INTEGRATED FLIGHT AND PROPULSION CONTROL - A REVIEW

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Abstract

Integrated Flight and Propulsion Control (IFPC) systems are gaining importance in modern fighter aircraft to enhance performance, safety and life. The performance enhancement of the aircraft can be achieved by making optimal use of the interactions between the propulsion system and the aircraft flight dynamics. The safety of the aircraft can be enhanced by the use of propulsion system forces and moments for reconfiguring flight control in the event of damage/failure of aerodynamic control surfaces. The life of the propulsion system can be traded for the performance and vice-versa by varying operating margins throughout the flight envelope. The integration of inlet control, nozzle control, thrust vector control and varying the stability margins of the engine according to the flight conditions offer unlimited possibilities in enhancing the performance and safety. This paper is aimed at summarizing all aspects of IFPC and provide an overview of research being carried-out in each of these fields.

Keywords: Control Integration, Centralized Control, Thrust Vector, Inlet Control, Stall Margin, Reconfiguration

Introduction

An aircraft is a system consisting of many sub-systems which function together to make the aircraft fly safe and efficiently. While integrating various sub-systems, the interactions between them need to be studied carefully. The interaction between the Flight Control System and the Propulsion System is evident because the propulsion system generates one of the three major forces (aerodynamic/Weight/thrust force) which act on the aircraft. In the past, very little integration of aircraft sub-systems has been achieved for several reasons. In the older generation aircraft, numbers of sub-systems were few and interactions between the sub-systems were small, and the pilot work load was less, hence the pilot could effectively control various sub-systems through his control inputs. Another reason is that, from aircraft designers view point, it was desirable to design and test the sub-systems independently. With this approach the designer could be confident of proper function of sub-system when integrated with the aircraft. But, today’s sophisticated aircraft have large number of control variables among various sub-systems, which are rapidly interacting with each other and the pilot can not be expected to react fast enough to effectively control the interactions.

Various interactions between the sub-systems can be favorable or unfavorable. It is of importance to make use of favorable interactions to improve the efficiency and safety of the aircraft and effectively suppress the unfavorable interactions through advanced control techniques. It is to be noted that even a favorable interaction may turn unfavorable if the control system does not cater for the interaction. With the development of various advanced control techniques and the use of digital control systems on the modern aircraft, it is imperative to take advantage of interactions between its various sub-systems.

The propulsion system being the major force and moment creator next only to the aerodynamic forces and moments, it is important to integrate the Flight Control System (FCS) and propulsion control system to take advantage of the interactions in improving the aircraft performance, handling qualities, safety and life. Integration
of FCS and propulsion systems can result in enhanced control power for the flight control. The propulsion system can also benefit from the integration by optimization of engine control such that the engine delivers its best when it matters most for the overall performance and safety of the aircraft.

**Historical Overview**

Historically, aircraft design has been based on the philosophy that flight and propulsion controls can be designed independently. It was assumed that the pilot could effectively integrate these subsystems by his control inputs. Future mission requirements, especially powered-lift aircraft, demand improved operational capabilities so that the pilot’s attention can no longer be directed to integrating the flight and propulsion control sub-systems. Pilot must instead direct his attention to higher levels of concern as demanded by his mission and monitor the progress of his mission through the imposed threats. This allows the pilot greater attention to those higher levels of concern by reducing the pilots workload towards integration function of the sub-systems interactions.

The propulsion system as a thrust force generator always has interaction with flight path control of the airframe. However, the interactions are managed usually by the pilot through manual control of engine throttle. The thrust force of the engine is used to counter the drag of the aircraft. When the thrust axis is above or below the aircraft CG, then a pitching moment is also produced by the engine throttle modulation. Some designs place engine slightly below the aircraft CG such that it provides additional pitch up moment for take-off rotation. Some aircraft provide a small angular tilt with respect to fuselage axis so that at small AOA during cruise, the thrust is placed along the flight path. Many such propulsion effects are usually considered during the aircraft design, but the aspects of active control of interaction in flight were not so common. With the transformation to flight control from analog to digital and fly-by-wire concept, the modeling and control of interactions are not difficult any more. The history of Integrated Control flight research program [1] is shown in Fig.1.

The F-111E experiment integrated the engine and inlet control systems. The Y-12C incorporated an integrated control system involving the inlet, autopilot, auto-throttle, airdata, navigation and stability augmentation systems. The F-15 Research involved integration of engine, flight and inlet control systems. Further extensions of the integration included real time onboard optimization of engine inlet, self-repairing flight control system, and a propulsion only control concept for emergency flight control. The F/A-18 aircraft incorporated thrust vectoring integrated with flight control system to provide enhanced maneuvering at high angles of attack.

There are various interactions between Propulsion system and Airframe control, based on which one may classify IFPC elements as shown below:

- Auto-throttle / Autopilot
- Air Intake/ exhaust nozzle integration
- Propulsion Controlled Aircraft (PCA) for emergency
- Thrust Vector Control Integration
- STOVL Propulsion control Technology
- Performance Seeking Control (PSC)
- Reconfigurable/ Adaptive Control
- IFPC Controller Design and Partitioning

The following sections in this paper briefly talks about the integration aspects of flight control with propulsion control and the research work being carried out in the above areas.
Auto-throttle/ Autopilot

The simplest form of Flight Control system and Propulsion integration is the auto-throttle/ autopilot functionality. The auto-throttle function enables automatic control of engine throttle through commands from FCS. This is achieved through integration of the engine controller with the FCS. The current generation engines have Full Authority Digital Electronic Control (FADEC) which enables integration with the flight control system.

