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An Assessment of a Reaction Driven Stopped Rotor/Wing Using Circulation Control in Forward Flight

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ABSTRACT

The desire of achieving faster cruise speed for rotorcraft vehicles has been around since the inception of the helicopter. Many unconventional concepts have been considered and researched such as the advanced tilt rotor with canards, the tilt-wing, the folding tiltrotor, the coaxial propfan/folding tiltrotor, the variable diameter tiltrotor, and the stopped rotor/wing concept, in order to fulfill this goal. The most notable program which addressed the technology challenges of accomplishing a high speed civil transport mission is the High Speed Rotorcraft Concept (HSRC) program. Among the long list of potential configurations to fulfill the HSRC intended mission, the stopped rotor/wing is the least investigated due to the fact that the existing rotorcraft synthesis codes cannot handle this type of vehicle. In order to develop such a tool, a designer must understand the physics behind this unique concept. The uniqueness of stopped rotor/wing vehicles that use reaction drive can be found in the tight coupling that is present between the rotor and the engine which in turn requires these subsystems to be sized concurrently rather than in isolation. A methodology and simulation tool capable of handling this coupling is under development at the Aerospace Systems Design Laboratory (ASDL) at Georgia Institute of Technology. The development of a new design tool (TJCC) and the use of a statistical technique called Response Surface Methodology linked into the V/STOL Aircraft Sizing and Performance Computer Program (VASCOMP II) has provided the capability of sizing stopped rotor/wings. The potential success of a stopped rotor/wing configuration can only be determined through direct performance comparisons with other high speed rotorcraft concepts using analytical methods of comparable sophistication. The authors have previously presented limited results from this study detailing the rotor/wing performance during hover. In this paper the forward flight regime for both the helicopter and fixed wing modes are discussed. Representative results presented include performance characteristics such as the horsepower required curves versus forward flight for both the rotorcraft and fixed wing modes of operation. Furthermore, the mass flow requirements, and transition performance associated with this aircraft are also examined in this paper.

INTRODUCTION

In order to realize the ability of taking off and landing vertically at vertiports located within major city limits while maintaining a high speed cruise capability, an aircraft is needed which marries together the low speed attributes of a helicopter and the high speed behavior of a fixed wing aircraft. NASA and U.S. helicopter industry have investigated a series of candidate rotorcraft configurations in the High Speed Rotorcraft Concept (HSRC) program. The findings of this investigation are documented in References 1, 2, 3, and 4. According to the requirements imposed on such a vehicle, the potential candidate aircraft must be able to cruise at high speeds (300 - 450 knots) and possess vertical take-off and landing (VTOL) capabilities. Furthermore, the HSRC must be reliable and affordable and possess the hover efficiency, low downwash characteristics, and low speed agility of a helicopter, as well as the high speed cruise, maneuverability, and handling qualities of a fixed wing aircraft. This NASA funded study produced several potential candidates concepts such as an advanced tiltrotor with canards, a tilt wing, a folding tiltrotor, a coaxial propfan/folding tiltrotor, a variable diameter tiltrotor, and a stopped rotor/wing configuration. Of these seven concepts, six of them can be readily modeled and analyzed by sizing/synthesis programs such as VASCOMP II[5] and HESCOMP[6]. The stopped rotor/wing has been somewhat overlooked since the appropriate analytical tools needed to assist in its design do not exist. For the past several years, the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech, in collaboration with the System Analysis Branch of NASA Ames Research Center, has been pursuing the development of a design methodology which will enable the designers to synthesize, size, and routinely predict the performance of stopped rotor/wing aircraft. Even though HSRC program was canceled in 1992, ASDL has continued to develop and implement this methodology in an effort to understand the physics of this complicated problem and advance the state-of-the-art. The step-by-step discussion of this overall methodology (see Figure 1) can be found in Reference 7. However, in this paper, the focus will be on the forward flight regime for both the helicopter and fixed-wing modes of operation as well as the transition between these modes.

