Steady-State/Transient Performance Simulation of the Propulsion System for the Canard Rotor Wing UAV during Flight Mode Transition

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Abstract

A steady-state/transient performance simulation model was newly developed for the propulsion system of the CRW (Canard Rotor Wing) type UAV (Unmanned Aerial Vehicle) during flight mode transition. The CRW type UAV has a new concept RPV (Remotely Piloted Vehicle) which can fly at two flight modes such as the take-off/landing and low speed forward flight mode using the rotary wing driven by engine bypass exhaust gas and the high speed forward flight mode using the stopped wing and main engine thrust.

The propulsion system of the CRW type UAV consists of the main engine system and the duct system. The flight vehicle may generally select a proper type and specific engine with acceptable thrust level to meet the flight mission in the propulsion system design phase. In this study, a turbojet engine with one spool was selected by decision of the vehicle system designer, and the duct system is composed of main duct, rotor duct, master valve, rotor tip-jet nozzles, and variable area main nozzle. In order to establish the safe flight mode transition region of the propulsion system, steady-state and transient performance simulation should be needed. Using this simulation model, the optimal fuel flow schedules were obtained to keep the proper surge margin and the turbine inlet temperature limitation through steady-state and transient performance estimation. Furthermore, these analysis results will be used to the control optimization of the propulsion system, later. In the transient performance model, ICV (Inter-Component Volume) model was used.

The performance analysis using the developed models was performed at various flight conditions and fuel flow schedules, and these results could set the safe flight mode transition region to satisfy the turbine inlet temperature overshoot limitation as well as the compressor surge margin. Because the engine performance simulation results without the duct system were well agreed with the engine manufacturer's data and the analysis results using a commercial program, it was confirmed that the validity of the proposed performance model was verified. However, the propulsion system performance model including the duct system will be compared with experimental measuring data, later.

Introduction

Recently, the KARI (Korea Aerospace Research Institute) has been developing the Smart UAV with new concept since 2002. This project is to develop the civil use UAV, which has some new smart technologies such as CRW concept with VTOL (Vertical Take-Off/Landing) and the high speed forward flight, high reliability, small, light and intelligent flight capability.

A research on this new concept propulsion system has been started since 1960's. Cohan et al.1) showed that a helicopter style flight could be possible if a rotary propulsion system using hot gas provided from the turbojet engine were used. Smith2) proposed a new concept aircraft which was capable of both forward flight mode with the fixed wing and helicopter flight mode with the rotary wing. Rutherford et al.3) defined the CRW concept as 'The CRW concept was a reaction drive rotor system which converts to a fixed wing'. Tai4) developed an analysis program for the propulsion system to design a flight vehicle with the reaction driven stopped rotor/wing concept using tip jets and the circulation control technique, and he carried out the development project on sizing the CRW propulsion system. In this study, he proposed a mathematical model to calculate the tip jet nozzle steady-state performance and the duct loss of the propulsion system.

The CRW concept, which uses a hot cycle, is suitable as a Smart UAV to fulfill the requirements of the VTOL UAV mission. This concept can operate the tip jet nozzle driven by hot gas from the main jet engine to rotate the rotary wing in the vertical flight mode and use the turbojet engine for the high speed forward flight.

The propulsion system for the new concept flight vehicle can be operated by dividing into three flight modes such as the hovering mode for the take-off/landing, the high speed forward flight mode with the fixed wing and the transition flight mode between the above two flight modes. In order to reduce the development cost and the risk of the proposed propulsion system, the precise performance simulation should be performed in advance. The performance simulation can provide important data not only to confirm the performance characteristics in much wider flight envelope, where the experimental tests are not able to carry out, but also to design the engine controller or the integrated flight control system.

In order to establish the safe flight mode transition region of the propulsion system, a steady-state/transient performance simulation should be needed. Using this simulation model, the optimal fuel flow schedules were obtained to keep the proper surge margin and the turbine inlet temperature limitation through steady-state and transient performance estimation. Furthermore, these analysis results will be used to the control optimization of the propulsion system, later. In the transient performance model, the Inter-Component Volume model was used.

In this study, steady-state/transient performance analysis using the developed models was performed at various flight conditions and fuel flow schedules, and these results could set the safe flight mode transition region to satisfy the turbine inlet temperature overshoot limitation as well as the compressor surge margin.

