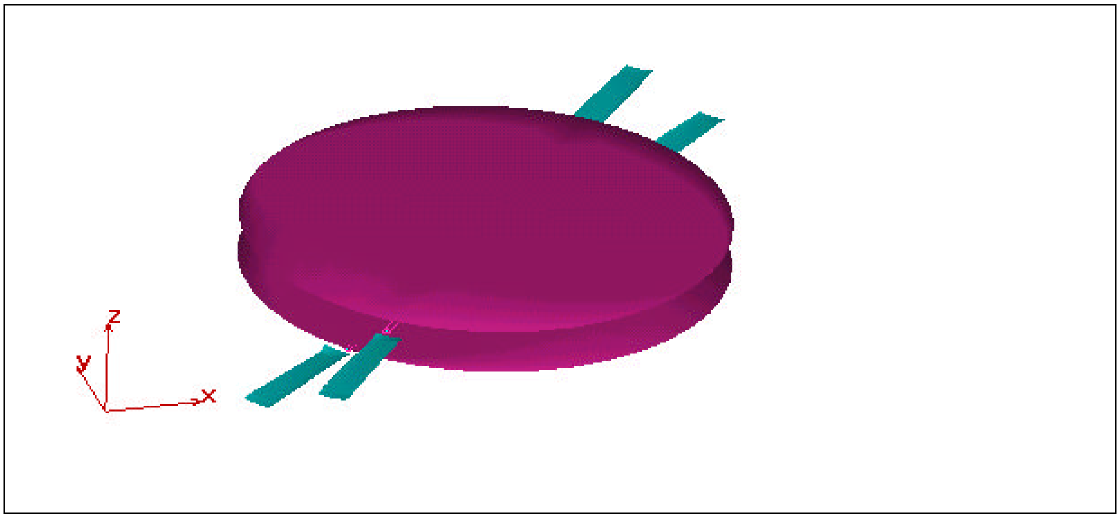

Figure 4.8.4 Results of dynamic simulation. Step 57 (time 3.56 E-2 sec)
(Time step 6.25E-4;angular velocity 78.5 rad/sec, tip speed 1020.5 ft/sec)

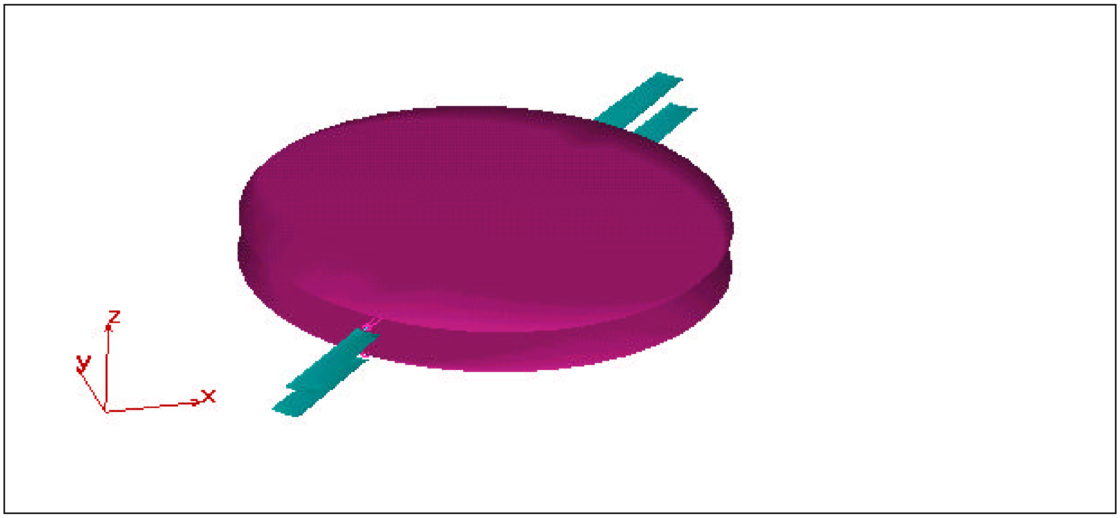

Figure 4.8.5 Results of dynamic simulation. Step 64 (time 4.00 E-2 sec)
(Time step 6.25E-4;angular velocity 78.5 rad/sec, tip speed 1020.5 ft/sec)

