Paper Number 975548

A COMPARATIVE ASSESSMENT OF HIGH-SPEED ROTORCRAFT CONCEPTS (HSRC): Reaction Driven Stopped Rotor/Wing And Variable Diameter Tiltrotor

Jimmy C. Tai, Dimitri N. Mavris, and Daniel P. Schrage
Aerospace Systems Design Laboratory, School of Aerospace Engineering, Georgia Institute of Technology

ABSTRACT

The objective of this paper is to illustrate the methods and tools developed to size and synthesize a stopped rotor/wing vehicle using a reaction drive system, including how this design capability is incorporated into a sizing and synthesis tool, VASCOMP II. This new capability is used to design a vehicle capable of performing a V-22 escort mission, and a sized vehicle description with performance characteristics is presented. The resulting vehicle is then compared side-by-side to a variable diameter tiltrotor designed for the same mission. Results of this analysis indicate that the reaction-driven rotor concept holds promise relative to alternative concepts, but that the variable diameter tiltrotor has several inherent performance advantages. Additionally, the stopped rotor/wing needs considerably more development to reach maturity.

INTRODUCTION

In recent years, the desire to build a machine capable of achieving cruise speeds similar to that of a fixed-wing vehicle while simultaneously retaining the VTOL capability of the helicopter has been the driving force behind recent interest in rotor/wing research programs. Many unconventional concepts have recently received attention, including advanced tilt rotor with canards, tilt-wing, folding tiltrotor, coaxial propfan/folding tiltrotor, variable diameter tiltrotor (VDTR), and stopped rotor/wing. The stopped rotor/wing configuration is the least studied among this list of potential candidates due to a lack of appropriate analytical tools to assist in the design of the highly coupled wing-rotor-engine system as well as a general lack of understanding of the physics behind this unconventional concept. Therefore, there is a need for design methodologies and tools capable of handling the synthesis and sizing of such vehicles.

The Georgia Tech Aerospace Systems Design Laboratory (ASDL) has conducted a considerable amount of research over the past few years directed towards fulfilling the need for sizing and synthesis techniques to analyze stopped rotor/wing configurations. The primary goal of this research is to develop design tools capable of capturing the physics of the reaction drive system utilized by stopped rotors and to develop methods capable of concurrently analyzing the highly coupled wing-rotor-engine system. Under this ASDL research effort, a new design tool (TJCC)[1] has been developed which enables the designer to analyze tipjet-driven rotor systems. TJCC is used in conjunction with Response Surface Methods to give the V/STOL Aircraft Sizing and Performance Computer Program (VASCOMP II)[2] the capability of sizing stopped rotor/wing concepts. This paper describes the techniques and methods used to size and synthesize stopped rotor/wing vehicles using the modified version of VASCOMP II. Additionally, this design tool is used to conduct a side-by-side comparison of a reaction-driven rotor vehicle to a VDTR for a V-22 escort mission.

Obviously, the potential success of a reaction-driven configuration can only be determined through direct performance comparisons with other high speed rotorcraft concepts using analytical methods of comparable sophistication. The development of TJCC and a modified version VASCOMP II has the effect of "leveling the playing field" by giving designers the means to predict the performance of a stopped rotor/wing vehicle at a level of fidelity comparable to those developed for the VDTR, and thus, assess its competitiveness as a high speed rotorcraft concept.

BACKGROUND

The U.S. Navy, in conjunction with Bell and Boeing Helicopter, are developing the V-22 "Osprey" to perform an "over-the-beach" assault mission primarily for the Marine Corps. Presently, the Marine Corps is planning on utilizing the AV-8B "Harrier" as the escort for the V-22 since it is the only Vertical Take-Off and Landing (VTOL) aircraft capable of matching the V-22's cruise speed. Unfortunately, since AV-8Bs are expensive and their number is limited, escort duty is

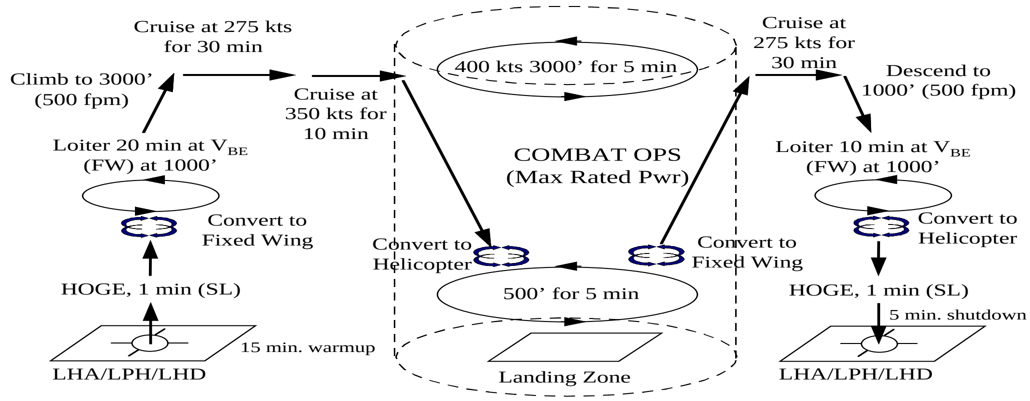


Figure 1 : V-22 Escort Mission

not considered to be effective use of an AV-8B, especially since it was designed for battle field interdiction, close air support, night attack, and reconnaissance missions. Therefore, there is a need for a dedicated escort vehicle capable of meeting the escort mission requirements.

As shown in the V-22 escort mission profile depicted in Figure 1, the V-22 escort aircraft is expected to serve in the air-to-air combat mode while escorting the V-22s to shore and back to ship-board base. Additionally, the escort is required to engage in air-to-ground warfare in the vicinity of the landing zone where the V-22 is off-loading troops and/or cargo. The basic mission requirements and constraints dictate that the vehicle must[3]:

- Be capable of operating from the same class of Navy ships as the V-22 (LHA, LPH, and LHD). I.e. - must be able to fit into the ship elevators and hanger decks.
- Have a two-man crew.
- Have a maximum hover-out-of-ground-effect (HOGE) disc loading of 20 lbs/ft^2 at maximum takeoff gross weight (TOGW) to minimize erosion and blowing dust from unprepared surfaces during VTOL operations .
- Have a vertical rate of climb (VROC) of at least 1,000 feet per minute at TOGW, standard sea level, maximum rated engine power (MRP).
- Have a dash speed of at least 400 knots at an altitude of 3,000 feet, MRP.
- Be able to sustain a 5.0 g turn at TOGW, flying at 250 knots at an altitude of 3,000 ft.
- Have a weapons load consisting of: internal or turreted 20 millimeter cannon+1500 rounds of ammunition, 4 AIM-9L air-to-air missiles, and 4 AGM-114 air-to-ground missiles.