Propulsion System Modeling

The research propulsion system is mainly composed of an engine and the duct system. A turbojet engine is used as a major power plant, and the duct system is divided into the straight duct for the main nozzle, the controllable main nozzle, the curved duct for the tip-jet nozzles and the master valve for controlling the tip-jet nozzle thrust. The hot pressure jet cycle was selected to rotate the rotary wings with the tip-jet nozzles driven by hot gas from the main turbojet engine.[2]

In the take-off/landing mode, the vehicle can hover using the rotary wing with the tip-jet nozzles driven by hot gas ejected through the curved and straight duct from the engine, but the main nozzle should be closed to prevent the forward flight. However, if the flight velocity reaches to the proper forward velocity more than the stall speed, then the vehicle can fly using the only main jet nozzle thrust but the master value should be closed. The main jet nozzle uses the variable convergent type, and the tip-jet nozzle uses the fixed convergent type. The Fig. 1 shows the schematic layout of the Smart UAV propulsion system.

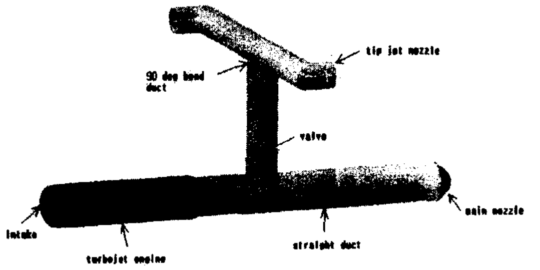


Fig. 1 Simplified layout of Smart UAV propulsion system

The design point performance was set at the sea level standard atmospheric condition and 100% engine rotational speed. Therefore the design point reference performance data of the engine major components without ducts and the master value could be determined.

Because the proposed propulsion system has the ducts between the gas generator and the tip-jet nozzles as well as the main nozzle, the duct loss should be estimated to simulate the precise propulsion system model depending on its length and shape. In modeling for the duct system, the Fanno line theory was used, and the detail equations related to the duct systems were referred from Tai's research results.[4]

Performance Simulation for Each Flight Modes

The developed steady-state/transient performance analysis program can perform the calculations for variations of flight conditions, valve angle positions and fuel flow schedules. Furthermore it can perform the analysis with the following four flight calculate modes;

a) Main engine performance analysis mode without the duct system (MODE=0)
b) The propulsion system performance analysis mode in the fixed wing flight (MODE=1)
c) The propulsion system performance analysis mode in the rotary wing flight (MODE=2)
d) The propulsion system performance analysis mode in the compound flight (MODE=3)

The steady-state/transient performance program is composed of a main program to manage the input/output data as well as to carry out the final mass flow matching process for steady-state calculation and Inter-Component Volume calculation for transient, 22 subroutines to treat atmospheric and flight conditions, to manage map data for compressor, combustor and turbine and to calculate the performance of the ducts and the valve, and 6 function subroutines to calculate air properties, fuel-air ratio, the enthalpy, and duct friction coefficients. In order to calculate much precisely the duct performance, the correction by the Reynolds's effect was considered, and the applied effective nozzle throat area was determined by considering the atmospheric and flight conditions.

Steady-State Performance Simulation

The performance analysis can be carried out with several flight modes depending on the steady-state or the transient-state. In case of the steady-state, the performance analysis is performed with input data of the flight modes and conditions given by the Smart UAV system department. The system department for the smart UAV development provided the following operating flight range of the propulsion system at each flight mode.(see Table 1)

In the rotary wing flight mode, the main nozzle is entirely closed and the master value is fully open with the 90° position. Therefore the total engine gas mass flow is ejected through the tip jet nozzle. In the fixed wing flight mode, the mast valve is completely closed with the 0° position, also the main nozzle is automatically adjusted by the actuator to keep the choke condition continuously. In the transition flight mode, both the master value and the main nozzle are partially open.

Table 1 Operating range of the propulsion system

Flight Modes	Altitude (km)	Flight Mach Number
Rotary Wing	0 ~ 1	0.0 ~ 0.2
Compound Flight	1	0.2 ~ 0.3
Fixed Wing	1 ~ 3	0.3 ~ 0.4

In this case, firstly the mass flow rate is calculated by the master valve (butterfly valve) position, and then the rest mass flow controls the main nozzle throat area to allow the choke condition. In this calculation, the total thrust is the tip jet nozzle thrust plus main nozzle thrust.