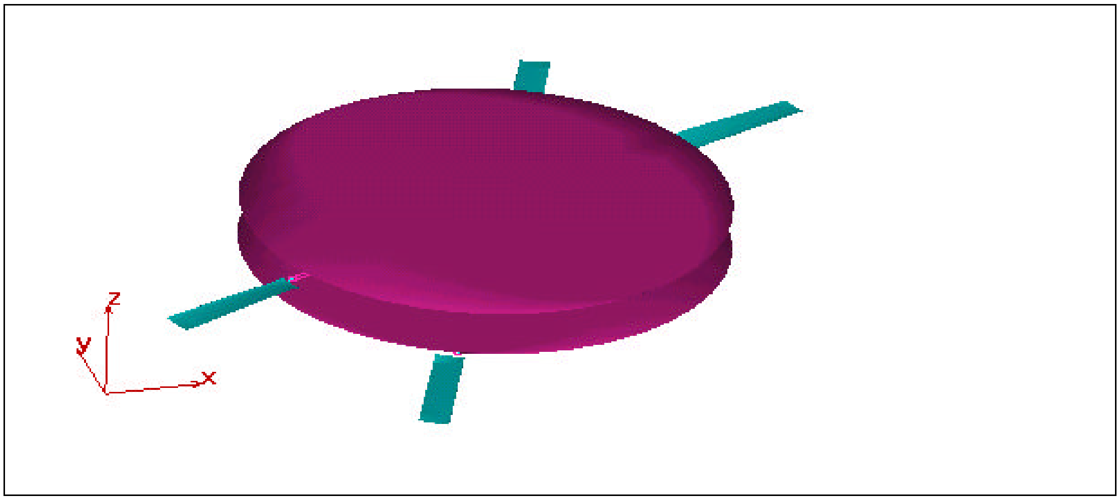

Figure 4.8.6 Results of dynamic simulation. Step 96 (time 6.00 E-2 sec)
(Time step 6.25E-4;angular velocity 78.5 rad/sec, tip speed 1020.5 ft/sec)

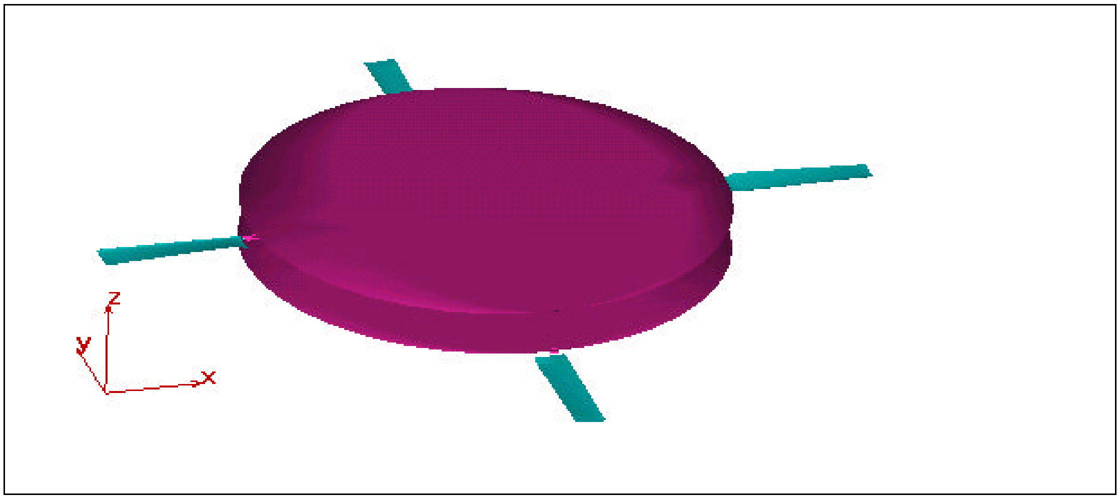

Figure 4.8.7 Results of dynamic simulation. Step 128 (time 8.00 E-2 sec)
(Time step 6.25E-4;angular velocity 78.5 rad/sec, tip speed 1020.5 ft/sec)