There are only a few VTOL concepts capable of meeting this set of requirements. The disc loading requirement precludes the use of Harrier-type vehicles, and helicopters are eliminated due to the cruise speed requirements. The two most promising VTOL candidates that can fulfill this mission are the Variable Diameter Tiltrotor (VDTR) and the Stopped Rotor/Wing (SRW). These concepts were selected for comparison in this study based on their potential to meet the dash requirement as well as the military nature of the mission.

CONCEPT DESCRIPTIONS

As mentioned earlier, one of the objectives of this paper is to compare the performance of stopped rotor/wing configurations to that of VDTR concepts. To this end, conceptual designs for a VDTR and stopped rotor/wing short-haul civil transport are described in order to give the reader a feel for the basic ideas underlying each concept.

STOPPED ROTOR/WING

The ASDL version of the stopped rotor/wing concept (GTM-85, see Figure 2) is a derivative of NASA Ames Research Center's M-85[4]. design. As mentioned before, the rotor drive system for the GTM-85 is pneumatically provided by one turbofan engine, and most of the lift is generated by the dual purpose rotor/wing system. Since the rotor is pneumatically driven, the engine exhaust is diverted during rotor-borne flight to drive the rotor and Circulation Control (CC) device. The center lifting disc is present mainly for transition between rotor- and wing-borne flight.

During the fixed wing mode with the tipjet turned off, the GTM-85 operates very much like an airplane powered by a turbofan engine. The only difference is that the wing (blade) performance is augmented by Circulation Control devices in order to increase lift. During the helicopter mode, the GTM-85 operates as a tipjet- powered helicopter. Forward flight in this mode is accomplished by diverting excess engine mass flow to the aircraft aft nozzle. Conversion from helicopter mode to fixed wing mode is accomplished by performing a pitch-up maneuver which unloads the rotor blades so they can be stopped. During this maneuver, the center lifting disc is providing the necessary lift to support the aircraft. The conversion from fixed wing mode to helicopter mode is accomplished by reactivating the tipjets after the aircraft has slowed down to a speed at which rotating the rotor does not cause instability. The different flight regimes discussed above are pictorially represented in Figure 3.

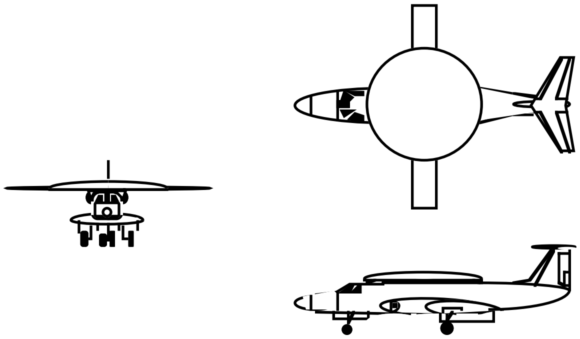


Figure 2: Stopped Rotor/Wing Concept (GTM-85)

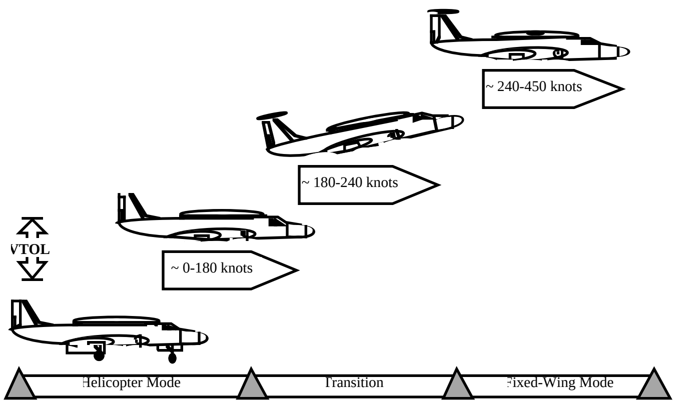


Figure 3: GTM-85 Flight Regimes

The enabling technology which makes stopped rotor/wings technically challenging is the reaction drive system. With this drive system, the rotor essentially becomes a direct power turbine which converts the energy of the propulsive gas from the engine directly into rotary power by using light weight ducting to channel gas up through the rotor mast, into the blades, and out the tip jets. The advantage of a reaction drive rotor is the elimination of the complexity and weight of gearbox(es), shafting, and tail rotor. However, the disadvantage of such a concept is the lower efficiency[5] of the tip jets relative to that of a power turbine and gearbox arrangement.

Figure 4 pictorially shows how torque is generated for a tipjet driven rotor. The mass flow ($\dot{m}_j$) ejected through the tipjets creates the necessary force (F_j) acting on the rotor tip to create the resulting torque. This torque-generating force is calculated by $F_j = \dot{m}_j \times (V_j - V_T)$, where V_j is the velocity at which the mass flow is being ejected and V_T is the rotor tip speed. The determination of $\dot{m}_j$ and V_j can only be accomplished by performing a detailed engine cycle analysis. Therefore, the tight coupling of the engine and rotor stems from the fact that the rotor performance depends on calculations of these engine parameters. As a result, both the rotor and engine must be sized concurrently.

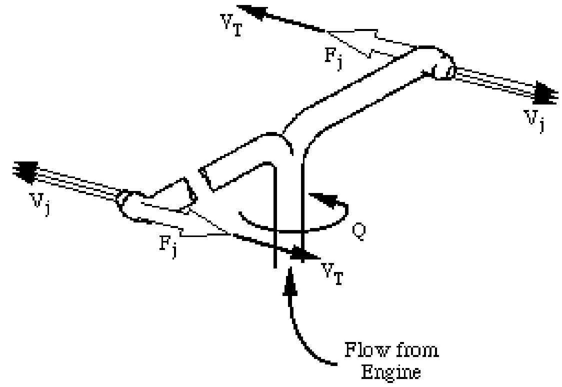


Figure 4: Radial Outflow Turbine[5]

Another enabling technology that is incorporated into the GTM-85 stopped rotor/wing is Circulation Control. The purpose of employing CC technology is to improve the aerodynamic performance of the blade airfoil, which is very poor due to the increased airfoil thickness (to accommodate the internal duct) and because the airfoil section is elliptical. The use of an elliptical airfoil eliminates the problem of having one trailing edge facing the freestream during stopped-rotor mode. In addition, the rounded trailing edge offers an ideal surface to take advantage of the Coanda effect[6].