In the conventional control system the throttle is controlled manually by the pilot. Pilot needs to control throttle in combination with the control stick for various control functions such as Acceleration, Deceleration, Climb, Level flight trim, Level turn, etc. The engine has much slower dynamics and the thrust response is also slow as compared to the airplane dynamics. The response of the aircraft to thrust is also slow as compared to other control surface inputs. So it is not very difficult for the pilot to control the engine throttles manually. However, throttle control is critical in certain maneuvers, for example in approach and landing phases, where slow dynamics of the engine makes the aircraft difficult to control manually by the pilot. It is advantageous to have automatic landing especially for landing the aircraft on the naval carrier through the use of auto-throttle and autopilot.

Though the pilot can manually execute the navigational functions of an autopilot, it is enduring to the pilot in long duration flight. It is convenient to use autopilot for such function. Also, some maneuvers which require precise co-ordination between the controls, it is convenient to use maneuver autopilots. Certain navigation functions which require precise timing are also candidates for autopilot. Some of the autopilot functions for a military aircraft are:

- Altitude hold autopilot
- Altitude/ Mach hold autopilot
- Terrain following/ terrain avoidance autopilot
- Pitch attitude hold autopilot
- Flare control autopilot
- Bank angle hold autopilot

An auto-throttle [3] architecture on YF-12C with Mach number/ altitude hold mode is shown in Fig.4.

Thrust Vector Control Integration

Introduction

Thrust vectoring is a maneuver effector which can be used to augment aerodynamic control moments in the conventional flight envelope and beyond. Thrust vectoring can be used at high angles of attack where conventional control surfaces become less effective or totally ineffective. This opens up the concept of a super-maneuverable aircraft capable of maintaining control at angles of attack greater than 90 degrees. Use of thrust vector control at low angles of attack enables reduction in the size of horizontal and vertical tails and thereby reduction in aircraft weight and drag. In additions it is reported in the literature that the reduction in vertical tail size reduces the radar signature of the aircraft [4].

The fighter aircraft of the future will require use of thrust vectoring controls to attain the maximum controllability during maneuvers and for the optimum performance. The pitch thrust vectoring can increase turn performance, reduce drag, and reduce take-off and landing distances. The benefits of yaw vectoring include directional control power at low speeds (high angles of attack), recovery from spins and stalls, where the traditional control surface effectiveness is reduced.

Types of Thrust Vector Nozzles

There are two different concepts of achieving thrust vectoring: (1) mechanically deflection of the nozzle, (2) deflection of jet by fluidic control. Mechanical thrust vectoring involves deflecting the engine nozzle and thus physically changing the direction of the primary jet. Fluidic thrust vectoring involves injecting fluid into primary jet to enable vectoring. Although a mechanical thrust vectoring system is effective, it can be heavy, complex, difficult to integrate and aerodynamically inefficient. A fluidic thrust vectoring system has the advantage of being lightweight, simple, inexpensive and free from moving parts, and can be potentially implemented with minimal penalty on aircraft observability.

Various types of fluidic thrust vectoring techniques have been discussed in the literature [5] namely shock thrust vector, co-flow and counter-flow control as shown in Fig.5.

The aircraft with no thrust vector feature can adapt a fixed thrust inclination angle so as to optimize flight regimes [6] such as takeoff, climb, cruise, final approach,
landing. If the inclination angle is positive (thrust is tilted down), an additional vertical force is contributed to the lift reducing the requirement of the wing lift. However, this also slightly reduces the horizontal thrust component; thus, an optimization procedure is required to determine the optimal angle.

The thrust vectored nozzle is of many types. A detailed description of the types and advantages in terms of enhancing the fighter aircraft maneuverability was discussed by Benjamin Gal-Or [7]. The following are the classifications of the vector nozzle:

- Based on Integration: (a) Aircraft Integrated Nozzle, (b) Engine Integrated Nozzle
- Based on DOF of the vector nozzle: (a) Multi-axis Thrust vectoring, (b) Pitch only Thrust vectoring
- Based on how the jet is deflected: (a) Mechanical Thrust Vectoring, (b) Fluidic Thrust Vectoring
- Based on where the nozzle is rotated: (a) baseframe is rotated before the geometrical nozzle throat, (b) baseframe is rotated at the nozzle throat, (c) baseframe is not rotated, but rather the additions of deflection vanes enables vectoring
- Based on where the gas is deflected: (a) Internal Thrust Vectoring (Gas is deflected before leaving the engine nozzle), (b) External Thrust Vectoring (Gas is deflected after is leaves the engine nozzle using post exit vanes)
- Based on how the Vectored forces are used for Flight Control: (a) Pure Thrust Vectored Aircraft (Aircraft is fully controlled by the thrust vector forces and the conventional aerodynamic controls such canard, horizontal tail, vertical tail are absent), (b) Partial Thrust Vectored Aircraft (Thrust Vector forces are used along with the conventional aerodynamic flight control surfaces to enhance performance/ to minimize drag/ to provide redundancy)