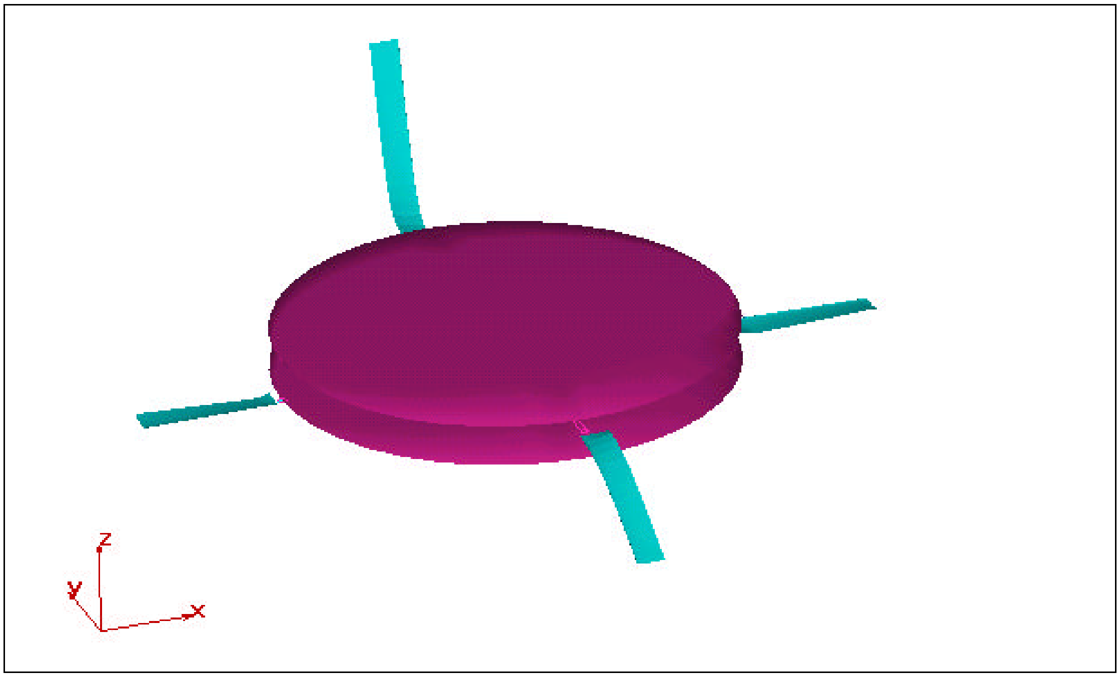

Figure 4.8.8 First flapping mode for counter-rotating configuration
(Magnitude is exaggerated)

4.9 Rotor Drawings for Prototype Development

A set of preliminary drawings, showing the disk-wing and the Hartzell rotor blade, were created using the Unigraphics Program, version 15. The file name for these drawings is J99004-001.prt, with the disk-wing data on sheet 1 and the Hartzell rotor blade on sheet 2. Figures 4.9.1 and 4.9.2 give a representation of these drawings.