VARIABLE DIAMETER TILTROTOR

The VDTR is very similar to the V-22 Osprey in operation since both are in the tiltrotor family. The most noticeable difference is the ability of the VDTR to extend/retract its rotor diameter, thus improving its performance in hover and cruise, respectively. The VDTR is Sikorsky Aircraft's answer to fulfilling VTOL missions which require high speed and long range. The ability to vary rotor diameter reduces the design compromises that fixed diameter tiltrotors must incur due to the vast difference in requirements for hover lift and cruise thrust. The hover condition requires the rotor diameter to be large in order to support the entire weight of the aircraft as well as the vertical drag resulting from the rotor download (low specific thrust). This hover requirement conflicts with that of high speed cruise which demands a propulsion system with a relatively high specific thrust. Under these conflicting requirements, a compromise design using a conventional tiltrotor results in an aircraft with an excessively high hover disk loading. Sikorsky Aircraft believes that the VDTR currently under development has the potential to reduce the disk loading to desirable values (less than 20 lbs/ft^2), match the rotor to both hover and cruise requirements, provide better Category A performance, offer greater operational flexibility, and provide better growth capability[7].

In order for the reader to better visualize the concept of a variable diameter tiltrotor and its blade retraction mechanism, Figure 5 shows a three view picture of a VDTR, while Figure 6 depicts a close up of one of its retractable blades.

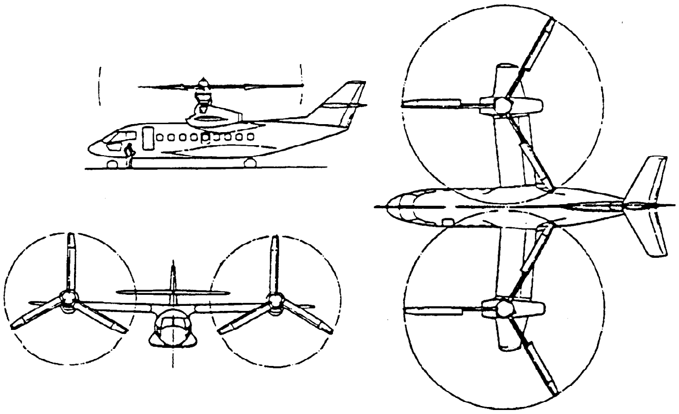
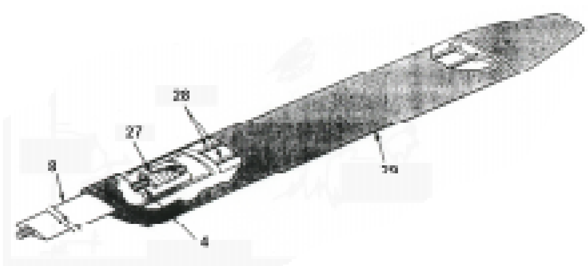


Figure 5: Variable Diameter Tiltrotor[7]



4 - Jackscrew
8 - Torque Tube
27 - Nut
28 - Straps
29 - Outboard Blade

Figure 6: VDTR Blade Retraction Mechanism[7]

DESIGN APPROACH

The SRW research effort conducted at ASDL has produced a step-by-step methodology, which will produce a design tool capable of sizing and synthesizing reaction driven SRW configurations. A flowchart showing each step of this methodology is depicted in Figure 7. The flowchart is separated into three major execution stages. The first stage is the selection of suitable physics-based analyses tools to capture the rotor and engine interaction. This is accomplished in Steps 1 through 7 of the flowchart. The second stage is the integration of the coupled engine/rotor system with the vehicle sizing and synthesis code, VASCOMP II. This stage is depicted in Steps 8 through 10. The final stage is the actual sizing, synthesis, optimization, and performance calculations which are labeled Steps 11 through 13. The interested reader is referred to Reference 8 for a detailed explanation of the sizing methodology.

VASCOMP II is the sizing and synthesis tool chosen to model the two candidate vehicles for the described mission. VASCOMP II was developed by Boeing Vertol for NASA Ames who now maintains and enhances the public domain version of this code. VASCOMP II was developed specifically to handle Vertical and Short Take-off and Landing (V/STOL) aircraft, and the equations within this sizing/synthesis program predict the behavior of turboshaft driven V/STOL concepts (such as those in the tiltrotor family) quite well. Furthermore, VASCOMP II has been modified several times to incorporate analysis capability for new technologies (such as the convertible engine) as well as more sophisticated analysis methods (such as blade element technique to calculate rotor/propeller aerodynamics). However, it does not have the capability of analyzing V/STOL concepts which utilize reaction drive systems to generate the torque necessary to drive the rotor system.

Since the equations within VASCOMP II capture the behavior of the tiltrotor fairly well, only the final results of the VDTR sizing and synthesis are presented whereas the sizing/synthesis of the SRW is presented in detail. Discussions on the design approach and on the issues related to VASCOMP II integration apply only to the stopped rotor/wing.

Thus far, the execution of the methodology shown in Figure 7 has proceeded to the VASCOMP II integration stage. The coupling of the engine and rotor has been accomplished in TJCC[1], and integration of this coupled subsystem into the system sizing and synthesis is accomplished through the use of Response Surface Methods[9]. TJCC is a newly developed code which resulted from the completion of stage one of the overall methodology. This program consists of ENGGEN[10], an engine cycle analysis code, CRUISE4 and CRUISE5[11], which are the aerodynamic/thermodynamic programs used to analyze the rotor/wing during the helicopter and fixed wing modes of operation, respectively. Even though these programs were functional, the logic behind them was muddled. Therefore, considerable efforts had to be spent to understand their logic and integrate them together. Furthermore, additional analysis functions had to be added in order to adopt them to handle stopped rotor/wing configurations, such as a subroutine to assess the losses as the airflow is being extracted from the turbofan engine mixer and ducted up to the rotor hub, a feature to perform the mass flow matching iteration, and the ability to throttle the engine during the forward flight conditions. These analysis modules linked together forming TJCC is the only public domain code available which can analyze reaction driven rotor in conjunction with the use of Circulation Control coupled to the propulsion system.