Benefits of Thrust Vectoring

The thrust vectoring feature on a fighter aircraft can enhance the maneuverability, agility, extend the flight envelope and reduce takeoff/ landing distances [4,5,6,7,8]

Take-off and Landing

The take-off distance of an aircraft is determined by two important factors; (1) the ability to accelerate the aircraft to the lift-off speed quickly, (2) the ability to rotate the nose to reach required angle of attack at low speeds. The first requires enough thrust from the engines and the second one requires huge elevator power to rotate. The elevator power is usually insufficient for rotation at low speeds and that is where the thrust vectoring is helpful in rotating the nose by vectoring the jet upwards at very low speed. The rotation at low speeds reduces the take-off distance considerably. A reduction of about 20 to 30% take-off distance has been reported in literature.

A comparison of pitching moment generated by a horizontal tail against a thrust vectoring nozzle [9] is shown in Fig.6. As seen in the figure, the control power of the horizontal tail reduces at low speed because of low dynamic pressure, but the control power of thrust vector is approximately constant. A precise control of flight path is possible with the use of thrust vectoring in the low-speed regime, such as landing. This help reducing the landing speed and hence the landing distance of the aircraft.

Flight Envelope

The effective integration of aerodynamics, propulsion and flight control provides performance enhancements in subsonic as well as in transonic speeds. Fig.7 illustrates the potential maneuvering performance improvements in the flight envelope [9] compared to a state of the art fighter aircraft without thrust vector nozzle.

Cruise

In cruise flight, the aircraft needs to be trimmed using elevator/elevon or canard to make the net pitching moment zero. The additional drag associated with this control surface deflection (trim drag) can be reduced by the use of vectored thrust. This can result in significant saving in fuel as the cruise segment is the longest in a mission.

Post-Stall Maneuvers

The greatest benefit of thrust vector control is in giving the aircraft the post-stall control capability. The fighter aircraft are susceptible to departures when operated near or above the stall angle of attack. The post stall maneuver offers an advantage over the conventional maneuvers in close combat. It offers Rapid Nose Pointing and Shooting opportunity. The conventional aerodynamic controls lose their effectiveness because of the wake due to high AOA. Also, the control power of the aerodynamic control surfaces is function of dynamic pressure which is low at high
AOA/ low speeds. Hence it is not possible to control the aircraft at high AOA using conventional flight control surfaces only. The thrust vector nozzle enables control of aircraft at high angles of attack as the propulsion forces are function of throttle setting only and not so strongly dependent on aircraft speed. However the fan of the engine encounters distorted flow at high AOA. An auxiliary air intake or a rotatable inlet lip is usually provided to reduce the distortion.

Agility

The ability of the aircraft to quickly change its state is defined to be the Agility of an aircraft. The agility is achieved by designing the aircraft less stable or unstable with sufficient control power to provide artificial stability and ensure controllability in maneuvers. The greater control power demands bigger tail/control surfaces, which have the penalty on weight and drag as discussed earlier. Also these aerodynamic controls are less effective at high AOA regime. The use of vectored nozzle can overcome these problems and provide greater control authority throughout the flight envelope.

Maneuverability

The maneuver performance is an important consideration in close combat. The aircraft must turn quickly to advantageous position by pointing the nose at the adversary. This requires greater turn rate. The use of thrust vectoring forces and moments can enhance greatly the low speed instantaneous turn performance and marginal improvement in sustained turn performance of the aircraft.

Reconfiguring Flight Control

The use of thrust vector control in addition to the conventional flight control surfaces opens up the possibility for optimum mix of both the aerodynamic and thrust vector control to enhance performance such as range/endurance. The redundancy in control power can be advantageously used in emergencies when a flight control surface fails. In the event of battle damage/ failure of aerodynamic controls, the remaining flight control surfaces and vector nozzle can be reconfigured to land the aircraft safely.

Air-Intake/Nozzle Integration

The air intake integration with engine control and flight control is important in order to obtain better intake recovery, lower spillage drag and buzz free safe operation of a fighter aircraft. There are different types of air intakes used depending on the maximum speed of the aircraft. The airflow into the engine is to be subsonic irrespective of the aircraft speed. Hence, in supersonic flight the flow is to be diffused to subsonic speed before it enters the engine. The air intake design and its control play a major role in obtaining the low total pressure loss (high recovery) in the supersonic flight by managing the shocks.

Supersonic Air Intake

A simple pitot intake (Fig.8) is inadequate to provide satisfactory recovery at speeds beyond 1.6 Mach. Since the total pressure decreases across a normal shock standing ahead of the intake, the pressure recovery and hence the engine thrust is reduced considerably. The shock strength and hence the total pressure loss increases exponentially as the flight Mach number increases. There are 3 types of design concepts adapted for high supersonic speed aircraft depending on where the compression takes place; (a) external compression intake (Fig.9), (b) internal compression intake (Fig.10), (c) mixed compression intake (Fig.11).

As the shock structure varies with the flight Mach number, the inlet geometry is to be controlled by integrating the flight control and propulsion control for maximum efficiency. Another important aspect is the drag due to spillage of air which is to be minimized by optimum scheduling of variable geometry/bypass door.