Transient Performance Simulation

In this study, the ICV (Inter-Component Volume) method is applied to transient performance simulation of the CRW propulsion system. The transient simulation can be performed with the scenario at various flight modes required by the system department. In the rotary wing flight mode, the take-off/landing and the low speed forward flight are undergone. In this flight mode, acceleration /deceleration of the propulsion system can be operated with the open master valve and the closed main nozzle. In the compound flight mode, because the flight vehicle must keep the level flight with a certain constant flight speed, the master valve may be partially closing under the proper fixed throttle position and the main nozzle may be simultaneously opening. However, in the highly speed forward flight mode, the engine may be only operated for acceleration/deceleration like a fixed wing aircraft. The table 2 shows the transient operation scenario used for the transient simulation of the propulsion system in this study.

Table 2 Transient Operation

Flight Modes	Main Engine Operation Condition	Master Valve /Main Nozzle Position
Rotary Wing	Acceleration /Deceleration (Idle to Max.)	Open/Closed
Compound Flight	Constant Thrust Rating	Partially Close/Opening
Fixed Wing (Cruise)	Acceleration /Deceleration (Intermediate to Max.)	Closed/Open

The Fig. 2 shows the flow chart of the developed steady-state/transient performance simulation program for the CRW UAV propulsion system.

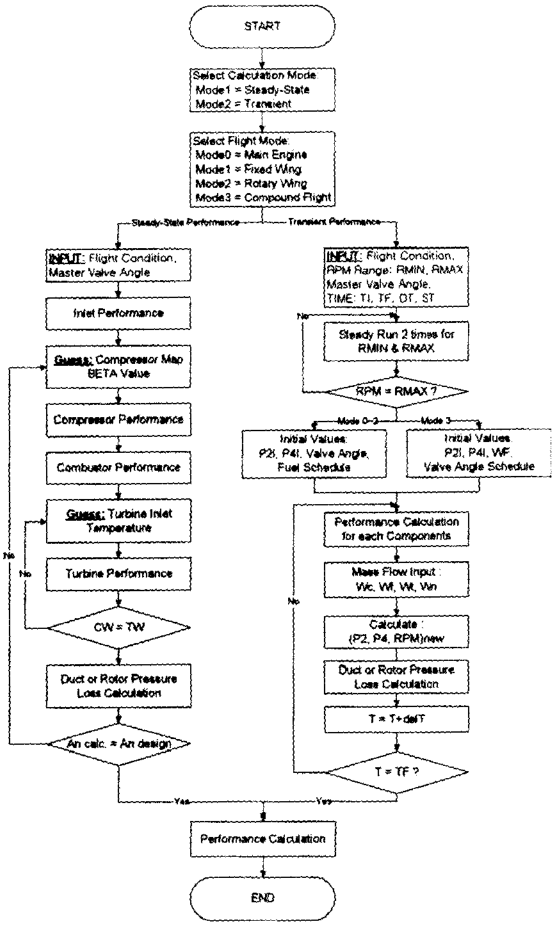


Fig. 2 Flowchart of the steady-state/transient performance simulation program for the CRW UAV propulsion system

Steady-State Performance Results

The steady-state performance analysis was performed at four flight modes with varying altitudes, flight Mach number and the gas generator rotational speed, the analysis results of each flight mode should be evaluated through comparison with the experimental test results later.

Performance analysis of main turbojet engine (MODE=0)

The table 3 shows comparison on the design point performance of the turbojet engine between the simulated engine and the real engine. In this comparison, it was confirmed that the design point performance of the proposed simulation engine was quite well agreed with that of the real engine provide by the system department (KARI).

Table 3 Design point performance of the turbojet engine

Performance Parameters	System Requirements	On-Design Performance	Errors (%)
Air flow (kg/s)	6.22	6.219	0.02
Fuel flow (kg/hr)	494.4	459.72	0.30
Compressor pressure ratio	3.83	3.831	0.03
Turbine inlet temperature (K)	1267	1267.7	0.20
Turbine outlet temperature (K)	1127	1125.0	0.20
Thrust (N)	3790	3782.6	0.21
Specific fuel consumption (kg/N/hr)	0.1304	0.1311	0.54

At off-design points, in order to verify the algorithms for both work and mass flow matching, the main engine performance analysis results in MODE=0 using the developed program (D.P.) were compared with them using the commercial program (C.P.). Fig. 3 shows the part throttle performance analysis results at the static sea level condition. In this comparison, it was noted that the analysis results by the D.P. were reasonably agreed with them by the C.P.

