Performance optimization control of supersonic variable cycle engines

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Abstract

First this paper introduces an advanced FADEC (Full Authority Digital Electric Control) for current and future jet engines. It is designed to realize not only stable thrust control, but also performance improvement, reliability enhancement, service life extension, etc. It can be built by using current micro-processor with high computational power and there exists no difficulties but reliability problem of the micro- processor.

Next, the simulation results of SFC minimization control are shown. The target engine is a supersonic, low-bypass ratio, 2-spool, combined cycle turbofan, designated as HYPR90T, which consists of a turbo engine for under Mach 3 flight and a ram engine for over Mach 3 flight. The results can then be used for performance optimization of the engine, which plays important role in the advanced FADEC.

Introduction

High performance of modern jet engines has been attained by steady efforts focused on technological improvements of individual engine components and materials. It is considered that the improvement is close to limitations and higher performance is difficult to attain without innovative new technologies. However, there is a possibility to improve performance by a control approach. Current engines are operating with sufficient safety margins, such as temperature and surge margin, considering engine to engine variations, deterioration, sensor and actuator error, distortion, etc. If important engine parameters can be identified precisely, the control can reduce these margins and improve performance by deriving the latent capabilities of the engine. An engine installing this kind of control is named an "Intelligent Engine"[1].

First, this paper introduces an advanced FADEC (Full Authority Digital Electric Control) for current and future jet engines. It is designed to realize not only stable thrust control, but also performance improvement, reliability enhancement, service life extension, etc. It should be named rather "performance management system" than "control system". To realize it, there exist no difficulties but reliability problem of micro- processor. These processors are currently manufactured for civil use or industrial use, and cannot meet the requirement for jet engine control, such as MIL specifications.

Next, the simulation results of SFC minimization control are shown. The target engine is a supersonic, low-bypass ratio, 2-spool, combined cycle turbofan, designated as HYPR90T, which consists of a turbo engine for under Mach 3 flight and a ram engine for over Mach 3 flight. The results can then be used for performance optimization of the engine, which plays important role in the advanced FADEC.

Concept of advanced FADEC

Performance seeking control (PSC)

To improve the overall performance of engine by control approach, there are two methods as shown in Fig.1.

· Gas turbine engines are operated by controllers having sufficient margins necessary for the engine-to-engine performance difference, performance deterioration, sensor/actuator errors, distortion, etc. If necessary engine parameters can be identified on-line with great accuracy, these margins can considerably be made smaller along with full extraction of the performance potentially possessed by the engine. Thus improvement of the overall performance can be expected. Supposing for example that the surge margin and turbine inlet temperature both of which are difficult to measure directly can be estimated with high accuracy, it becomes possible to allow the engine to exhibit the performance as close as to the limitation.

Meanwhile with the engines having plural control variables, degree-of-freedom is noted in generating required power. Within the restriction of the degree-of-freedom, it is possible to realize a variety of control modes corresponding to the utility. Supposing for example that the required power should be generated, it might be advantageous from a point of view of economy to select the combination of the control variables so that specific fuel consumption (SFC) will be minimized. Taking account of the engine service life, it might be advantageous to select the combination of the control variables so that the turbine inlet temperature will be made lowest.

This type of control is designated as Performance Seeking Control (PSC)[2] which can realize the operations advantageous enough to accomplish the economy, safety, service life, and environmental issues by reducing the control margin to the extremity together with selection of the control variables so that various kinds of parameters will be minimized or maximized. These parameters are supplied from an "on-line model engine" built inside the advanced FADEC as shown in Fig.2.

Condition monitoring

To fully extract the performance potentially possessed by the engine, it is important to maintain the engine in best condition. Current maintenance procedure for jet engine is adopting "on-condition maintenance procedure" which assumes existence of condition monitoring system, instead of "scheduled maintenance procedure" used before. Good quality information on health condition of the engine can extend Time Between Overhauls (TBO), minimize the number of cost consuming "open, inspect and repair" routines, and improve availability of the engine.

Fig.3 shows a concept of condition monitoring [3]. The occurrence of malfunctions causes the component performance changes and then produces changes in measured variables describing the engine operation. Using the measured data and some analytical tools, it is possible to deduce the most likely estimation on location and severe level of malfunctions. There are several analytical tools for estimation, such as Gas Path Analysis (GPA), Kalman Filter method, etc. It should be noted that this model engine is almost the same with the model engine for PSC (refer to Fig.2) described above. In fact, there is a technological convergence between control system and monitoring system.

Advanced FADEC

Configuration of an advanced FADEC proposed here is shown in Fig.4. It consists of three layers, which correspond to reliability level of hardware.