A typical axi-symmetric mixed compression supersonic inlet [10] is shown in Fig.12 in a normal operating configuration. The supersonic flow enters the inlet past a weak oblique shock wave and then compressed in the convergent passage until the minimum area point (throat), and become subsonic through a weak terminal normal shock. It is important to maintain the terminal normal shock downstream of the throat for stable operation. A flow disturbance from upstream or downstream may cause the normal shock to move ahead of the throat. When this occurs, the inlet unstarts and enters into an undesirable operation. In order to prevent unstart and to maintain the desired operation of the inlet, a throat area control and a bypass door downstream of throat is required. The translating centerbody shown in Fig.12 vary the throat area so that the throat Mach number can be kept above one, even if the free stream Mach number decreases. The second control input, the bypass door is controlled to dump excess air in case a disturbance causes a pressure rise at the fan
face. By dumping excess air, the pressure disturbance is prevented from pushing the normal shock forward of the throat. The overall control design goals are:

- to keep the throat Mach number and shock position as close as possible to their unstart limits to maximize efficiency.
- to keep the deviations of throat Mach number and shock position small so as to prevent unstart.
- to design a control which produces desired results while using a reasonable amount of control power.

**YF-12C Flight Propulsion Interaction**

In the late 1970’s a digital cooperative control system was flown on the NASA YF12C airplane. This system integrated the inlet control, auto-throttle, air-data and navigation functions (Fig.13) resulting in dramatic improvements in flight path control and range even though the integration was not optimized. This technology was later used on SR-71.

The airplane has two axisymmetric mixed compression inlets supplying air to two J58 engines. Each inlet has a translating spike and forward bypass doors, which are controlled by a closed loop system as a function of flight conditions and duct pressure to position the terminal normal shock wave downstream of throat.

The supersonic cruise operation at $M > 2.5$ at 70kft highlighted many new airframe-propulsion system interdisciplinary problems [3]. The results showed strong interactions between control systems; the bypass doors were as effective as the rudders in providing yawing moment. The inlet control system operation destabilized the aircraft without the directional stability augmentation system. The integration of subsystems is an effective way to take advantage of favorable interactions and to minimize unfavorable interactions. The incorporation of inlet control into lateral-directional stability augmentation was effective in increasing Dutch roll damping. The study also showed that the use propulsion system to augment flight controls resulted in reducing the take-off gross weight of a supersonic cruise aircraft design by up to 7%. In addition more precise inlet control was obtained with digital system, and inlet stability margins were reduced.

**SR-71 (Production Version of YF-12C)**

Based on the success of digital flight-propulsion control system on YF-12C the SR-71 incorporated cooperative control system which realized range improvements of 7% and eliminated occurrence of inlet unstarts.

With integrated inlet-flight control on YF-12 airplane and later on the F-15, have demonstrated increased thrust, reduced fuel consumption, increased engine life and improved aircraft performance with improvements in the range of 5 to 10% with no changes to hardware [3].

**F-15 Flight Research**

An extensive testing of flight propulsion control technologies were carried out on F-15 by NASA [11,12,13]. The F-15 aircraft has two-dimensional variable geometry external compression inlets as shown in Fig.14 [13]. Compression is accomplished through three oblique shocks and a normal shock during supersonic flight. Actuators provide independent control of the first ramp (Cow) and the third ramp. A digital control system based on the variables Mach number, angle of attack, and fan inlet total pressure controls the variable inlet geometry.

The F-15 variable inlet geometry schedules were determined from the airflow demands of engine. The information of pressure distortion levels behind the inlet was available. Engine control laws were produced with sufficient stability margins to ensure stall free engine operation at the worst levels of distortion.

Figure 15 is a conceptual block diagram of an integrated inlet control. The bypass control mode uses bypass door position to position the terminal shock wave to maximize inlet pressure recovery. Without integration, an unstart margin of approximately 5% is necessary which results in the reduction of the overall thrust minus drag of the inlet. The throat Mach number is a function of Mach, angle of attack, and angle of sideslip. The integration can provide these signals and allow the margin to be reduced to increase the performance.

The integrated inlet control mode discussed above has been implemented on the F-15 HIDE airplane. The schedules of controls are computed based on the inputs from engine and airplane. The inlet third ramp is repositioned to move the terminal shock closer to the cowl lip which reduces spillage and increases pressure recovery. The engine airflow requirement is needed to control the inlet to prevent supercritical operation, and resulting dis-
tortion. Also the cowl has some pitching moment authority on this aircraft, and hence cowl position can be optimized to minimize horizontal tail trim drag, inlet drag, and inlet recovery. The HIDEC inlet integration control mode demonstrated improvement in thrust of 10% at a Mach number of 1.9.

Nozzle Control

High performance supersonic aircraft use variable area Convergent-Divergent nozzle. The nozzle performance is defined in terms of Gross Thrust coefficient (Thrust produced by nozzle) and Net Thrust coefficient (thrust available for propulsion after deducting the drag due to the nozzle operation). Fig. 16 shows the typical difference in uninstalled \( C_{Fg} \)/ installed performance \( C_{Fn} \), ratio at transonic flight Mach number. The optimum expansion ratio for installed performance is 1.9 against the design expansion ratio of 1.55 as shown.