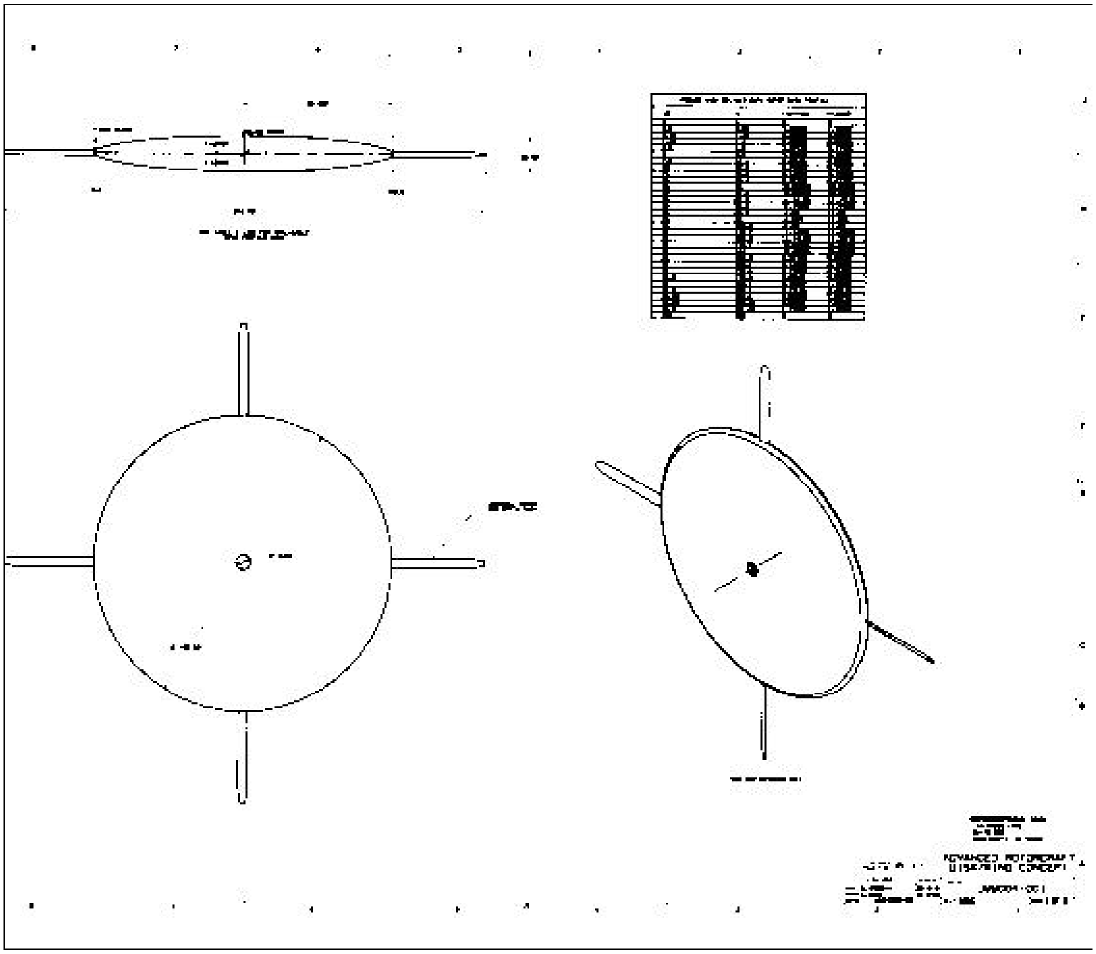

Figure 4.9.1: Drawing J99004-001, sheet 1

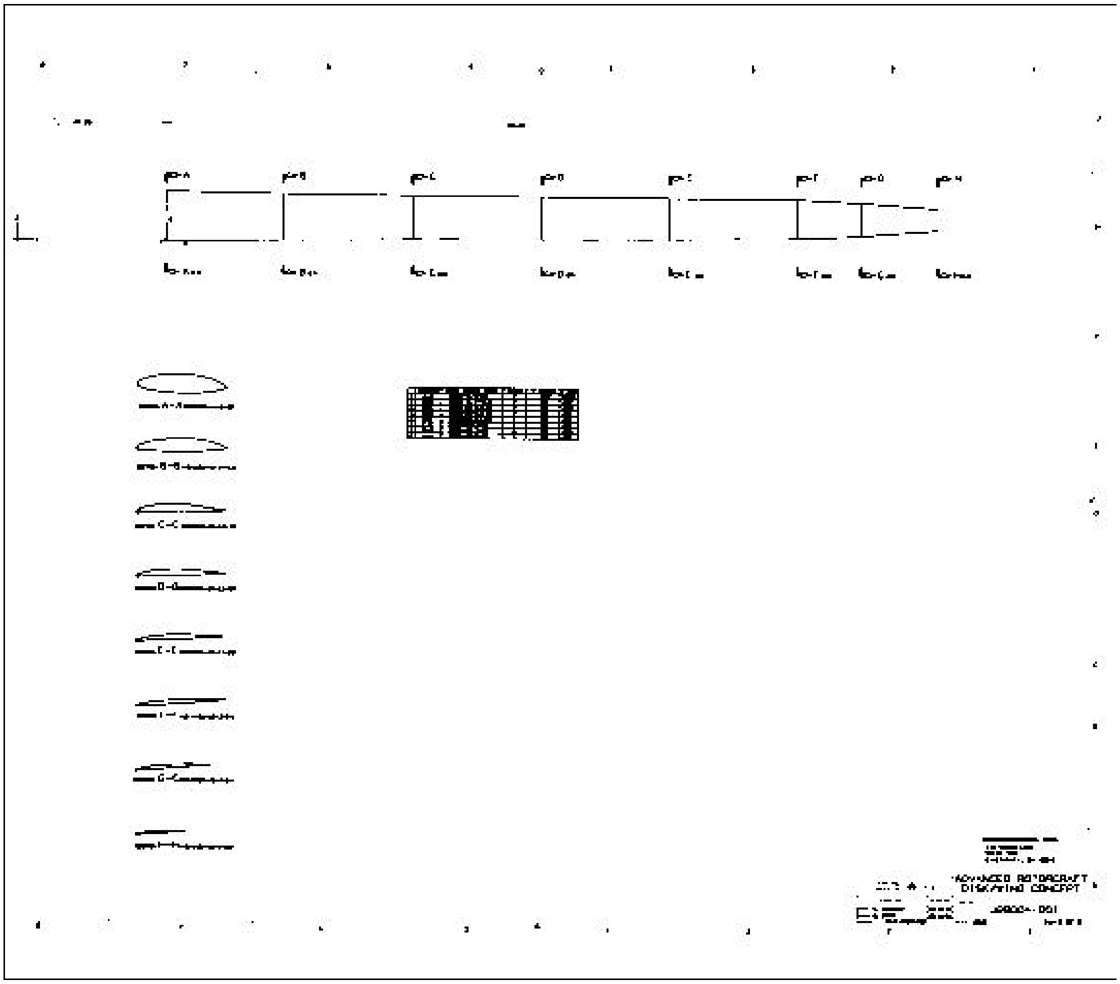

Figure 4.9.2: drawing J99004-001, sheet2

5.0 RELATED R/R&D, ROTORCRAFT DEVELOPMENT HISTORY

Early attempts described in, ref.[9] & ref.[10], to increase helicopter speed involved adding direct propulsion and aerodynamic lift to off load the main rotor. Compound autogyros were built by McDonnell (XV-1) in the mid 1950's, three programs by Fairey in England (the Gyrodyne, Jet Gyrodyne, and Rotodyne) from 1947 to 1962, and by Kamov in Russia (Ka-22) which flew from 1960 to 1966. The small 5,500 lb XV-1 was the first rotorcraft to reach 200 mph in 1956. The Rotodyne was intended as a 40 seat VTOL transport for both civil and military markets. Its four bladed 60 ft rotor was driven by compressed air tip mounted ramjets during hover, and autorotated in forward flight powered by two 2,800 shp turboprop engines. In 1958, the Rotodyne set a 100 km closed course speed record of 191 mph. There was strong interest in the design from the British government and overseas commercial operators, but development dragged on, and the excessive noise from the tip ramjets was unacceptable in urban environments. The program was canceled in 1962. Advances in conventional helicopter performance contributed to the demise of the compound autogyro.

There were also several compound helicopters. The Piasecki 16H-1 had a ducted tail propeller for anti-torque in hover and direct propulsion in forward flight along with short wings to off load the rotor. The Pathfinder first flew in 1962 and after extensive modifications reached 195 knots before the program ended in 1965. The Lockheed XH-51 first tested as a rigid rotor helicopter in 1964. The XH-51A Compound added 17 ft wings and a 2,600 lb thrust turbojet to reach a top speed of over 300 mph. Lockheed followed up with the AH-56A Cheyenne attack helicopter.