- **Layer-0 (Hardware Layer):**
  Hydro-mechanical hardware attached to the engine. Normally, actuators, valves, solenoids, etc. of this layer are controlled by commands from layer-1. In the case of trouble in layer-1, this layer can perform a minimum backup function, such as manual fuel control, freezing or actuators to fail safe positions, to operate engine safely. Reliability of this layer should be very high, more than 20,000 hours of Mean Time Between Failure (MTBF). Fuel Control Systems for current jet engine have this capability.

  Layer-1 (Basic Control Layer):
  Basic thrust control and limit control are performed. Thrust control produces stable thrust, respond to thrust lever command by pilot. Limit control keeps the engine inside safety operating region, such as rotor speed limit, compressor surge limit, temperature limit, etc., no matter what thrust command and flight condition are given. This layer is constructed by computer system based on micro-processor. Computational power may be less than layer-2, but reliability must be comparable to layer-0. FADECs for current jet engines almost correspond to this layer. However, control software of current FADEC is obtained by simply replacing the control logic of hydro-mechanical control system designed by Single Input Single Output (SISO) method. In advanced FADEC proposed here, multivariable robust control design method must be applied to fully exploit the maximum capability of the engine.

- **Layer-2 (Performance Management Layer):**
  This layer performs performance seeking control and condition monitoring described above. Other than these, included are (i) redundancy control which detect, isolate and accommodate sensor

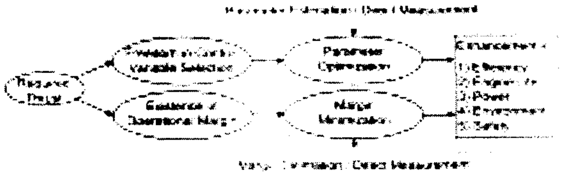

Fig.1 Performance improvement approach

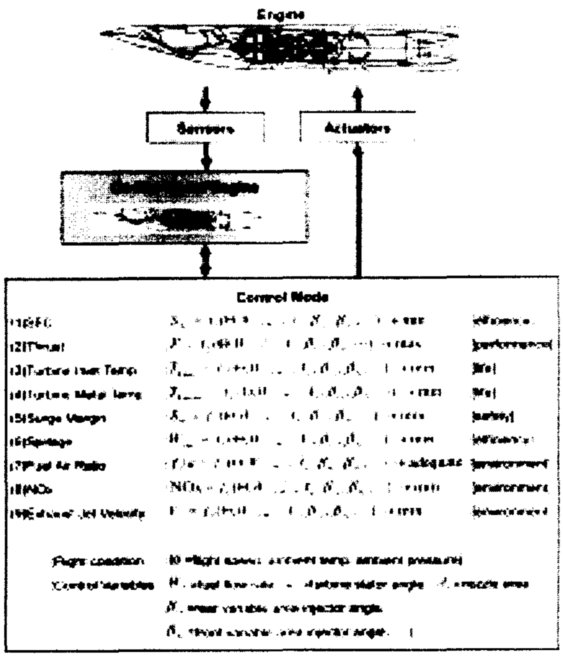

Fig.2 Concept of performance seeking control

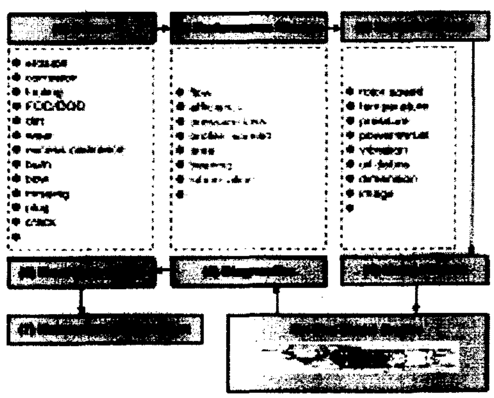

Fig.3 Concept of condition monitoring

failure, (ii) integration with flight control, (iii) mass memory and communication for on-line and off-line condition monitoring by ground support system. Most of functions included in this layer are performed by communication with the "on-line model engine", which is a high fidelity dynamic model of actual engine and tuned on-line reflecting engine performance changes. It is possible to build this layer using a modern micro-processor with high computational power. Since its reliability is lower than layer-1's, it is recommended that the hardware is separated from the layer-1.

Currently, there is a trend toward a distributed control[4] of jet engine, where intelligent sensors and intelligent actuators along with control processors are linked on a single information bus like Local Area Network (LAN), aiming at weight/cabling reduction, sensor/actuator generalization, maintenance simplification, etc. This configuration is suitable for the advanced FADEC.