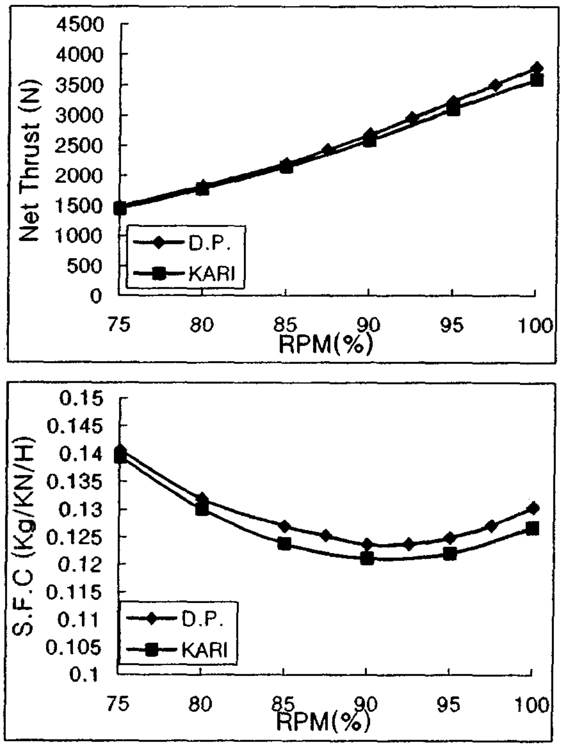


Fig. 3 Results of engine performance analysis at part throttle condition

Performance Analysis of the Propulsion System at Flight Modes (MODE=1,2,3)

In case of performance analysis with variation of flight conditions, the limitations of the engine performance were considered. In this calculation, the positions of the master value were set 0° at the fixed wing mode (MODE1), 90° at the rotary wing modes (MODE2), and 45° at the transition flight mode, respectively. The analysis results on the net thrust with variation of altitude, flight Mach number and engine rotational speed are shown as Fig. 4.

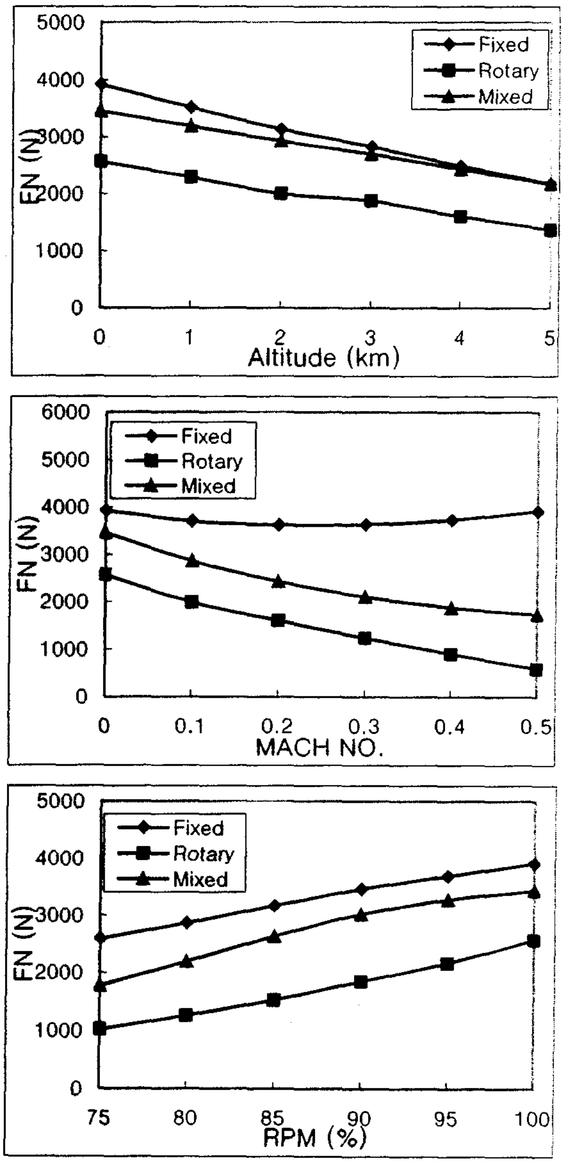


Fig. 4 Results of performance analysis with variation of altitude, flight Mach number and rotational speed

In this analysis, it was noted that the net thrust at the fixed wing mode was greater than it at the rotary wing mode. However, the net thrust magnitude in the transition flight mode was located between the fixed wing mode and the rotary wing mode. Moreover, it was found that the performance in the compound flight mode was partially limited at the idle engine rotational speed because of the compressor surge due to the frictional duct loss.(see Fig. 5)