The authors elected to avoid directly linking TJCC with VASCOMP II because direct integration would be both time consuming and tedious. Furthermore, integration of large iterative codes (such as these two programs) may cause serious convergence problems and these errors are usually difficult to identify. The advantage of the RSM approach is that it allows the essence of the SRW's coupled rotor/engine subsystem to

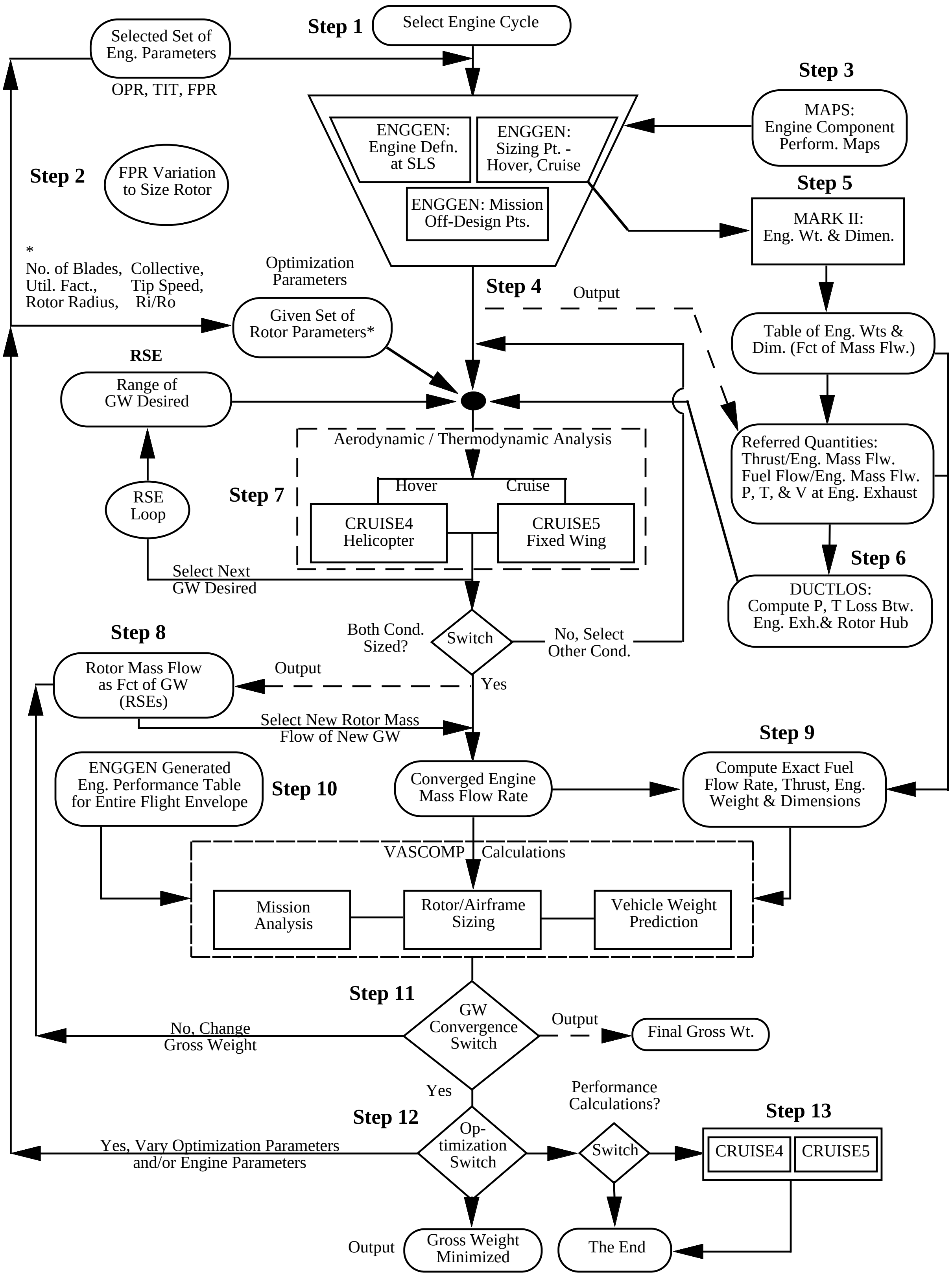


Figure 7 : Reaction Driven Stopped Rotor/Wing Overall Design Methodology

be integrated into VASCOMP via Response Surface Equations (RSEs) without the need for extensive code modification. These RSEs are polynomial expressions of the desired responses as a function of the most significant design variables. Therefore, the problem of non-convergence is avoided. However, the caveat of using RSEs is that they are valid only within the ranges for which they are generated.

The VASCOMP II integration effort will be accomplished in phases. The first phase, which is part of the focus of this paper, consists of using TJCC to generate the RSEs which represent the aerodynamic characteristics of the lifting system (center lifting disc plus the Circulation Control blades/wings). In reality, the SRW has two unique forward flight modes because its transition procedure requires it to accelerate in helicopter mode to a speed at which the center lifting disc is able to generate enough lift to support the vehicle weight. Therefore, two sets of RSEs are required, one to approximate the aerodynamics during the helicopter forward flight mode and the other to approximate the aerodynamics of the fixed wing mode. Examining the aerodynamics routine within VASCOMP II revealed that RSEs for the profile drag (CDO) and induced drag (CDI) are needed for the fixed wing mode. For the helicopter mode, total power (CP), rotor/wing profile and induced power (CP IND+PROF), and rotor/wing drag (CH) relations are needed.

RSE GENERATION SET-UP

The first step in RSE generation is the identification of the most relevant design variables. Examination of TJCC's input file revealed that the relevant variables are those that pertained to the engine, rotor geometry, and flight operating condition. These variables are identified in Table 2 along with their definition and the mode (FW - Fixed Wing or RW - Rotor Wing) to which they are relevant. In addition, to identify the list of design variables, the ranges for each must also be defined. Based on experience working with stopped rotor/wing concepts, these ranges are established in Table 2. In examining this variable list, one would expect GW, RIRO, and RAD to have a large impact on the desired response. Therefore, the ranges selected for these variables deserve more scrutiny.

Since the radius and the ratio of the lifting disc to rotor radius most likely will dictate how much lift can be produced, these variable settings are sensitive to the desired gross weight. Therefore, examining the extremes of the design space created with just these three variables reveals some infeasible designs for the SRW. For example, if the desired gross weight is at its upper bound of 28,000 lbs and if the rotor radius and the radius ratio are set at their lower bound of 30 and 0.24, respectively, TJCC cannot converge on a solution when it performs the thrust/lift loop calculations. This is due to the fact that the combination of the rotor/wing system variables cannot produce enough lift to support the desired gross weight of 28,000 lbs. Therefore, the design space must be divided into domains in which the combinations of GW, RIRO, and RAD design variables are feasible for the stopped rotor/wing. These domains are defined in Table 3.