Installed performance considers afterbody drag induced by the nozzle external flaps and may actually dictate that the nozzle be over-expanded over a significant portion of the flight envelope.

Propulsion Controlled Aircraft

Propulsion Controlled Aircraft (PCA) is a concept where the aircraft is controlled using only the thrust forces. This is also called Throttle Only Control (TOC). This is another use of IFPC, where the throttle is used for emergency flight control for safe landing in case of failure of flight control surface or total hydraulic system failure. The history of TOC started with crash landing of DC-10 transport aircraft [15] after the loss of hydraulic systems. The pilots could manage to fly the aircraft and approach for landing successfully. The pilot used differential throttles on this multi-engined aircraft to control the aircraft, but he could not control the aircraft for final touch down. The aircraft landed on right wing tip and then right landing gear and crashed due high descent rate. In an another incident an L-1011 aircraft which had a stabilizer failure, was controlled using differential engine thrust to supplement remaining flight controls and it completed a safe landing [16]. These incidents uncovered the control power of the propulsion system, and necessitated need for integration of controls to exploit the benefits.

The aircraft with multiple engines may be controlled to a rudimentary degree with the throttles. The use of differential thrust induces yaw and the dihedral effect results in roll. Many transport airplanes exhibit nose-up pitching moments as the thrust increases that may be useful for pitch control [17]. However, the problem is that an aircraft cannot be precisely controlled by the pilot with the throttles alone due to the long time constants and couplings between dynamic modes. Even though it is possible for the pilot to fly the aircraft, it is uncertain and unsafe for demanding tasks such as landing. Exposure to these situations in training simulations may alleviate the gross misapplication of throttles, but will not eliminate the potential for a serious accident to occur [17]. The TOC, where the pilot maneuvered the airplane using only the throttles, was demonstrated over a wide range of commercial and fighter aircraft [18]. These demonstrations pointed out the maneuverability issues resulting from slow engine response and the high level of pilot workload required during landing. Previous experience on the PCA study [4] shows that the engine response time has a major impact on the ability of the pilot to handle the aircraft for a safe landing.

After recognizing the potential of control power from the propulsion system in the operation of a damaged aircraft, NASA initiated the PCA research [1] effort in the early 1990’s. A PCA system that generates appropriate engine thrust commands in response to flight-path command inputs and airplane sensor feedback parameters to control the aircraft in emergency (Fig. 17).

If the flight-control surfaces of an airplane are locked at a given position, the trim airspeed of most airplanes can only vary slightly by engine thrust. Hence changing the speed require other techniques, such as variable stabilizer control, CG control, or lowering of flaps/ landing gear, etc.. The speed needs to be reduced to an acceptable landing speed, which require nose up pitching moment. For the F-15, moving the inlets to the full-up emergency position reduces the trim speed by 20 knots.

STOVL Flight-Propulsion Control

The Short Take-Off/ Vertical Landing (STOVL) aircraft have unique operational requirements in addition to those of conventional aircraft. The first requirement is the ability of the aircraft to takeoff and climb from confined spaces. This requires the aircraft to use powered lift for the take-off and landing. Apart from this, it is required to carry out transition from aerodynamic lift to powered lift and vice-versa. Control in these modes are influenced by low speed instabilities and forces and moments associated with thrust induced effects, ground effects, hot gas inges-
tion, and engine thrust dynamics. Providing sufficient control power to overcome these problems imposes severe penalty (weight and performance) on the propulsion system because, at low speeds the control power must come from the engine in one form or the other.

The difficulty in developing STOVL propulsion system concepts is designing systems which provide the required aircraft handling qualities in powered-lift modes without much penalty on the power plant. Thus, highly coordinated flight and propulsion control systems are critical to the success of these advanced STOVL aircraft. An effective integration must optimize the favorable interactions to enhance aircraft maneuverability, flight path control, and fault tolerant systems design.

**STOVL Propulsion Concepts**

There are different supersonic STOVL propulsion concepts for STOVL aircraft. Some of them are shown in Fig.18. The schematics shown are: Remote Augmented lift system, Tandem Fan system, Deflected or Vectored Thrust and Ejector system.

**Control Authority**

Firstly, the force and moment authority needed to develop the required vehicle accelerations must be defined for each of the flight mode of STOVL aircraft. In hover, the entire control capability must come from the propulsion system, either through vectored thrust or Reaction Control System (RCS) driven by bleed-air from the engine compressor. The combined control in pitch, roll, yaw and trim is of major concern to the flight control designer. The combined requirement for control power penalizes engine to the extent of one-fourth of the thrust-to-weight ratio needed to simply hover. Other options may be considered for alleviating this substantial demand on the propulsion system for control. These include using short takeoff and prioritization of control command for each of the control axes. In the case of the later, when the aircraft is operating below maximum thrust, each individual control axis would have full authority; at maximum thrust with more than one control demanding, a proportional reduction is applied to each axis depending on the control priority. Attitude control systems which can reduce or totally eliminate bleed dependency should be the goal of any future powered-lift concept. This could be accomplished / attempted through use of differential thrust. These effectors can include thrust vectoring-thrust reversing, split deflecting, and ventral nozzles.