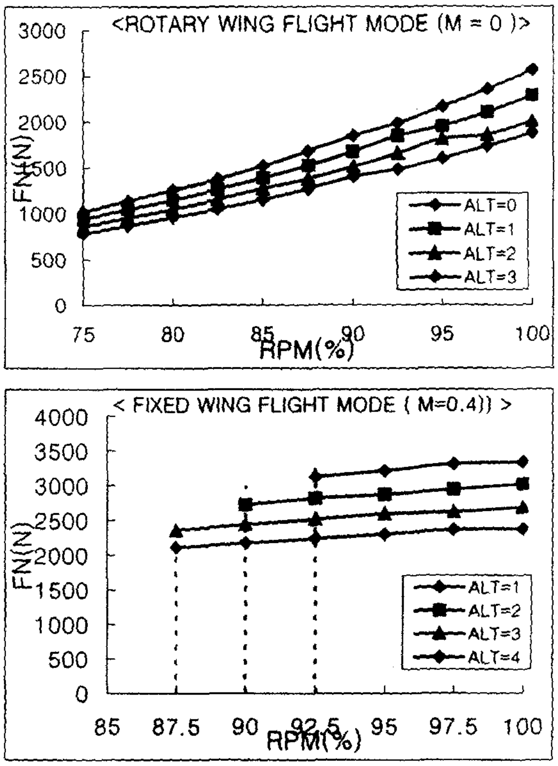


Fig. 5 Rotational speed limit at Rotary and Fixed wing mode

Transient Performance Results

Transient performance analysis for main engine

The transient performance analysis was performed with various fuel flow schedules with 3 calculation modes such as main engine, rotary wing and fixed wing mode. In order to verify the proposed program algorithms, the analysis results of main engine calculation mode were compared with them using a commercial performance simulation program GSP[5], which can consider the volume dynamics in transient analysis.

The Fig. 6 and 7 show the transient performance analysis results for the main engine calculation mode. The analysis condition was the acceleration phase from idle of 75% rpm to maximum rotational speed of 100% rpm at sea level static standard atmospheric condition with various fuel flow schedules. As shown in comparison at the step fuel flow increase schedule of Fig. 6, the turbine inlet temperature, T3, calculated by the D.P. (developed program) converges to relatively higher value than it calculated by the GSP, and both the thrust and the engine rotational speed calculated by the D.P. converges to relatively quicker than it calculated by the GSP but steady-state values by two programs are almost same.

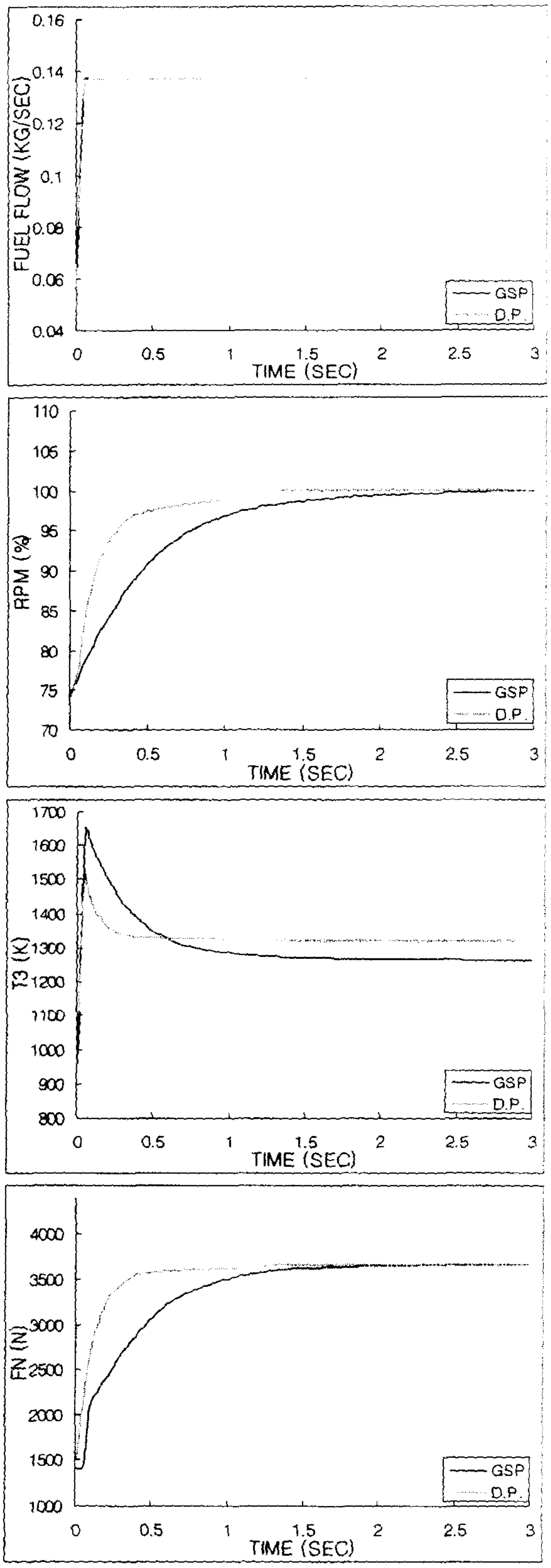


Fig. 6 Results of transient performance analysis for main engine calculation mode with step fuel flow increase schedule