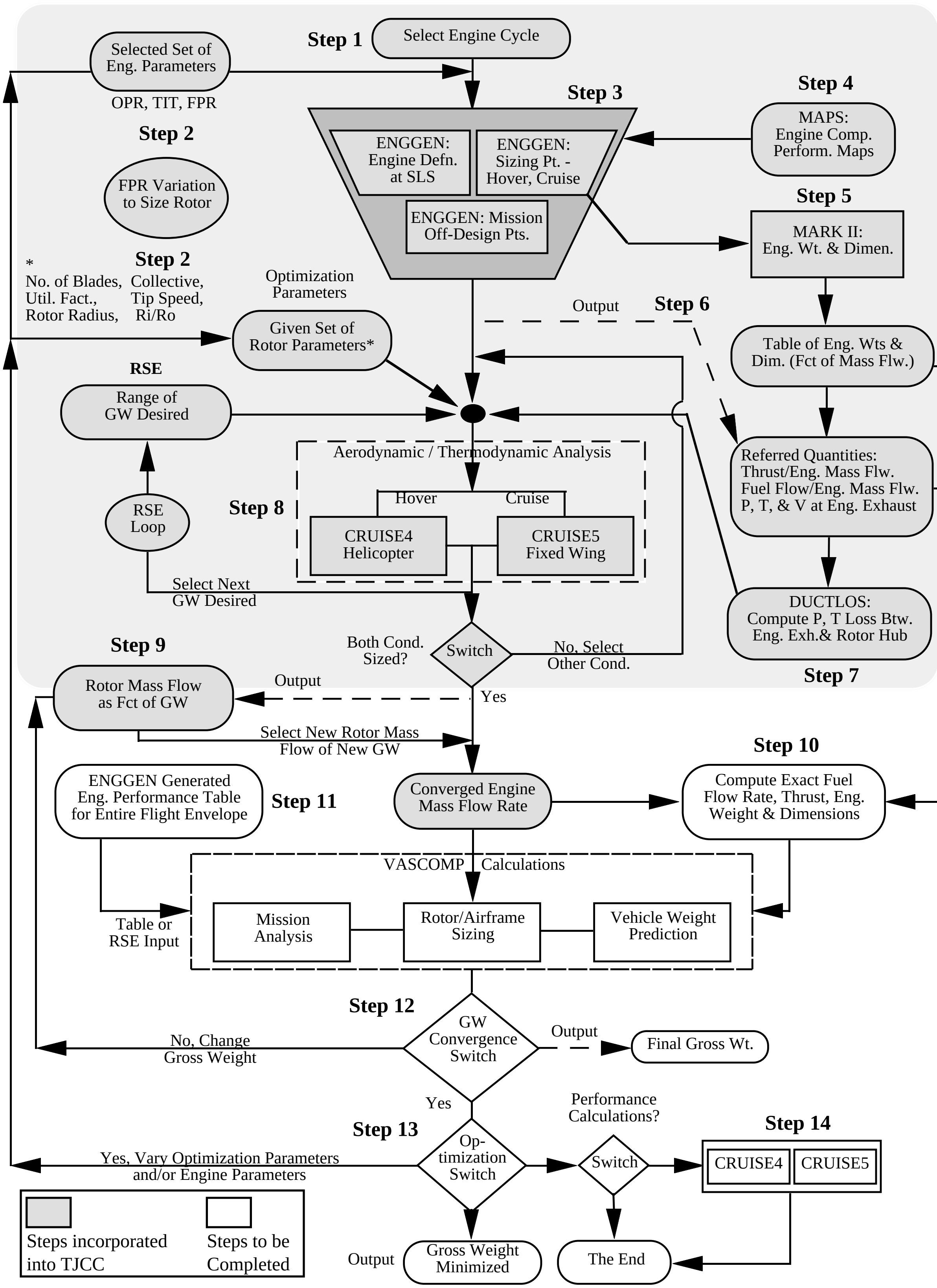

Figure 1: Reaction Driven Stopped Rotor/Wing Overall Design Methodology

Figure 3: GTM-85 Flight Regimes

There are two enabling technologies (reaction drive system and Circulation Control) that are incorporated in the GTM-85 which make stopped rotor/wings technically challenging. A reaction driven rotor acts as a power turbine which directly converts the energy of the gases from the engine into rotary power by using light weight ducting (see Figure 4).

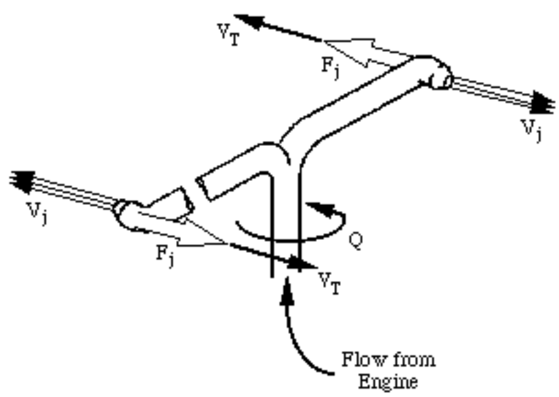

Figure 4: Radial Outflow Turbine[9]