**Control Effect or Dynamics**

The transient and dynamic performance of thrust effectors is important to an STOVL aircraft. These effectors include ejector augmenters, remote and fan flow burners, thrust vectoring, thrust reversing and ventral nozzles. The dynamic characteristics of associated flow switching valves and bleed flow extraction are also of interest. Propulsion induced effects created by these thrust effectors have great impact on aircraft stability and control. It is required to define the force/ moment envelopes in take-off/ transition phase, thrust modulation and deflection capabilities, reaction control demand of bleed requirement and their effect on engine performance. These simulation models play an important role in systems and control analysis and overall system evaluations.

**Performance Seeking Control (PSC)**

The main objective of integration of flight control system and propulsion system is to take maximum advantage of integration and enhance the performance of both airframe and propulsion system. The interactions between the propulsion system elements and flight control system have been identified [12, 21, 22, 23, 24] by many researchers. The interactions are in both ways, i.e. from engine-to-airframe and airframe-to-engine. The propulsion system generated forces and moments affect the flight path; for example the air intake, nozzle operation, engine transients are known to affect the airframe dynamics. Similarly, the angle of attack, sideslip, maneuvers, missile firing, and accelerations affect the engine operation. For the engine to operate within its stable limits, it must operate with required stall margin to avoid excursion into unstable region. The excursion into stall region (unstable) can occur due to many factors such as engine transients, high angle of attack and sideslip of the aircraft, missile gas ingestion, etc. In order to meet these contingences, the engine is scheduled to operate with a large stall margin, which degrades the engine performance such as thrust and SFC. The integration of flight control system helps propulsion system to operate with lower stall margin and hence enhanced performance.

The Airdata system provides important input to the cockpit, flight-control system, navigation system, and propulsion system. A nose mounted laser based airdata system which could sense air turbulence several meters ahead of inlets may be able to provide advance warning that can be used by the inlet/ engine control system to transfer operation to higher stability mode. Further the integration of inlet, nozzle, engine and FCS can provide higher bene-
fits. The engine thrust improvements from F-15 HIDEC flight test programme [1] is shown in Fig. 19.

The thrust improvements in supersonic flight are not as large as those predicted for subsonic conditions as shown in the figure above, but equally significant performance improvement can be expected because of the smaller excess thrust at supersonic speeds [25]. The performance seeking control concept [26] tested on F-15 aircraft is shown in the form of a flow chart in Fig. 20.

The PSC algorithm optimizes the combined system, including the engine, nozzle, inlet, and trim drag for any of the performance objectives such as:

- Maximum thrust
- Minimum fuel consumption
- Maximum engine life at constant thrust
- Maximum thrust at constant temperature

For the PSC on F-15 HIDEC, the important constraints of the optimization are fan/ compressor stall margin, temperature limits, engine variable geometry and inlet geometry limits. The outputs of the optimization are the two inlet variables (the cowl position and the third ramp positions), the nozzle area, engine fan and compressor variables geometry vane positions, core and afterburner combustor fuel flow, fan airflow, and fan speed. These parameters are computed as trims to the current control inputs and are sent to the DEEC and inlet control systems.

The PSC was first tested on F-111E aircraft. The performance benefits demonstrated in these flight tests are shown in Fig. 21 over the flight envelope. A 7% increase in thrust at high speeds and 16% increase in supersonic dash have been demonstrated [1]. The increase in thrust or reduction in SFC is obtained by reducing the stall margin, i.e. by increasing the Engine Pressure Ratio (EPR). The EPR uptrim (higher EPR) control law is implemented in the DFCC. When the predicted AOA and AOSS are moderate the DFCC issues an EPR command to the engine to operate close to the surge line to improve the performance. The DFCC uses airframe pitch, roll and yaw rates and normal, lateral and axial accelerations to predict angle of attack and sideslip. As these predicted angles become large, the controller decreases the uptrim signal to ensure stall free engine operation.

Extended Engine Life Mode of Operation

The control system can also provide Extended Engine Life (EEL) mode that improves the engine specific fuel consumption and increases engine life by reducing turbine temperature at a given thrust. This EEL mode increases EPR and reduces turbine temperature to maintain constant thrust for a given power setting as shown in Fig. 22.

Rapid Descent Mode

In supersonic aircraft there may be requirement to rapid deceleration and descent. At supersonic speeds, engine thrust is normally maintained at or above intermediate power to avoid inlet buzz (Inlet buzz is a potentially violent pressure oscillation). An integrated control mode can help in minimizing propulsion system thrust to the lowest possible level, yet avoid strong inlet buzz. That is the engine airflow will have to be kept up well above idle values. If the aircraft has mixed compression inlets, they can be operated either unstarted or in a very low performance mode until the inlet starting Mach number is reached.

Adaptive Optimization

The Performance seeking control with many operating modes and variables involved in optimization, it is difficult to develop an a priori optimization scheme [25]. Also, such schemes must assume a nominal engine model. A better approach is to perform the optimization onboard the airplane, using many measured parameters that are already available from the control systems. The measurements can be used to update models of engine components which may vary over time.