As shown in Fig. 7, it was found that the turbine inlet temperature overshoot occurs greatly at the fuel flow increase schedule within very short period less than 0.2 sec.

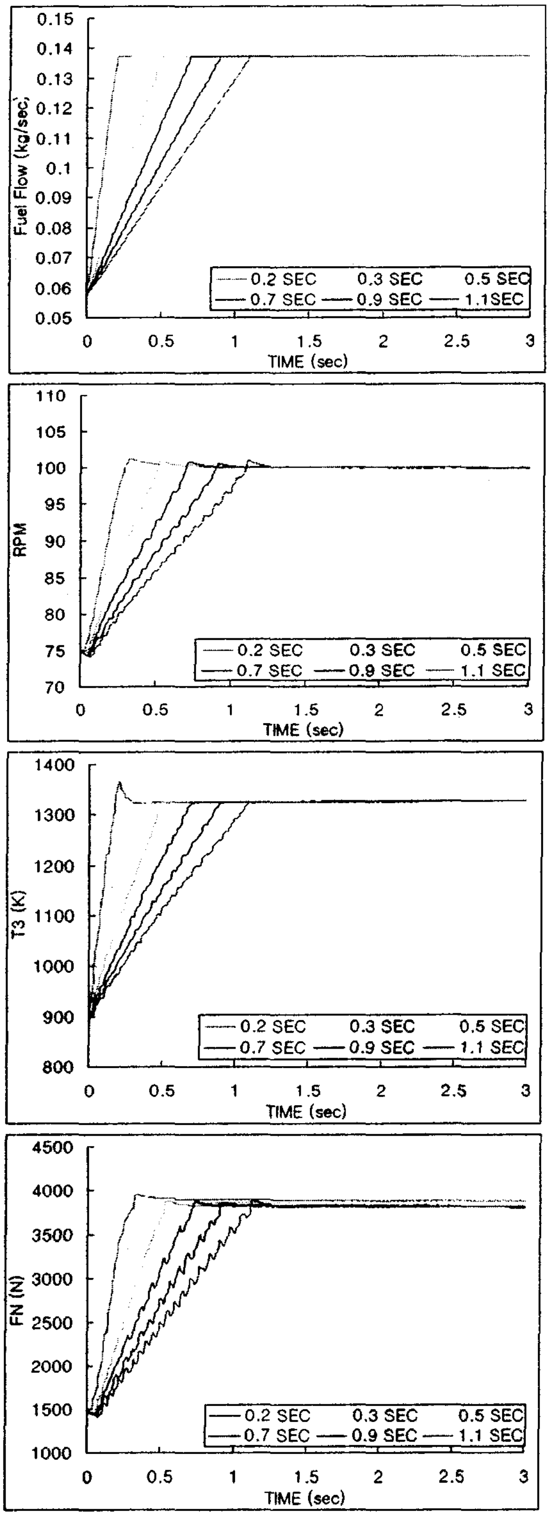
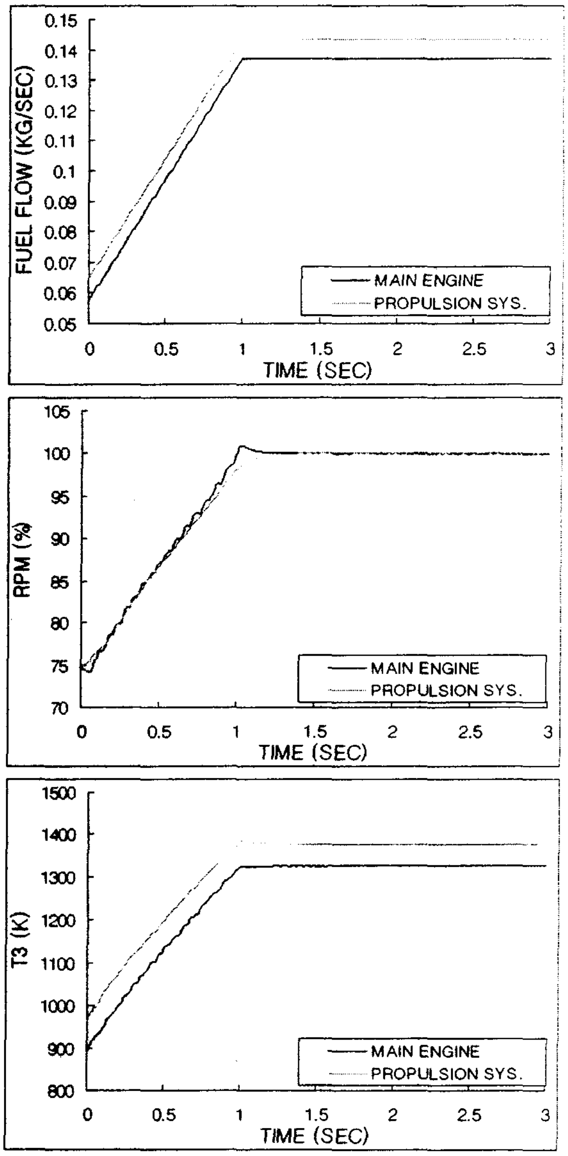