With this air-powered transfer system, the complexity and excess weight of the gearbox(es), shafting, and tail rotor are eliminated. This is due to the fact that the reaction drive concept does not impart a torque on the fuselage of the rotary wing, and therefore there is no need for a tail rotor[10]. The necessary torque that creates the rotor rotation is now being generated by the moment arm (i.e. rotor radius) and by the force (F_j) created when mass flow is ejected through the tipjets located at the blade tips. The magnitude of this torque-generating force is based on the amount of mass flow ($\dot{m}_j$) ejected and by the net velocity between the tipjet (V_j) and tip speed (V_T) (See Equation 1).

$$F_j = \dot{m}_j \times (V_j - V_T) \qquad (1)$$

In order to calculate F_j, the mass flow and velocity of the tipjet, $\dot{m}_j$ and V_j , respectively, must be calculated first. Both of these parameters depend on the results of the engine cycle analysis[11]. Based on these facts, it is obvious that the engine and rotor form a highly coupled system. In fact, they can no longer be sized independently from each other when dealing with reaction driven vehicles.

The other unique characteristic of the GTM-85 is the use of Circulation Control (CC) devices. There are two reasons that this pneumatic technology is selected to enhance the aerodynamic performance of the airfoil. One is the increased airfoil thickness needed in order to accommodate the necessary airflow being ducted to the rotor tips, and the other is the use of elliptical airfoils. The reason elliptical airfoils are used is to remedy the degradation of performance associated with the operation of one of its rotor blades with its trailing edge facing the freestream after conversion. Also, the rounded trailing edge of elliptical airfoils is ideal for the benefits associated with the Coanda effect. The Coanda principle describes the behavior of a thin jet of air being ejected through a small slot at the trailing (and/or leading) edge. This higher velocity CC jet, referred to as CC blowing, remains attached to the rounded trailing edge due to the balance between the pressure differential created by the CC jet velocity and the centrifugal force. This effect causes the rear stagnation point to move below and toward the center chord; therefore, increasing the airfoil's effective camber which in turn allows for high lift generation (see Figure 5). Figure 6 shows an example of an elliptical airfoil with Circulation Control devices as is envisioned to be used in the GTM-85.

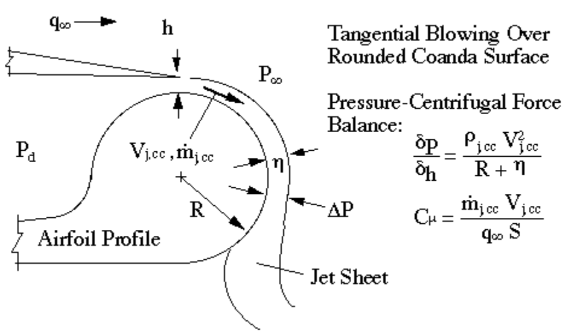

Figure 5: The Coanda Principle[12]

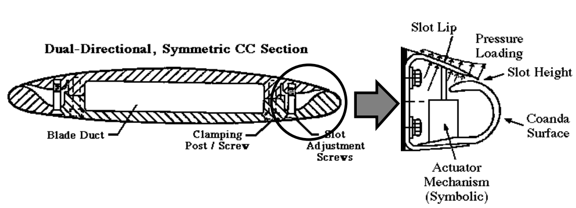

Figure 6: Elliptical Circulation Control Airfoil[13]

ANALYSIS TOOLS

One of the challenges for developing a design tool for sizing and synthesis of stopped rotor/wing vehicles is the selection of suitable physics based analysis codes. Since a reaction drive concept is employed, the engine and rotor must be sized concurrently[11]; therefore, the programs used for sizing and analyzing these subsystems must be linked. The engine cycle analysis program used to generate the necessary on and off-design point performance behaviors is a derivative of QNEP[14] called ENGGEN[15]. Both of these programs are the smaller (and quicker) versions of NASA's Engine Performance Program (NEPP)[16]. ENGGEN is an engine simulation computer code that performs a one dimensional steady state thermodynamic analyses of engine cycles. ENGGEN is a much smaller version of its parent, but it basically performs the same task with fewer features. This engine cycle analysis program is linked to CRUISE4 and CRUISE5[17] which are the aerodynamic/thermodynamic programs used to analyze the rotor/wing during the helicopter and fixed wing modes of operation, respectively. Both of these computer programs are developed by the organization formerly known as David Taylor Naval Research Center (DTNRC), and they are the only public domain code available which can analyze reaction driven rotor in conjunction with the use of Circulation Control. CRUISE4 and CRUISE5 are both based on blade element strip theory, and the aerodynamics are computed based on experimental CC airfoil data gathered at DTNRC. The resulting program after the integration of the engine and rotor analysis codes is referred to as TJCC.