Optimization is carried out on the combined system, including the engine, inlet, and aerodynamic trim characteristics for the desired performance parameter, using an optimization algorithm. The performance objectives could be maximum thrust, minimum fuel, maximum engine life, and maximum thrust at constant temperature. Outputs of the optimization are engine, inlet, nozzle, CG, and aerodynamic flight-control parameters. These parameters are computed as trims to the current control inputs and as such are summed with the current control positions.

The schematic of the onboard adaptive optimization is shown in Fig. 23 which is implemented on F-15.
The results of onboard real-time adaptive optimization of engine, inlet, and nozzle parameters at a Mach number of 1.9 at partial afterburning is shown in Fig. 24.

The objective is to minimize fuel flow to provide the required thrust for level flight. Predictions obtained from a full nonlinear PSC simulation show that the engine, inlet, horizontal tail, and nozzle parameters are all changed as a result of PSC. After approximately 80 iterations through the optimization, a 12% reduction in fuel flow was achieved. As seen in the figure, the engine thrust is decreased, the nozzle drag is increased and the inlet drag is decreased to hold constant net propulsive force.

A typical drag minimization using adaptive optimization is shown in Fig. 25. Here, the cowl position is varied along with stabilator in order to search for optimum trim. These optimization benefits would not be possible in a system where the optimization being performed on the engine, inlet, nozzle, and horizontal tail independently.

**Reconfigurable Control**

Gas Turbine Engines are designed with sufficient safety margins for robust operation. However, engine performance requirements may be drastically altered during abnormal flight conditions in emergency. In such situations, the conservative design of the engine control may not be in the best interest of overall aircraft safety. It may be advantageous to sacrifice the engine to save the aircraft. The NASA Aviation Safety Program has conducted resilient propulsion research aimed at developing adaptive engine control to operate the engine beyond the normal domain for emergency operations to safely land the damaged aircraft. The research studies show that the propulsion system can be used to help control and eventually land a damaged aircraft [27]. With the redundant flight control surfaces, a fighter aircraft can be reconfigured to fly with reduced number of surfaces and yet maintain control authority. An advanced aircraft with additional control effectors such as thrust vectoring, canards and variable geometry inlets possess even greater possibilities.

F-15 performed several integrated flight propulsion control demonstrations. Its digital engine controls had the capability to share information with the flight control computers and the inlet controller. This aircraft also experimented the concept of self-repairing flight control laws. In the event of loss of a stabilizer, control would not fall on another surface operating at brute force to compensate; instead the system would reconfigure the remaining flight control surfaces to enabling the airplane to continue flying with reduced capability. Further if a control retained even partial capability that too would be utilized in the reconfiguration.

**Engine Failure at Takeoff Rotation**

Another candidate application for IFPC is the loss of an engine at takeoff rotation. Current regulations require that the takeoff be completed without throttle motion. The asymmetric thrust caused by the loss of an outboard engine would be the critical case for sizing the vertical tail. An integrated control mode could be used to allow the tail size to be reduced by approximately 25 percent. This can be achieved by reducing the thrust on the opposite outboard engine, increase thrust on the inboard engines, retract the noise suppressors. This advantage may be used to reduce the High Speed Civil Transport (HSCT) weight and drag [25].

Another area of the integrated control study is the manipulation of engine control actuators such as variable stator vanes, bleed valves at different stages, custom bleed valves, and the Active Clearance Control (ACC) that are usually scheduled during the flight. It is important to study all possible options in the emergency operation of engine because the priority changes with the safety and performance considerations.

One of the important functions of the adaptive engine control is the thrust management which plays an active role in flight control. The engine can receive direct commands from the flight controller for differential thrust to utilize the pair of engines as a redundant set of flight actuators. The thrust management will also include the life/performance trade-off evaluation and optimization for the constraints specified by the flight controller [18]. The self-repairing flight control system on F-15 is shown in Fig. 26.

**Neural Network Based IFPC**

Neural network based approach is generally used for applying alternate sources of control power in the event of damage or failures. Neural networks are used to provide consistent handling qualities across flight conditions and for different aircraft configurations. The system can utilize unconventional control power allocations, along with integrated propulsion control. The neural networks are used to adapt to changes in aircraft dynamics and control allocation schemes. The Neural Network system can operate
without emergency or backup flight control mode operations, also does not require, fault detection and isolation information or explicit parameter identification.

In order to adapt to varying levels of performance under different control allocation schemes, PCA technologies can be incorporated into neural flight control architecture, called Integrated Neural Flight and Propulsion Control System (INFPCS) which uses a daisy-chain control allocation technique. This ensures that conventional flight control surfaces will be utilized under normal operating conditions and in damage or failure conditions, the system would allocate to healthy flight control surfaces and propulsion control necessary for achieving desired flight control performance.

The neural network-based approach incorporates direct adaptive control with dynamic inversion to provide consistent handling qualities without requiring gain-scheduling or explicit system identification. This architecture uses both pre-trained and on-line learning neural networks, and reference models to specify desired handling qualities. Pre-trained neural networks are used to provide estimates of aerodynamic stability and control characteristics required for model inversion. On-line learning neural networks are used to compensate for errors and adapt to changes in aircraft.