Fig. 7 Results of transient performance analysis for main engine calculation mode with various fuel flow schedules

Performance analysis of the rotary wing flight mode

In the rotary wing flight mode, the transient performance analysis was performed with the fully open master valve to allow the exhaust gas ejection to the tip-jet nozzles and the completely closed main nozzle condition for investigation of acceleration performance at various fuel flow schedules. The Fig. 8 shows the transient performance analysis results for this flight mode. The analysis condition was the acceleration phase from idle to maximum rotational speed at sea level static standard atmospheric condition with the fuel flow increase schedule during 1sec.



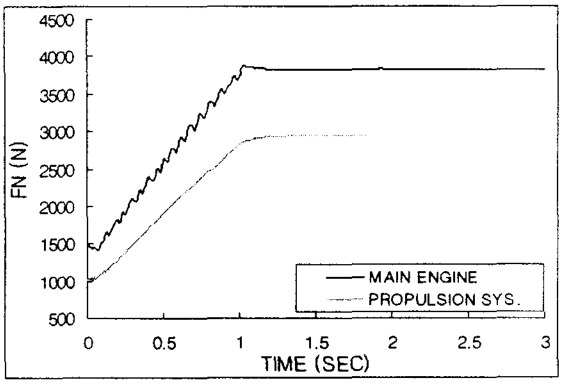


Fig. 8 Results of transient performance analysis for SUAV propulsion system at the rotary wing flight mode

According to analysis results, it shows tendencies that the turbine inlet temperature of the rotary wing mode increases more than that of the engine mode, but the net thrust of the rotary wing mode decreases less than that of the engine mode.

Performance analysis of the fixed wing flight mode

In the fixed wing flight mode, the transient performance analysis was performed with the fully open main nozzle to obtain the proper thrust for cruising flight, and the completely closed master valve condition for investigation of acceleration performance at various fuel flow schedules. The Fig. 9 shows the transient performance analysis results for this flight mode. The analysis condition was the acceleration phase from idle to maxmum rotational speed at 2km altitude, cruising flight speed Mach number 0.3 and standard atmospheric condition with the fuel flow increase schedule during 1second.

As shown in analysis results, it was noted that the turbine inlet temperature of the fixed wing mode increases greatly than that of the engine mode, but the net thrust of the fixed wing mode increases inversely than that of the engine mode due to much higher fuel flow requirement of the fixed wing mode to keep the main nozzle choke-condition in all part throttle range regardless of the straight duct loss. It means that not only the variable nozzle, which must keep the choke condition at all operation range even at idle, may be not realistic, but also the engine operational condition should be limited similar to the steady-state analysis results of the fixed wing mode.