Rotor instability problems and massive cost overruns led to its cancellation in 1972.

The Sikorsky S-72 was built for NASA as a Rotor Systems Research Aircraft (RSRA) and first flown in 1976. The 18,000 lb helicopter has a 62 ft diameter standard rotor with detachable 45 ft span wings and two 9,000 lb thrust turbofans. In 1984 Sikorsky began a program to convert the RSRA into the X-Wing demonstrator. The four symmetrical rigid blades of the X-Wing have slots along their leading and trailing edges to allow compressed air to be blown out. The functions of cyclic and collective pitch control is controlled in hover by modulating the airflow. For high speed flight, the rotor could be stopped and locked in the X position. Air could be blown out the slots to reduce blade drag and provide roll control. While simple in concept, the mechanical actuation of the pneumo-dynamic control system proved to be extremely complex, and the program was abandoned. The tilt wing concept was first explored by Vertol in 1957 with the VZ-2. It had a gross weight of 3200 lb and was powered by a single 860 hp turboshaft driving two 9.5 ft diameter propellers mounted midspan on its 26 ft wing.

The Hiller corporation flew their much larger 33,000 lb X-18 in 1959. Although it flew only 20 times (and never hovered), it did provide useful data for the next project; the LTV-Hiller-Ryan XC142A. This four engine .45,000 lb tilt wing was a prototype for a tri-service cargo/transport aircraft that nearly went into production.