IFPC Controller Design and Partitioning

The aircraft is a system with various interacting subsystems. The aircraft flight path is concerned; the major subsystems involved are flight control and propulsion control. It is possible to treat the airframe and propulsion system as just one system and design a single controller, but it is inevitable to design a separate controller for the propulsion system and flight control system, because these two systems are usually designed and certified by two separate design houses. In the high performance aircraft, the interactions cannot be neglected without taking performance penalties and hence IFPC plays a major role. There are two approaches to design an IFPC controller. In the first approach, a controller is designed for the overall system and then it is partitioned into subsystem controllers, which is called the centralized approach. The other approach is to design the subsystem controllers first and then design another controller to achieve global objectives of the overall system, which is called the hierarchical approach.

Centralized Approach

In this approach a centralized controller is designed considering the airframe and propulsion subsystems as one integrated system, and then this centralized controller is partitioned into decentralized sub-controllers for design, development and certification purposes. A critical issue here is the choice of the control synthesis technique which ensures performance objectives of the global system. In the literature, robust controller design techniques such as $H_\infty$ and LQG/LTR have been shown to deliver centralized controllers which satisfy nominal performance and robust stability design requirements. However, the disadvantage of the above approach is that the resulting centralized controller is of very high order, and use feedback paths which are unrealistic in the context of available sensor. Also, the complex centralized controllers are difficult to certify for flight-clearance. Further, the engine manufacturers must guarantee satisfactory operation of the engine; hence a separate engine sub-controller is required for integrity and performance testing. Once the centralized design is complete, controller partitioning can be achieved by modal analysis or parametric optimization techniques. The sub-controllers can then be implemented independently with minimum degradation on performance. A systematic partitioning procedure which largely preserves the performance and robustness properties associated with the centralized controller was first proposed by S.Garg [28]. This method was applied for the VAAC Harrier aircraft IFPC designed using the method of $H_\infty$ loop-shaping.

Hierarchical Approach

In this approach the integrated aircraft system is first partitioned into various subsystems and separate sub-controllers are designed for each subsystem. A controller is then designed for the whole system, with the various closed loop subsystems being replaced by a set of equivalent actuator characteristics that define the nominal performance of subsystems. Therefore the sub-controllers must not only satisfy internal subsystem specifications, but must be designed to meet mission level performance. A major part of the design effort in this approach is spent on generating specifications for each separate sub-controller which will ensure that the overall integrated system will achieve its performance goals in the presence of interactions and model uncertainty. Hence, the generation of subsystem specifications can be thought of as a robust design problem. The objective is to design various closed loop subsystems with their maximum allowable deviation
of nominal performance such that the mission level performance is maintained.

Comparison of the Two Approaches

There are advantages and disadvantages to both of the above approaches. The disadvantage of the centralized approach is that synthesized controller will be of high order and also may use unrealistic feedback paths. The easiness of partitioning this controller is highly dependent on the level and nature of the interactions between various subsystems. While the single integrated controller provides a useful baseline for the best achievable performance, there is an inherent difficulty in finding a single performance index which completely defines the details of both the aerodynamic and propulsion control problems. This is due to the very different nature of these problems. Flight control problems typically involve the design of regulators with input shaping to meet certain flying and handling quality criteria whereas propulsion control is primarily concerned with nonlinear limit tracking and guaranteed stability margins.

The advantage of the decentralized hierarchical approach is that flight and propulsion control systems can be designed independently by the respective experts in each field. The respective agencies are accountable and take control over all aspects of the subsystems including their control laws. However deciding subsystem specifications for each to ensure that overall system performance and not just stability is maintained which is highly non-trivial.

An approach to integrated control design which combines the best aspects of the centralized and decentralized approaches has been suggested in literature. This approach consists of first designing a centralized controller considering the airframe and propulsion systems as one integrated system, and then partitioning the centralized controller into decentralized sub-controllers with required interconnections. The partitioning of high order centralized controller with lower order sub-controllers with coupling between them must ensure closed-loop performance and robustness characteristics of the centralized controller. The centralized controller considers all the subsystem interactions and provides a baseline for the best achievable performance with a fully integrated system. The partitioning results in easy to implement sub-controllers that allow for independent subsystem validation and also allow for the system nonlinearities to be considered in detail at the subsystem level. A trade-off is inevitable between sub-controller complexity and the performance achievable for the integrated system against the performance baseline established with the centralized controller.

Conclusions

- The Integrated Flight Propulsion Control (IFPC) offers unlimited possibilities to enhance the aircraft performance, safety and life.
- The interactions between the aircraft subsystems are multi-directional. The individual subsystems should perform at their best when it matters the most to the performance or safety of the aircraft. This may happen during a combat or during failure of a subsystem, where enhanced thrust is expected from the propulsion system. When flight condition demand only nominal thrust performance the propulsion system must reconfigure its control to optimize efficiency or the life of the engine. Hence, aircraft control system has a whole should adapt to the current flight conditions.
- The thrust vector control as part of IFPC can expand the flight envelope of the aircraft to improve its low speed maneuverability and agility which is unimaginable otherwise.
- The optimal control of air inlet and nozzle with flight conditions can offer substantial benefits in reducing the propulsion system associated drag especially in supersonic flight regime.
- The propulsion system can offer control power to control the aircraft in emergency situations such as partial/ complete failure of aerodynamic controls through IFPC.
- Every aircraft of future would implement IFPC in one form or the other to stay lethal and safe.

References