Table 1: Relevant TJCC Design Variables

Design Variables	Definition	Modes
GW	Gross Weight (lbs)	FW, RW
RIRO	Ratio of Lifting Disc to Rotor Radius	FW, RW
RAD	Rotor Radius (ft)	FW, RW
BPR	Bypass Ratio	FW, RW
FPR	Fan Pressure Ratio	FW, RW
OPR	Overall Pressure Ratio	FW, RW
TIT	Turbine Inlet Temperature (°R)	FW, RW
JPOS	Throttle Setting	FW
VTIP	Tip Speed (ft/sec)	RW
AREARAT	Blade Utilization Factor	FW, RW
FUSAREA	Aircraft Flat Plate Drag Area (ft^2)	FW, RW
ALT	Altitude (ft)	FW, RW
COVR	Ratio of Chord to Radius	FW, RW
TOVC	Airfoil Thickness	FW, RW

Table 2: Relevant Design Variable Ranges

Design Variables	Min	Most Likely	Max
GW	12,000	20,000	28,000
RIRO	0.24	0.29	0.34
RAD	30	37.5	45
BPR	2.6	3.1	3.6
FPR	2.0	2.2	2.4
OPR	20.5	21.5	22.5
TIT	2800	2925	3050
JPOS	4	8	12
VTIP	600	650	700
AREARAT	0.40	0.50	0.60
FUSAREA	5	7.5	10
ALT	vary	vary	vary
COVR	0.10	0.15	0.20
TOVC	0.175	0.180	0.185

Table 3: Design Space Definition

Design Variables	Domain 1	Domain 2	Domain 3
GW	12,000 to 18,000	17,000 to 23,000	22,000 to 28,000
RIRO	0.24 to 0.28	0.27 to 0.31	0.30 to 0.34
RAD	30 to 36	35 to 41	40 to 45

Another issue that must be addressed before the RSEs are generated is the operational flight envelope. This will also dictate the number of RSEs to be generated since each response is required at different flight speeds for the two modes of operation. Figure 8 shows the flight envelope of the SRW for both helicopter and fixed wing mode. Notice that these operational modes overlap each other to form the transition regime. As shown in Figure 8, the altitude range is a function of flight speed. Therefore, this operating altitude range dependence is propagated to the RSE generation.

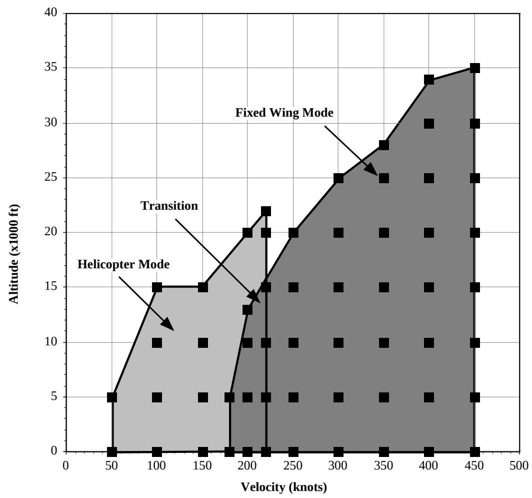


Figure 8: SRW Flight Envelope

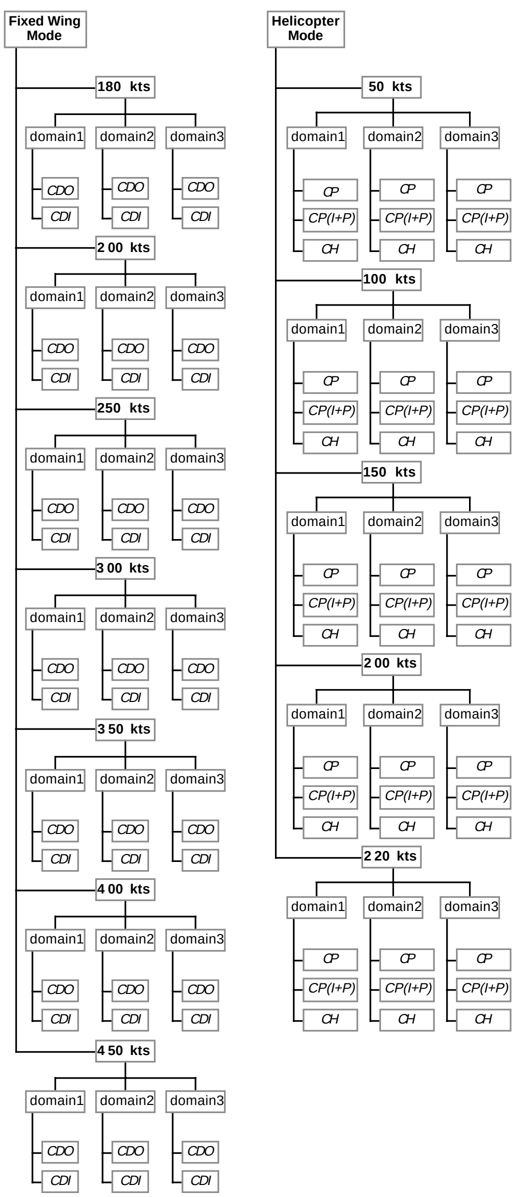


Figure 9: RSE Generation Tree

Based on the design space definition (Table 3) and the flight envelope (Figure 8), there are two classes of RSEs to be generated, one for the fixed wing mode, and one for the helicopter mode. Within each class, the RSEs (for each desired response) are generated at each flight speed. Furthermore, these RSEs are generated for each domain within each flight speed. Figure 9 shows the number of the RSEs generated and how they are organized.

With the desired family of Response Surface Equations established, the next step is to determine which variables among the ones listed in Table 1 have the most influence on the desired response. This screening process is executed using a statistical package called JMP[12]. This program visually shows how much each design variable impacts the desired response by the use of Pareto Plots. Figure 10 and Figure 11 show the Pareto Plots for the helicopter and fixed wing modes, respectively. Based on these plots, the variables selected to generate the RSEs are presented in Table 4. The ranges for these variables are the same as those presented in Table 2, and the values for those that are not selected are fixed at their "most likely" settings.