On-line model engine

The advanced FADEC installs "on-line model engine" inside and constitutes adaptive Model-Based Control, where optimization controls are performed adaptively corresponding to its mission and flight condition.

The model engine must have following characteristics;

- It is a high fidelity dynamic model of actual engine over full flight envelops and tuned on-line reflecting engine performance changes.
- It can recognize component performance changes and can estimate immeasurable variables. This function is important for performance seeking control and condition monitoring.
- It runs faster than real-time.
- It can be realized by current micro-processors technologies, considering computational speed, computational precision, memory capacity, weight, size, power consumption, etc.).

Such an on-line model engine can be realized by Constant Gain Extended Kalman Filter (CGEKF)[5] shown in Fig.5. Most of the computation in CGEKF is a nonlinear dynamic simulation of jet engine and the rest is a computation of the so-called innovation process where tuning parameters are changed so that the differences between measured values and estimated values are eliminated. Faster-than-real-time simulation of jet engine as shown in Fig.6 can be realized by today's micro-processors technologies.

Performance optimization of variable cycle engine

Variable cycle engine

The target engine is a supersonic, low-bypass ratio, 2-spool, combined cycle turbofan, designated as

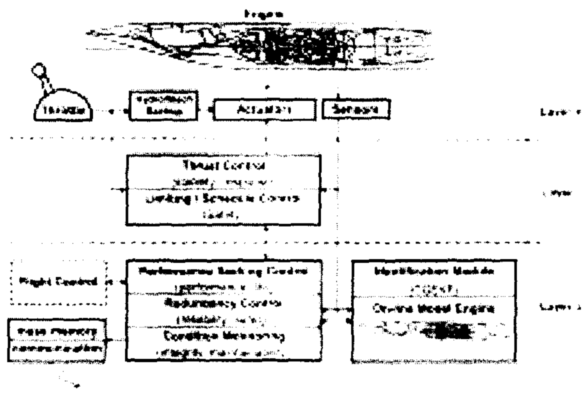

Fig.4 Configuration of advanced FADEC

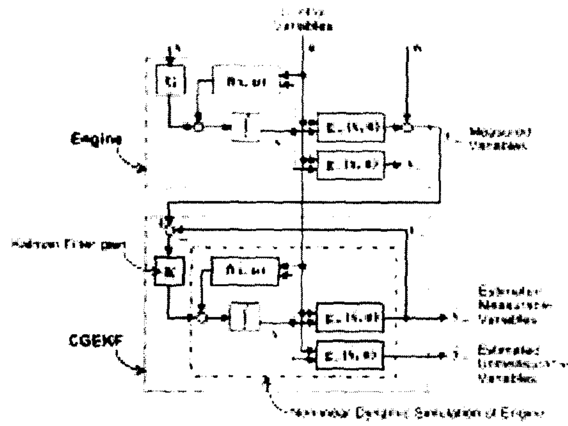

Fig.5 Constant Gain Extended Kalman Filter (CGEKF)

HYPR90T, which consists of a turbo engine for under Mach 3 flight and a ram engine for over Mach 3 flight. It was built in "R&D of Super/Hypersonic Transport Propulsion System (HYPR)" program[6]. HYPR90T incorporates six control variables; (i) fuel flow rate (W_f), (ii) HP compressor stator angle (ξ_c), (iii) rear bypass injector area (β_{rv}), (iv) LP turbine nozzle angle (ξ_t), (v) exhaust nozzle throat area (A_n), and (vi) exhaust nozzle exit area (A_e).

First, a dynamic simulation of HYPR90T turbo engine is developed. Then, an optimization control for SFC reduction is designed and evaluated by closed-loop performance test by using the simulation. Fig.6 shows the simulation block diagram of HYPR90T turbo engine. Note that the convergent-divergent exhaust nozzle is regarded as an ideal nozzle where nozzle exit area is determined by nozzle throat area so as to perform ideal expansion.

Performance optimization of variable cycle engine

Fig.7 shows closed-loop test results of SFC minimization control at flight Mach number 2.5. After minimization control is engaged at time 0[s], controller set W_f so as to maintain F, and is closing exhaust nozzle area A_n to its minimum so as to reduce S_m, and is opening turbine stator angle ξ_t so as not to exceed N_1 limit. Then SFC is reduced approximately 10%. Fig.8 shows closed-loop test results of SFC minimization control at flight Mach number 0.95. Controller set A_n, ξ_t and ξ_c so as to reduce SFC within the limit of N_1. No significant SFC reduction is observed. It's only approximately 0.68%.