Even though these programs were functional, the logic behind them was muddled, which is typical of codes developed over a long period of time by numerous developers. 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. For instance, a new program had to be written specifically for the integration of the engine to the rotor called DUCTLOS to assess the losses as the airflow is being extracted from the turbofan engine mixer and ducted up to the rotor hub. DUCTLOS is programmed to calculate the resultant pressure, temperature, and velocity of the airflow as it goes through the user-defined ducting system. Technically, the integration between the engine and rotor is coupled through DUCTLOS. Two other major analysis features, also added to both CRUISE4 and CRUISE5, are the mass flow matching iteration and the ability to throttle the engine during the forward flight conditions. These two "add-on's" to TJCC are discussed in more detail next.

MASS FLOW MATCHING AND ENGINE THROTTLING

One of the most important features that the stopped rotor/wing simulation code requires is the ability to throttle the engine in order to match the flow requirements of the rotor/wing system and the available engine flow. The need for this mass flow matching iteration stems from the use of the reaction drive system and Circulation Control. The mass flow available from the engine must be enough to satisfy the rotor/wing system's requirements as well as enough to generate thrust to balance drag during forward flight or to produce thrust for acceleration. The rotor/wing system's mass flow requirements are much more severe during the helicopter mode than the fixed wing mode because of the required airflow to drive both the tipjets as well as the CC device. Since the "rotor blades" are fixed during cruise, the tipjets are closed, and the only flow required is for Circulation Control. This process of throttling the engine and matching the airflow between these two coupled subsystems are depicted in a flowchart presented in Figure 7, and a detailed narrative description is presented next.

Prior to exercising this flow matching process, the engine sizing point must be decided. The two most critical engine sizing points can be found during hover and at the high speed cruise condition. The hover condition is considered because the rotor blades alone must generate enough lift to support the entire vehicle weight. Also, all the engine mass flow is ducted to the rotor during hover since none is required to counteract forward flight drag. Therefore, the mass flow requirement to drive both the tipjets and Circulation Control is the most demanding or most severe during this flight condition. On the other hand, the airflow requirement during the high speed flight condition is minimal because the lift during high speed cruise condition is generated mostly by the center lifting disc and only partly by the CC wings. Even though the fixed-wing airflow requirments are small compared to that of the helicopter mode, the thrust requirements at the high speed cruise condition is critical to overcome the profile/parasite drag. So, with the engine sizing point fixed, the engine design parameters (fan pressure ratio - FPR, overall pressure ratio - OPR, bypass ratio - BPR, and turbine inlet temperature - TIT) are set to make sure that the engine cycle provides sufficient mass flow and/or thrust. Next, a mass flow schedule (i.e. engine throttling) is developed as the rotor/wing lift system is put into forward flight. This flow schedule is needed because the airflow requirements change as the convertiplane proceeds through its forward flight regime in both helicopter and fixed-wing modes.

This mass flow matching and engine throttling loop begins by supplying CRUISE4 and CRUISE5 with the pressure, temperature, and mass flow rate coming out of the engine mixer at full throttle via the user-defined mixer-hub ducting system. Using this information and performing a radial and azimuthal integration, both programs calculate the flow requirement of the rotor/wing system for a given speed. CRUISE4 calculates the required amount of flow for both the tipjets and CC devices, whereas CRUISE5 only performs the same calculations for the CC devices. The CRUISE4 tipjet calculations assume that the flow expands isentropically from the rotor hub out through the tipjets. The mass flow needed to generate enough force to create the torque necessary to drive the rotor/wing system at a specified tip speed is calculated. Both CRUISE4 and CRUISE5 also use this same flow condition at the hub to calculate the amount of blowing that is required by the CC device. Based on the pressure difference between the rotor blade interior and exterior as well as the CC slot opening, a blowing level is calculated. Lift based on this blowing level is calculated next, and if this rotor lift combined with that from the center lifting disc is insufficient to support the aircraft, the CC slot height is adjusted, and the CC mass flow and lift calculations are repeated. This iteration continues until the rotor/wing along with the lifting disc provide enough lift to support the desired gross weight. Then, the total flow requirement is compared to the amount of airflow available from the engine. Since the engine is sized for the most critcal sizing point, the available mass flow should always be greater than the required amount. The excess amount of airflow from the engine is ducted to the aircraft nozzle via the diverter valve to produce the necessary thrust to counteract the vehicle drag in forward flight.