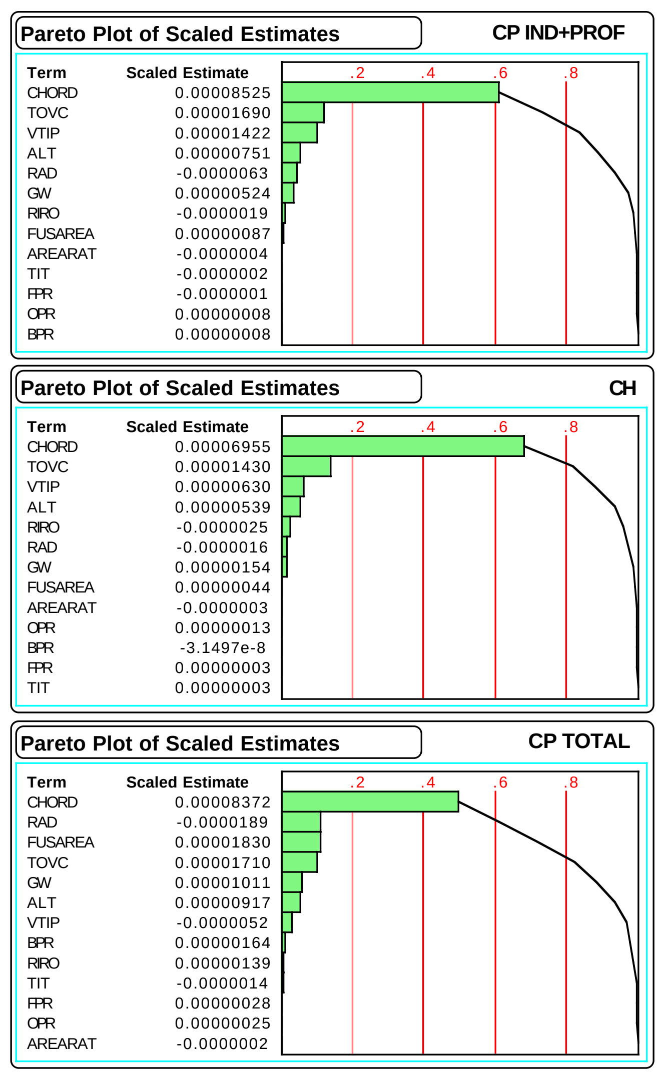


Figure 10: Screening for Helicopter Mode

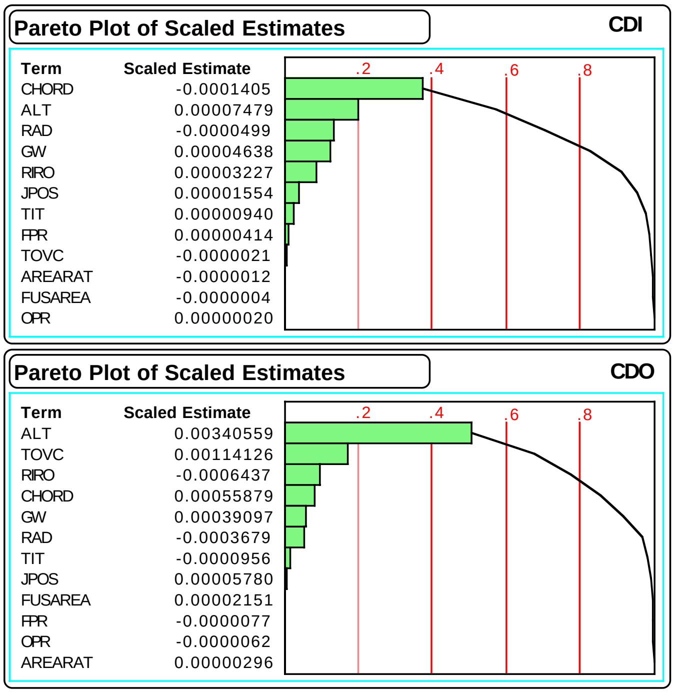


Figure 11 : Screening for Fixed Wing Mode

Table 4 : Selected Variables for RSE Generation

Design Variables	Definition	Modes
GW	Gross Weight (lbs)	FW, RW
RIRO	Ratio of Lifting Disc to Rotor Radius	FW
RAD	Rotor Radius (ft)	FW, RW
ALT	Altitude (ft)	FW, RW
COVR	Ratio of Chord to Radius	FW, RW
TOVC	Airfoil Thickness	FW, RW
VTIP	Tip Speed	RW
FUSAREA	Flat Plate Drag Area	RW

RSE GENERATION

With the design variables identified, a Face-Centered Central Composite DOE is set up to determine the number of cases and combination of variable levels which yields the best possible response surface fit. As each DOE case is executed, the response values from TJCC are recorded. The recorded responses (i.e. raw data) are used in a least squares analysis to generate the coefficients of the Response Surface Equations in the form of Equation 1. The experiment set-up and statistical analyses are performed using JMP.

$$RSE = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j \quad (1)$$

where b_i are the regression coefficients for linear terms; b_{ii} are the coefficients for pure quadratic terms; b_{ij} are the coefficients for cross product terms; and x_i and x_j are design variables

One of the most valuable tools within JMP is the prediction profiler which allows the designer to graphically visualize how each design variables affect each of the responses. A representative prediction profile for the fixed wing mode (V = 350 knots, Domain 1) is shown in Figure 12, and a similar profile is shown for the helicopter mode (V = 200 knots, Domain 1) in Figure 13. The advantage of this tool is that it provides a visual means of verifying that the behavior of the response relative to the design variables makes sense. The trends exhibited in these figures show that TJCC is predicting the correct behavior of the desired responses (as a function of the design variables).

In order to evaluate how well these RSEs fit the raw data, a statistical value called R^2 is used. For a perfect fit where there is no statistical error, the R^2 value would be one. However, for this model, a value above 0.90 indicates that most of the main and quadratic effects along with second-order interactions are captured. Along with the prediction profiles, Figure 12 and Figure 13 also show that each of the desired responses fit very well since all of the R^2 values are above 0.90.