Canadair also built and successfully flew a twin-engine tilt wing, the CL-84 Dynavert. Three prototypes of the 12,200 lb aircraft flew from 1965 thru 1974. A NASA study, ref.[4], by Rutherford, et.al., in 1991 examined several high-speed VTOL configurations and identified the tilt-wing as the best candidate. Recently, a private company was set up to develop a 14 passenger civil tilt wing as described by Channa , ref. [11]. Unfortunately, production plans have been suspended due to lack of development funds from private investors. Curtiss-Wright tested their model X-100 tilt propeller during 1960 to provide data for their X-200 tandem wing six seat civil design. The USAF bought both of the twin-engine, four propeller prototype and contracted Curtiss-Wright to develop and test them as the X-19 in 1963. The program was abandoned at the end of 1965 due to hover control problems and the crash of the first prototype. The tilt duct designs enjoyed a more successful test program than the tilt propeller. The Doak model 16 or VZ-4 was a 3,200lb aircraft powered by a single 850 shp turboshaft driving two 4 ft diameter ducts on the ends of its wing. It flew successfully from 1958 to 1960.

Bell Aircraft began work on ducted propellers in 1953, and in 1962 was awarded a contract to build and test two X-22A four engine (1,250 shp each,), four duct aircraft. Gross weight was 17,000 lb with accommodations for two pilots and six passengers with 465 gallons of fuel. The X-22 could hover at over 8,000 ft and had a top speed of 315 mph. The test program lasted over 15 years, but was never developed as a commercial or military transport. The tilt rotor configuration has probably had the longest development program of any VTOL airplane covering three different designs from Bell Aircraft; the XV-3, XV-15, and V-22. The XV-3 contract was awarded by the Army in 1951 and the first flight occurred in 1955 with the 23 ft diameter three-bladed rotors powered by an R-985 450 hp piston engine. Flight testing continued under Bell, USAF, and NASA contracts until 1965. In 1973 Bell began work on two new prototypes, designated the XV-15. The 25 ft diameter rotors were powered by 1,800 shp turboshaft engines which tilted with the rotor on the wing tips. First flight of the 13,000 lb aircraft was in 1977 and testing continued through 1993. In 1986 work began on the V-22 Osprey for use by all three services. After a difficult off and on development program, the V-22 has began production, after more than 40 years and over $3 billion of tilt rotor research and development.

The NASA M-85 rotorcraft concept, which comprises a single large circular hub fairing that is large enough to support the aircraft during conversion between rotary-wing and fixed wing modes, is described by Stroub, Ref.[3]. For vertical flight a number of blades are extended from the periphery of the disk to provide lift under rotating wing mode, and for horizontal flight the blades are drawn into the disk and the disk rotation is stopped. A considerable amount of analysis and wind tunnel testing has been performed in support of the M-85 rotorcraft concept.

6.0 RELATIONSHIP WITH PHASE II OR OTHER FUTURE R/R&D

It was intended that this sized preliminary design could be studied in further detail, in a Phase II, with respect to aerodynamics and aeromechanics of the hover through transition to forward flight envelope, preliminary mechanical design along with aerodynamic and control analyses. The intent was for the Phase I work effort to directly set the stage for a Phase II continuation.

The results of the Phase I study indicated that the Vmax design is potentially under powered and a higher horsepower engine may be required, particularly during the transition phase of flight. The design maximum and cruise speeds appear to be in doubt and further studies of the fixed wing flight are suggested. The generic nature of the analyses performed under the Phase I contract make them applicable to may permutations of the disc wing rotorcraft design. In particular the study of both single disc and counter-rotating discs were performed during the aeromechanical analysis with the resulting conclusion of no major aeroelastic concerns existing for either the single or counter-rotating rotor systems. The analyses performed, with respect to hover, fixed-wing flight, and potential for transition, did not account for the separation of the counter-rotating disk system. Because of the complex nature of the counter-rotating disc system, and the potential for an excessively overweight vehicle, one of the conclusions drawn from this analysis was that the single disc system would be better suited to this type of rotorcraft vehicle. In addition to this, the use of the gimbal and RPM control for the vehicle, whilst not actually studied under the Phase I contract, is considered to be a sufficiently unrealistic method of control. It was, therefore, concluded that the Gimbal and RPM control should be replace with a simpler circulation control system. The advantage of circulation control is the reduced system weight and complexity that would otherwise be associated with the traditional cyclic/collective or gimbal rpm systems. Reaction drive was also suggested for the rotor system in order to remove the need for torque control.

Under the Phase II effort a review of the basic rotorcraft design, and its applicability to a generic Air Force VTOL mission, needs to be performed.