Since the flow has being diverted from the engine mixer, the throat area of a variable-geometry, convergent-divergent nozzle must be reduced in order to maintain the same mixer pressure before the flow extraction. This nozzle airflow is then expanded to atmospheric conditions to produce thrust. In order to balance drag with this calculated thrust (as a function of the remaining mass flow) the nozzle exit area must either be increased or decreased within a limited range. If thrust is less than the vehicle drag, then the engine nozzle area is decreased to compensate, and if the thrust is greater than drag, the exit area is increased. Thrust is recalculated based on the new nozzle exit area (and the available nozzle flow). If the new calculated area does not violate the nozzle geometry limits, a converged solution is reached. However, if the geometry limits are violated, then the engine must be throttled. Recall that the engine at this point is at full throttle; therefore, it can only throttle back. If thrust is less than drag and if the nozzle exit area reduction cannot compensate enough for the extra thrust needed, the engine sizing point has been violated which means the engine needs to be resized. Similarly, if the available mass flow is less than that required by the rotor/wing for any forward flight speed, the engine sizing point is violated.

As the engine is throttled back for the case that the nozzle exit area cannot expanded large enough to handle the remainder of the flow, the mixer flow properties of the next throttle setting is used, and the DUCTLOS program is called again and the process described above is repeated. This throttling loop continues until a converged solution of thrust equals drag that satisfy the nozzle geometry constraints is reached.

RESULTS

After integrating the throttling algorithm described above and depicted in Figure 7 into TJCC, the performance characteristics of the coupled engine/rotor subsystem can be calculated, and they are presented next. The results show the behavior of the rotor/wing system, the center lifting disc, and the mass flow requirements as the stopped rotor/wing proceeds through its flight regimes.