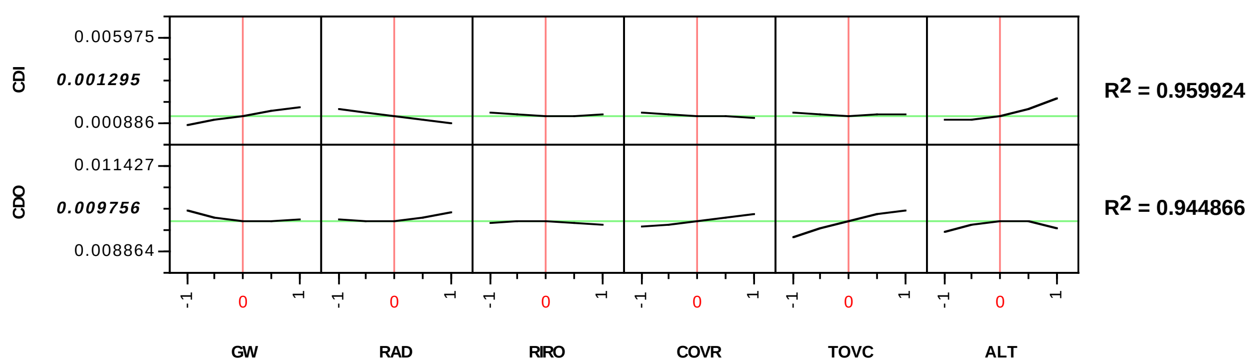


Figure 12 : Prediction Profile for Fixed Wing Mode (V = 350 kts, Domain 1)

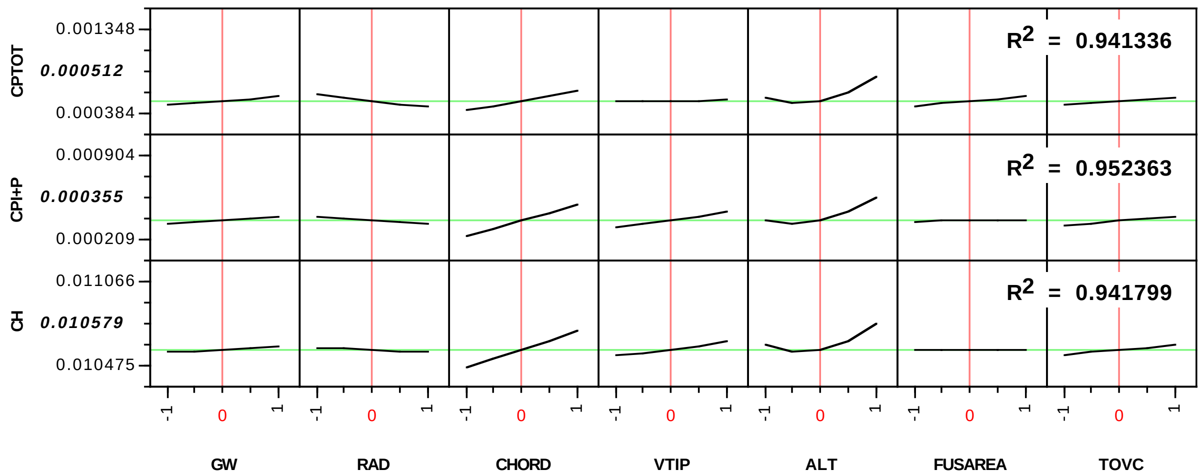


Figure 13 : Prediction Profile for Helicopter Mode (V = 200 kts, Domain 1)

VASCOMP II INTEGRATION

Major modifications were performed in order to extend VASCOMP II's capabilities to size and synthesize stopped rotor/wing vehicles. These modifications are briefly described along with some modeling issues specific to SRW.

AERODYNAMICS

One of the major modifications performed is the inclusion of subroutines to evaluate the Response Surface Equations that are generated to represent the coupled rotor/engine subsystem. Prior to this modification, the user was required to supply representative profile drag information which the program used to estimate aircraft drag. This option is still available for other concepts, but the drag of the SRW is captured within the RSEs as a function of rotor geometry, gross weight, and flight condition. Extensive coding was required to make sure that the correct drag (both induced and profile) value was evaluated from the RSEs. Extra caution is also taken to make sure that the design does not violate the design space prescribed for stopped rotor/wing configurations. Also, logic was installed to interpolate between the discrete flight velocities for which the RSEs are generated.

GEOMETRY

Modifications were made to VASCOMP II to accommodate the rotor/wing dual lifting system. Specifically, the inclusion of the center lifting disc required the code to re-compute values such as wing area and aspect ratio for the SRW.

CONVERSION

The conversion routine was extensively modified to accommodate the conversion procedure for the SRW. The conversion for the SRW is accomplished using the center lifting disc, and therefore, a force balance is required between the gross weight and the lift provided by the lifting disc. The new conversion routine converges on a flight speed and angle of attack at which this balance can be achieved for the gross weight at which the vehicle enters the conversion maneuver.

PROPULSION MODELING

Presently, the propulsion information is entered through the existing input deck. However, future modifications are underway to extend VASCOMP II's capability to generate the turbojet/turbofan engine information by incorporating an engine simulation code that performs a one-dimensional steady state thermodynamic analysis of the engine cycle. This cycle program, called ENGGEN[13], is the tool which generated the propulsion information required by VASCOMP II for this study.

An empirical approximation is made in the propulsion routine in order to simulate the SRW's requirement to provide mass flow from the engine to drive the rotor system and for the Circulation Control device. This is necessary because the engine should be penalized for these requirements during the mission analysis in order to obtain an accurate model of the vehicle.

HOVER PERFORMANCE MODELING

Since the SRW is a tipjet powered helicopter during hover, its performance is vastly different from that of a conventional helicopter. The hover analysis in VASCOMP II relies mainly on the user's input of figure of merit (FM) as a function of tip speed. This information is supplied by TJCC for a representative SRW configuration. This is also an approximation because the FM is only valid for one configuration. Future modification to VASCOMP II will include RSEs for the figure of merit that is valid for a family of configurations.

WEIGHTS MODELING

The weights breakdown for VASCOMP II is extensive and requires the user to input many weight factors and scaling laws. Fortunately, many of these weight groups such as gearboxes, tail rotor, shaft, transmission, and rotor tilt mechanism are not applicable for the SWR vehicle and are set to zero in the model input. Additionally, the rotor/wing weight is bookkept as wing weight in the VASCOMP model, and therefore the rotor weight is zero as well. The engine weight scaling laws were developed based on weight trends for several turbofan engines of similar size and cycle, and the structural weight scaling laws are based on NASA Ames M85 studies.