A feasibility study, that compares the helicopter and tilt rotor aircraft with a stopped rotor concept, will be performed.

Based on the results obtained under the Phase I study, and the Phase II feasibility study, a simple rotorcraft vehicle design will be investigated. At this stage it is assumed that this vehicle will be similar to the NASA M-85 concept, that doesn't retract the blades, but does include circulation control.

The starting point for the analysis of the baseline concept would be to perform an assessment of the mechanical design for both the disk and blade components.

Once a satisfactory baseline mechanical design has been created a new fixed wing mission analysis will be performed in order to verify the vehicle sizing.

An assessment of the performance advantages, by adding additional technologies, will be made along with and evaluation of their benefits and costs.

In parallel an aeromechanics analysis will be conducted for the transition and stopping of the rotor.

The results of these efforts will be used to determine the final vehicle design configuration, in particular, the most viable technologies to be include to best meet the mission requirement.

Once this final vehicle design has been determined another pass through the above design analyses, where required, will be necessary in order to verify the systems integrity.

Finally a detailed set of engineering drawings will be created in preparation for wind tunnel model development.

As a follow on to the Phase II analysis work it is proposed that a scale model wind tunnel test program be performed in order to experimentally verify the aerodynamic performance and aeromechanical stability results for the fixed wing / hover / and transition flight conditions.

7.0 COMMERCIAL APPLICATION POTENTIAL

Many concepts have been tried in an effort to combine vertical and high speed horizontal flight. A successful design must have an efficient hover and low noise. This implies a low disk loading, large diameter propulsive system. For a new commercial aircraft to be competitive with fixed wing aircraft, it would have to match their cruise speeds on the typical 300 to 600 nm trips. For business class aircraft a 200 knot speed would be required, and for a commuter, 250 to 300 knots. For these speed and hover requirements, jet propulsion would not be very efficient, therefore, concepts which employed tilting wings, rotors, propellers, and ducted fans would be suitable for commercial VTOL aircraft. The helicopter is not a very efficient form of transportation compared to fixed wing aircraft, with the penalty for VTOL operation being a four fold increase in fuel consumption per seat compared to fixed wing aircraft, as well as a speed limit well below 200 knots. As a result of the low cruise speeds and high fuel consumption, the range capability of helicopters is also lower than fixed wing aircraft. Helicopters are more expensive to operate than fixed wing aircraft, due to their higher maintenance demands and fuel consumption. Data on direct operating costs per mile (fuel + maintenance labor and parts + overhaul reserve), published by Conklin & deDecker Associates, Inc., is listed below in Table 10.1.

Table 10.1: showing Aircraft Direct Operating Cost ($)per Mile.

Aircraft Size	Helicopter	Turboprop	Jets
Small (4-6 pax)	$2.31	$1.86	$1.72
Medium (6-8 pax)	$4.41	$1.86	$2.10
Large (8+ pax)	$5.76	$2.11	$2.76

As can be seen, medium and large helicopters cost more than twice as much per mile as a fixed wing aircraft to operate. In addition to the expense, helicopter cabins are much noisier than fixed wing aircraft due to the engine and transmission noise, as well as the aerodynamic beating from the rotor blades. The interior cabin noise level of various aircraft types is indicated in ref. [17].

Helicopter noise levels are about 10 dBA higher than commuter and short range transport. Adding insulation and noise suppression equipment can reduce internal noise levels, but at a cost in payload capacity. In spite of all these limitations in performance and operating expenses, commercial helicopter operations are expanding. Helicopters are used in missions where precise hovering and VTOL capability outweigh the expense and performance limitations. For those missions which involve mainly transporting people, a new vehicle, such as the proposed design, which combines the vertical flight capability of the helicopter with speed, comfort, and economy of fixed wing aircraft would extend that market to many more customers. In addition to the commercial aviation applications, there also exists the potential as a multi-mission military vehicle for use by all military services. Included in the amphibious assault and land warfare capabilities are applications such as; combat assault, assault support, special operations, medical evacuation, fleet logistics support and combat search and rescue.

8.0 CONCLUSIONS

The FLOPS analysis results indicate that the maximum speed for the study vehicle is M0.5, approximately 300knots. A maximum endurance cruise speed of approximately M0.325 was also calculated. The average mission endurance was determined to be approximately 4hrs, and the maximum range was determined to be approximately 650nm.