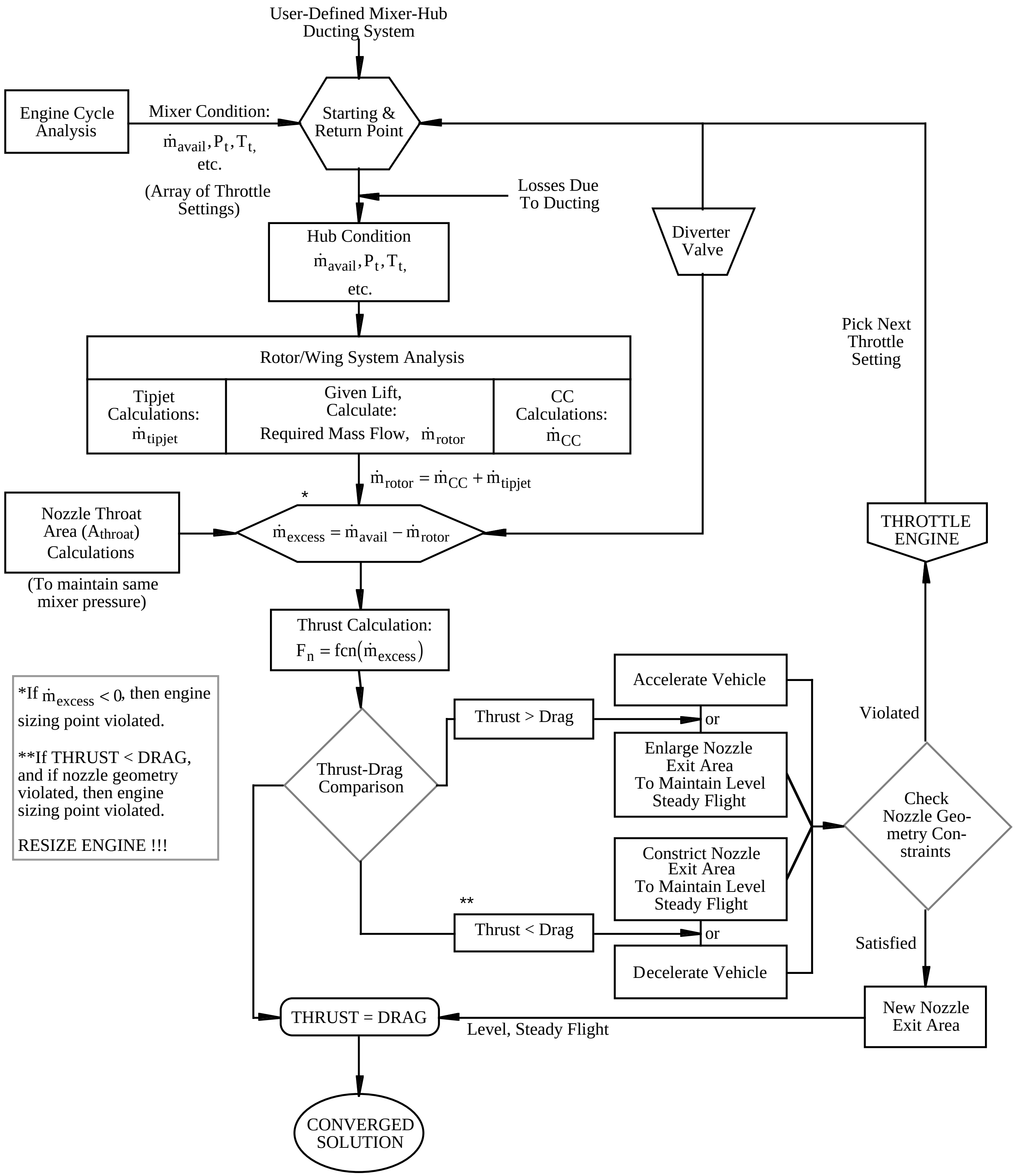

Figure 7: Stopped Rotor/Wing Throttling Scheme for Forward Flight

Figure 10: Mass Flow Requirements for the Rotor/Wing System

As discussed in the previous sections, the torque needed to drive the rotor is produced by the tipjet force and the rotor radius as the moment arm. When the engine throttles back, the conditions at the rotor hub change (along with mass flow). Specifically, the total temperature and pressure has decreased. Since the tipjet velocity, V_j, is a function of these two parameters, it is also decreased (see Equation 2). Since the

Figure 13: Fixed-Wing Horsepower Required Due to Lifting Disc Size Variation at 10,000 Feet

These figures show that different disc sizes become an issue (with regards to horsepower required) at high speeds (excess of 300 knots) or at higher altitudes (excess of 10,000 feet). Obviously, the best solution for high speed cruise is to have the smallest disc size possible; however one must see how well the smallest disc performs during transition, and Figure 15 is generated just for that purpose. This figure shows the lift characteristics for different lifting disc sizes at various angles of attack.

Figure 15: Center Lifting Disc Performance

Examining Figure 15 obviously show that the smallest disc cannot provide sufficient lift for a practical transition speed. Therefore, the disc size must be increased. The compromise to be made next is the angle of attack. There are two possible scenarios. One is to select the larger disc (Ri/Ro=0.45) and have a lower transition speed and lower angle of attack but sacrifice the high speed performance. The other is to have the smaller disc (Ri/Ro=0.35) and to delay the transition to a higher speed and limit the higher angle of attack to the shortest possible time (i.e. just long enough to stopped the rotor system's rotation). This second scenario significantly decreases the required horsepower at altitude (see Figure 14). Also, the smaller disc also forces the stopped rotor/wing to stay in the helicopter mode longer, but since the excess power is already present (see Figure 11) due to the oversized engine for the cruise condition, this will not pose any problems. In other words, to minimize the size of the lifting disc for more efficient cruise, the GTM-85 must perform a pull up maneuver in order to transition from helicopter to fixed-wing mode.

CONCLUSIONS

The figures presented in the Results section show the unique performance characteristics of the rotor/wing system coupled with the propulsion unit. Furthermore, the logic or methodology which enables the engine to throttle during forward flight has also been discussed and implemented. In fact, it is this new capability added to the coupled engine/rotor/wing system that allowed the simulation code, TJCC, to predict realistically the forward flight performance. These results indicate that TJCC can indeed predict the behavior of this coupled system that are representative of the physics behind this unique rotary wing concept. More importantly, a tool exists now so that performance trade-offs can be made to further understand the physics which is essential to the sizing and synthesis process for the stopped rotor/wing concept.

The next development phase is to exercise the Response Surface Methodology (RSM)[18] using TJCC for the forward flight case and to incorporate the resulting Response Surface Equations (RSEs) into VASCOMP II. These RSEs (along with those generated in Reference 11) will provide VASCOMP II with the ability to size reaction driven stopped rotor/wing vehicles that utilizes Circulation Control for airfoil performance enhancements.

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