Fig.9 shows effect of efficiency deterioration on engine performance for normal control and SFC minimization control, at flight Mach 0.95 and fixed thrust. For simplicity, it is assumed that the decreases of efficiencies $-\eta$ [%] are same in each engine components such as fan, compressor, turbines, and combustor. In the SFC minimization control case, SFC can be decreased approximately 0.2% at the point η = 1%, compared to the normal control case. Exhaust nozzle area A_n is controlled so as to keep N1 on the boundary of speed limit. For both control cases, the difference in EGT is large, but the difference in T_4 is small.

Remarks

It is noted that optimum performance is obtained, in many case, on the boundary of operational limits, such as T_4 limit, N_1 limit, S_m limit, etc. This means that performance optimization can be realized by a conventional feedback controller which moves operating point to boundary. However, optimum operation point is not on the boundaries in general, and a complex controller, which searches optimum point numerically by using optimization procedure like steepest decent method, is necessary. This can be realized by using the "on-line model engine".

Conclusion

The advanced FADEC introduced here aims at not only stable thrust control, but also performance improvement, reliability enhancement, service life extension and environment acceptability increase.

Future aircraft engine such as supersonic engine, ultra high bypass ratio subsonic engine and engine for powered lift aircraft, highly depends on capability of control system. The advanced FADEC developed here can be applied flexibly to such future engines. Also it is applicable to many gas turbines for power generation, industrial use, ships and vehicles.

References

1) Timothy, J.L., "Future Aircraft Jet Engines will Think for Themselves", ASME International, Global Gas Turbine News, Vol.42: 2002, No.2, pp4-5, 2002.
2) Orme, J.S. and Schkolnik, G.S., "Flight Assessment of the Onboard Propulsion System Model for the Performance Seeking Control Algorithm on an F-15 Aircraft", AIAA paper 95-2361, 1995.
3) Consumi, M. and d'Agostino, L., "A Statistical Inference Approach to Gas Path Analysis of a Turbofan", AIAA 98-3551, 1998.
4) Schley, W.R., "Distributed Flight Control & Propulsion Control Implementation Issues & Lessons Learned", ASME paper 98-GT-3, 1998.

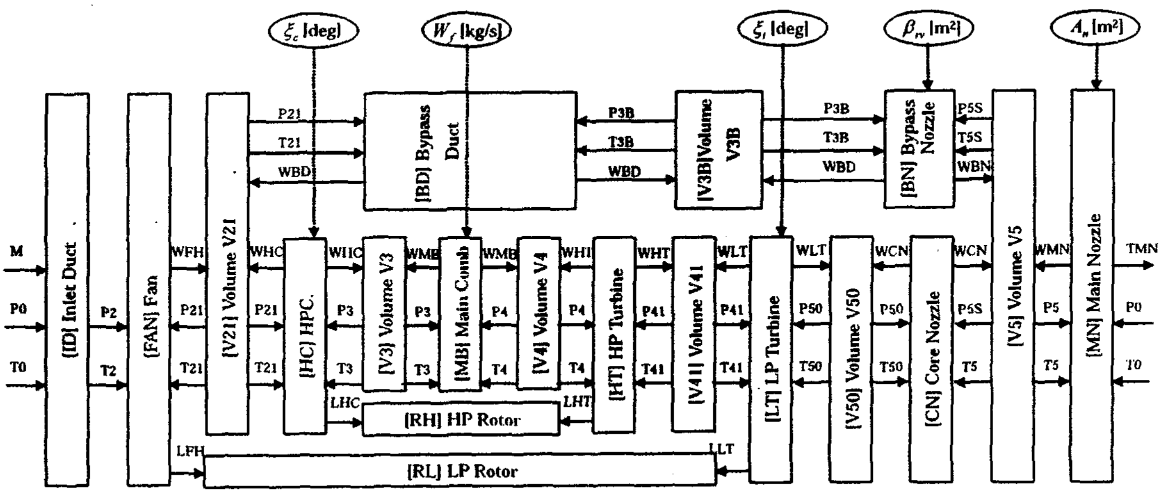

Fig. 6 Simulation block diagram of HYPR90T variable cycle engine

5) Sugiyama, N., "System Identification of Jet Engines", Transaction of ASME, Journal of Engineering for Gas Turbines and Power, Vol.122, pp19-26, Jan 2000.
6) Miyagi, H., et al, "Combined Cycle Engine Research in Japanese HYPR program", AIAA paper 98-3278, 1998.