RESULTS

After performing the modifications to the design algorithm as well as the required discipline modeling, VASCOMP II is able to size/synthesize a stopped rotor/wing vehicle. The objective of this study, which is to compare the VDTR with the SRW for a V-22 escort mission, can now be performed using this modified version of the program. The analysis for the variable diameter tiltrotor was performed as part of the Georgia Tech's graduate entry to the 1997 AHS/Industry/NASA Student Design Competition.[14]

The results of the VASCOMP II analyses of these two high speed rotorcraft concepts are summarized in Table 5 in terms of weights, size, critical performance parameters, and cost. In most categories, the VDTR appears to be the better candidate to fulfill the role of an V-22 escort. Although the SRW is capable of achieving the high cruise speeds required, it is at the expense of high drag at cruise which results in an excessively large engine. This trend is evident in the horsepower required curve shown in Figure 14. The data for helicopter forward flight mode is generated for 500 ft standard day conditions, while the data for fixed wing mode is generated for cruise speed at 3,000 ft standard day. This figure shows that the horsepower required for the SRW to achieve the desired 400 knot cruise speed is much more demanding than that of the VDTR. This is caused by the poor aerodynamic performance of the airfoil which is, in turn, a result of the requirements of the reaction drive system. The cruise aerodynamic characteristics also affect the total fuel burn, and thus, the range performance of the SRW as compared to the VDTR. Figure 15 shows the design point range-payload sensitivity for both concepts.

The fact that the wing also acts as the rotor gives the SRW an advantage in terms of disk loading. Note that the SRW disk loading is calculated using only the area swept by the blades, not the entire disk. In other words, the area of the lifting disk does not contribute to the disk loading calculation.

Table 5: Sized Vehicle Comparison

	VDTR	SRW
Weights		
TOGW (lbs)	19,535	27,731
Empty (lbs)	13,790	18,333
Fuel (lbs)	3,045	6,199
Dimensions		
Length (ft)	49.00	49.0
Height (ft)	14.67	13.50
Wing Span (ft)	30.92	70.0
Rotor Diameter, extended (ft)	26.25	N/A
Rotor Diameter, retracted (ft)	15.67	N/A
Performance		
Cruise Speed (kts)	275	275
Dash Speed (kts)	415	400
Stall Speed (kts)	105	146
Max VROC (fpm)	3,300	3,300
Tip Speed (fps)	735	700
Figure of Merit	0.82	0.56
Payload		
AIM-9L Sidewinder Missiles	4	4
AGM-114 Hellfire Missiles	4	4
20 mm Cannon	1	1
Ammunitions (rounds)	15,000	15,000
Crew	2	2
Acquisition Cost (1997 $M)	24	29

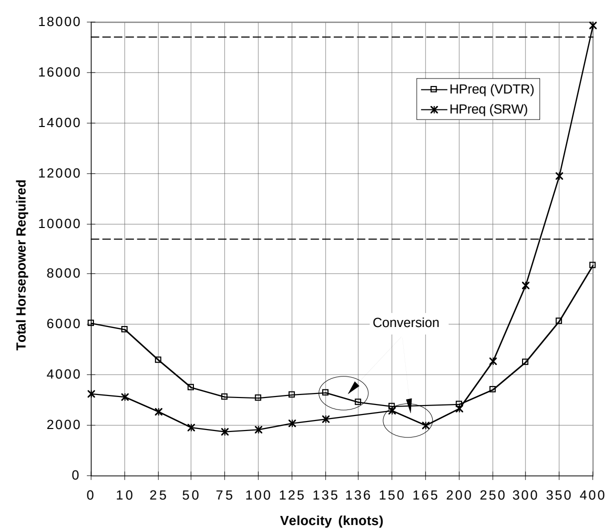


Figure 14 : Horsepower Required Comparison

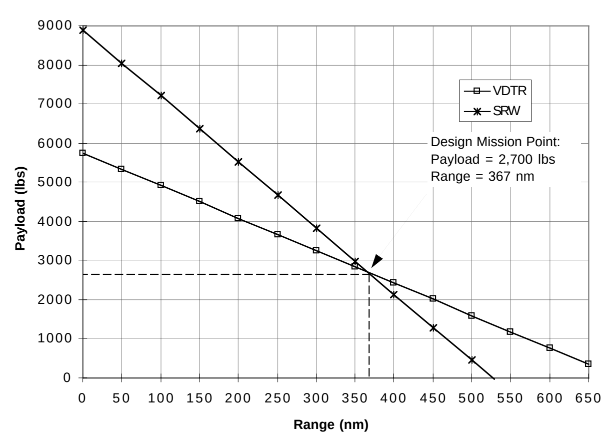


Figure 15 : Payload vs. Range Sensitivity

CONCLUSIONS

The sizing and synthesis methodology required to size vehicles that utilize reaction drive systems has been developed at Georgia Tech, and this paper demonstrates the implementation of this methodology to the design of a V-22 escort vehicle. A framework now exists in a sizing and synthesis program which is able to capture the physics behind the reaction drive propulsion system. Without this capability, the comparison shown in this paper would not be possible. However, the modification effort to include this analysis capability in VASCOMP II is an on-going research effort at Georgia Tech, and it is envisioned that future versions of this program will fully simulate the physics behind this unique concept.

The authors have shown for the first time a comparative assessment of a stopped rotor/wing against another high speed rotorcraft concept using the same analysis tool. *The results clearly show that the variable diameter tiltrotor has several performance advantages over the SRW for the V-22 escort concept*. Both the VDTR and the SRW are risky alternatives for the rotorcraft industry to attempt. Even though the VDTR concept is a more mature technology because it belongs to the tiltrotor family, significant challenges remain in the construction of a reliable, maintainable, and producible retracting mechanism for the rotor blades. The same issues also apply to the SRW except for the implementation of the reaction drive in conjunction with Circulation Control. The latter technology shows promise with respect to performance attributes, but it remains impractical due to the challenges in constructing a modulation system to regulate the airflow from the engine to the rotor. The reliability, complexity, maintainability, and producibility of such a flow regulator are major issues which must be overcome in order to make the stopped rotor/wing an attractive concept. Furthermore, all enabling technologies have development cost associated with them and the VDTR is presently more mature that SRW technologies, the implication being that the former would have less development cost required to bring it to maturity.

ACKNOWLEDGMENTS

The authors would like to extend special thanks to Dr. Ivan Burdun, Dr. Fidencio Tapia, Dr. Mark Hale, Mr. Bryce Roth, Ms. Elena Garcia, and Mr. Noel Macsotai for their contributions to this study.

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