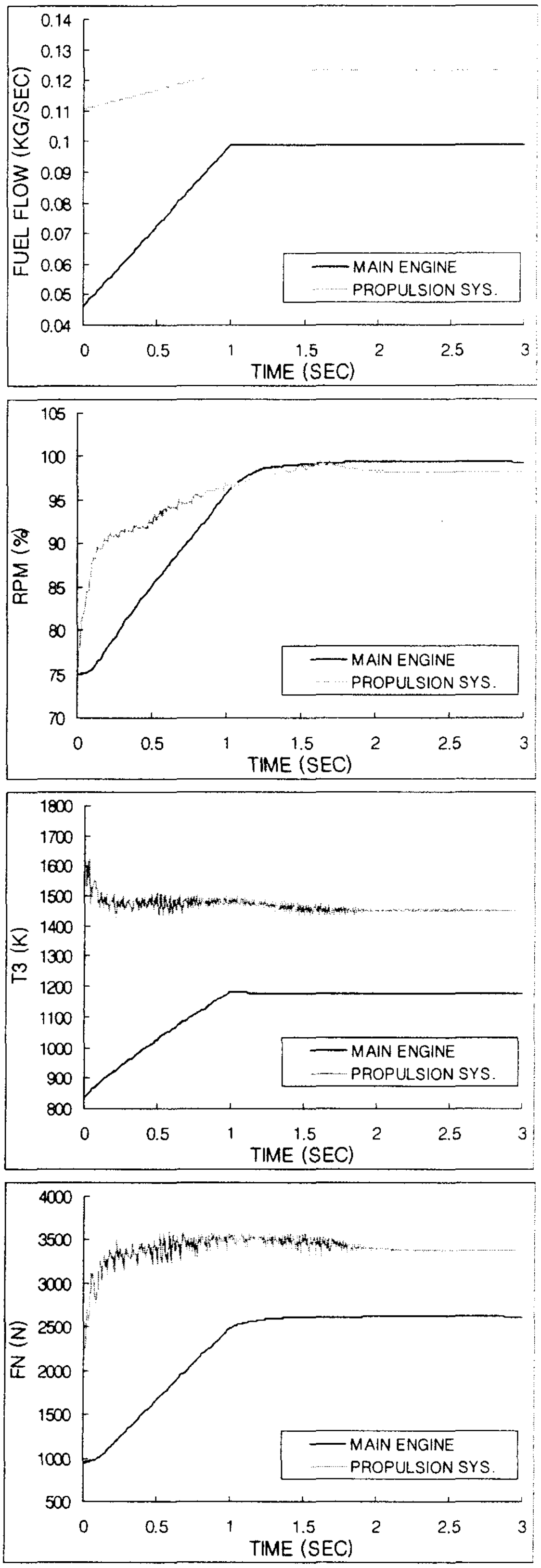


Fig. 9 Results of transient performance analysis for SUAV propulsion system at the fixed wing flight mode

Conclusions

A new concept propulsion system, which can operate the flight vehicle in the vertical flight mode for take-off/landing using the rotary wing driven by the tip-jet nozzle as well as in the flight speed forward flight mode with the fixed wing using the main thrust nozzle, was modeled, and the steady-state and transient performance analysis of this propulsion system was performed.

In steady-state performance analysis results of the main turbojet engine using the developed program was compared with them using the commercial program in the analysis mode 0 (the main engine analysis only), and the analysis results using the developed program were well agreed witch them using the commercial program. In the fixed wing flight mode among three flight modes, the performance analysis of the propulsion system was performed with varying altitudes and flight Mach numbers using the nozzle throat choking condition to keep the best thrust. According to analysis results, it was noted that the thrust and the specific fuel consumption ratio of the rotary wing flight mode were relatively greater than that of the fixed wing flight mode because the losses of ducts and the master valve for the tip jet nozzle system was much greater than the losses of the main duct-nozzle system. Moreover it was found that the performance in the transition flight mode was partially limited at the idle condition because of the compressor surge due to the frictional duct loss.

In case of transient analysis, in order to verify the proposed program algorithms, the analysis results of main engine calculation mode were compared with them using a commercial performance simulation program GSP. As results, the turbine inlet temperature, T3, calculated by the D.P. (developed program) converged to relatively higher value than it calculated by the GSP, and both the thrust and the engine rotational speed calculated by the D.P. converged to relatively quicker than it calculated by the GSP but steady-state values by two programs were almost same. In the rotary wing flight mode, according to analysis results, it showed tendencies that the turbine inlet temperature of the rotary wing mode increased more than it of the engine mode, but the net thrust of the rotary wing mode decreased less than it of the engine mode. In the fixed wing flight mode, as shown in analysis results, it was noted that the turbine inlet temperature of the fixed wing mode increased greatly than it of the engine mode, but the net thrust of the fixed wing mode increased inversely than it of the engine mode due to much higher fuel flow requirement of the fixed wing mode to keep the main nozzle choke-condition in all part throttle range regardless of the straight duct loss. It means that not only the variable nozzle, which must keep the choke condition at all operation range even at idle, may be not realistic, but also the engine operational condition should be limited similar to the steady-state analysis results of the fixed wing mode.

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