Appendix

Nomenclature

A_n = nozzle throat area [m^2]
F = net thrust [N]
M = flight Mach number [-]
N_1 = fan rotor speed [%]
N_2 = core rotor speed [%]
P = pressure [Pa]
S_m = fan surge margin [-]
T = temperature [K]
T_4 = turbine inlet temperature [K]
T_{4metal} = turbine inlet metal temperature [K]
W_f = fuel flow rate [kg/s]
β_{fv} = front bypass injector area [m^2]
β_{rv} = rear bypass injector area [m^2]
Θ = flight condition (flight speed, ambient temperature, ambient pressure)
ξ_c = HP compressor stator angle [deg]
ξ_t = LP turbine nozzle angle [deg]

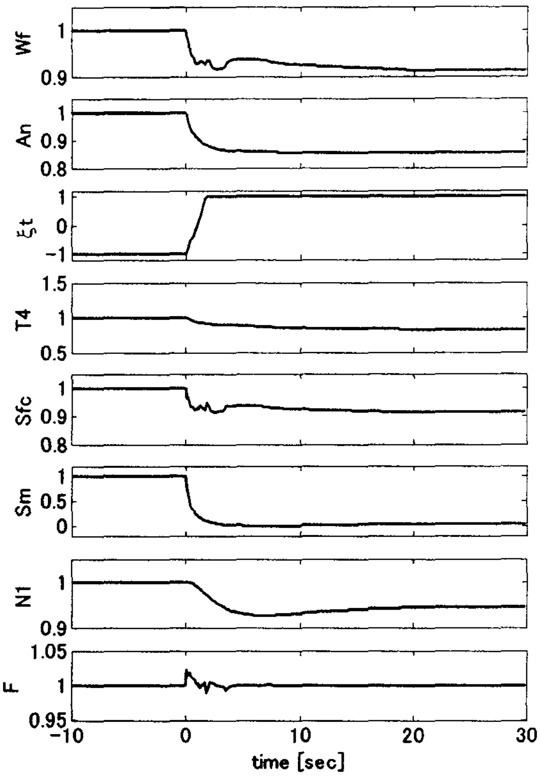

Fig. 7 SFC minimization Control at Mach 2.5

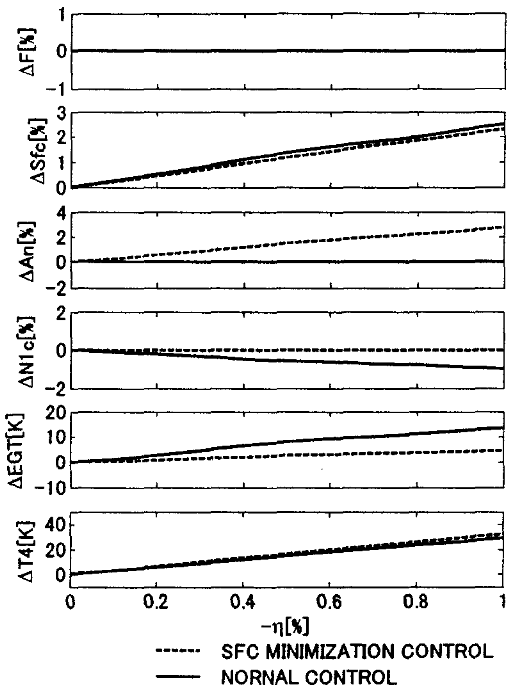

Fig. 9 Performance Comparison vs. efficiency deterioration between normal and SFC minimization control at Mach 0.95

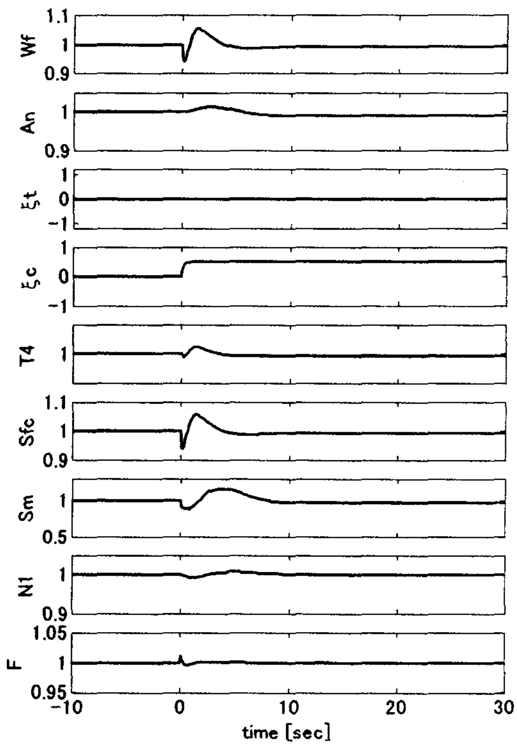

Fig. 8 SFC minimization Control at Mach 0.95