A separate analysis, using the Air Force DATCOM program, that studied the aerodynamic characteristics of the chosen NACA 66_1-012 disk wing profile indicated that, at 12,500ft altitude with 650hp available, the maximum speed is slightly less than 240 knots. At the same altitude, with only 450hp available, the maximum speed was slightly less than 175 knots. Clearly, since the FLOPS and DATCOM results do not agree, a refined FLOPS analysis, that includes the correct drag polars for the NACA 66_1-012 disk wing, is suggested in order to confirm the conclusions of the initial FLOPS analysis.

The ability for the rotor system to lift the 3500lb GTOW vehicle, with the available engine power, was demonstrated. The results of this analysis show that, with 650shp available, approximately 5000lbs of lift can be generated. The results also indicate that with 450shp available, approximately 4000lbs of lift can be generated. The 450shp condition allows remaining horsepower to be used for up&away forward flight

The preliminary aeroelastic analysis did not revealed any major aeromechanics problems for the current rotor blade design, however, it is important to emphasize that, while elastic interaction of the two discs is considered to be modeled adequately, the aerodynamics of the wake interaction was not included in the analysis. Due to the unacceptable 1F 2/rev frequency margin, it is, therefore, suggested that the blade design used may need to be modified in order to avoid any potentially damaging blade stimuli.

The conclusions drawn from the results of the Aeromechanics Multi-Body Non-Linear Dynamics Analysis indicate similar results to the preliminary aeromechanical analysis. The counter-rotating disc with two blades per disc, see Fig. 4.8.1, and single disc configuration with four blades, see Fig. 4.8.2 were modeled in a non-linear multibody dynamics code DYMORE. The analysis indicates that the single disc configuration is aeromechanically stable in hover. For the counter-rotating system the results of the analysis are inconclusive at the present time and further study is deemed to be appropriate. It has to be noted that, based on the traditional frequency Campbell diagram method (see fan diagram, Fig. 4.7.4), the close proximity of the first flapping mode to the 2 per rev frequency is the subject of some concern. For both configurations, transition and the fast forward flight prior to the transition should be thoroughly investigated before final decision about the viability of the concept from the aeromechanics standpoint is made. This and other modifications to the model are required to conduct a comprehensive aeromechanics assessment of the Vmax concept.

The gimbal and RPM control system, suggested for the Vmax conceptual vehicle, is not considered to be a viable control method when considering the precise vehicle control required during both the transition phase of flight and hover. Although not studied in detail, an attempt to demonstrate the ability of the system to transition at 150knots forward speed, and 2,000ft altitude, was made. The results indicated that there was marginally sufficient engine power to both maintain 3500 lb of rotor thrust whilst also maintaining 150knot forward speed. It was, therefore, concluded that transition would only just be possible with the installed engine power available. The postulated method for transitioning was to transfer power from the rotor to the propeller, whilst simultaneously changing AOA on the disc. The increased disk lift will need to compensate for the reduced rotor lift due to the decreasing rotor power. It is, therefore, felt that the sensitivity of gimbal and RPM control would be insufficient to perform this task since the pitch of the rotor blades will also need to be changed in order to maximize the rotor vertical thrust at a given engine power setting.

In summary the results of the Phase I study indicate that the Vmax design is potentially under powered and a higher horsepower engine may be required, particularly during the transition phase of flight. The design maximum and cruise speeds appear to be in doubt and further studies of the fixed wing flight are suggested. The generic nature of the analyses performed under the Phase I contract make them applicable to may permutations of the disc wing rotorcraft design. In particular the study of both single disc and counter-rotating discs were performed during the aeromechanical analysis with the resulting conclusion of no major aeroelastic concerns for either the single or counter-rotating rotor systems. The analyses performed, with respect to hover, fixed-wing flight, and potential for transition, did not account for the separation of the counter-rotating disk system. Because of the complex nature of the counter-rotating disc system, and the potential for an excessively overweight vehicle, one of the conclusions drawn from this analysis was that the single disc system would be better suited to this type of rotorcraft vehicle. In addition to this, the use of the gimbal and RPM control for the vehicle, whilst not actually studied under the Phase I contract, is considered to be a sufficiently unrealistic method of control. It was, therefore, concluded that the Gimbal and RPM control should be replace with a simpler circulation control system. The advantage of circulation control is the reduced system weight and complexity that would otherwise be associated with the traditional cyclic/collective or gimbal rpm systems. Reaction drive is also suggested for the rotor system in order to remove the need for torque control.

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