A TURBOFAN CONTROL SYSTEM USING A NONLINEAR PRECOMPENSATOR AND A MODEL-FOLLOWING RICCATI-FEEDBACK

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Abstract

An interesting control-system concept for turbofan engines was published by Froriep, Joos and Kreisselmeier (1978). The system structure uses an open loop compensator combined with a Riccati-feedback. In application to a linear engine model the optimal control gains could be obtained from an explicit formula. This paper will discuss the advanced application of this structure in a nonlinear simulation and optimization process. After deriving the specifications of the whole control system from the demands of engine operation the structure of the control system can be designed, and a cost functional can be defined. In successive optimizations the parameters of the control are then calculated using a numeric optimization technique. The results of the optimization are validated by discussing simulated time histories.

Introduction

The demands on aircraft engines are increasing continually. The performance has to be improved, the fuel consumption has to be reduced, maintenance has to be simplified and the engine has to be more reliable. This cannot be reached only by improving the components of the engine. The control system also has to get more sophisticated. To satisfy these requirements, modern control devices use digital calculators with more complex control laws and expanded functions. The design of turbofan engine control structures is based on the requirements of the Federal Aviation Agency, which are published in the Federal Aviation Rules, Part 33. Two general demands are made there. The first is, that design and construction of the engine and its control unit must enable an increase from minimum to takeoff power with maximum bleed air and power extraction to be permitted, without leaving the safe operation area of the engine whenever the power control lever is moved from the minimum to the maximum position in not more than one second. Furtheron an increase from idle position to 95 percent of the rated takeoff power must be possible within five seconds. These specifications can be expressed as a cost functional to optimize the parameters of a given control structure in a computer simulation of the engine.

The Turbofan Engine Process

A turbofan engine is a two spool gas turbine. After passing the low-pressure compressor, the so called fan, the airflow is divided into one part passing the rest of the engine and one bypassing it. The ratio of the two airflows is in the range of about 0.9 up to 6.5.

Figure 1 shows the relation between the main controller input, i. e. the supplied fuel-flow, and the speed of the high-pressure rotor in steady-state, together with the limits of the safe operation area of the engine during acceleration and deceleration. The most important task of the controller is to keep the engine state inside this area.

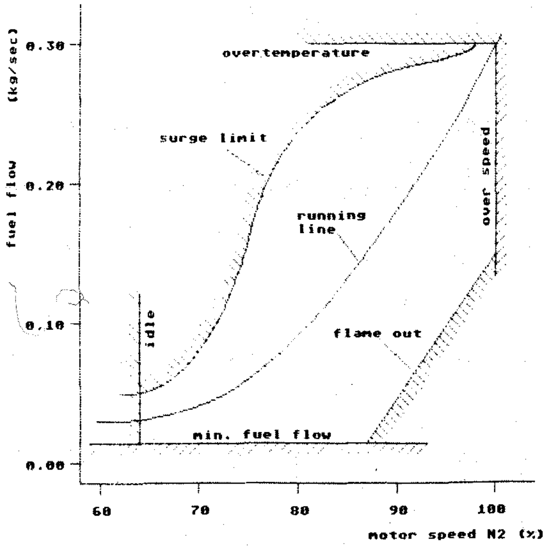


figure 1: Safe Operating Area of a Turbo-Engine

Six limits of operation have to be observed:

1. the idle speed, which must be at a safe margin above the self sustain speed, which is the lowest speed the engine can work at without external power,

2. the maximum allowable rotor speed (overspeed limit),

3. the minimum fuel flow permitted for correct operation of the fuel injection system,

4. the maximum allowable temperature at the high-pressure turbine inlet (overtemperature limit),

5. the minimum fuel-to-air ratio needed for combustion (flame-out limit),

6. the surge-limit (stall line), which represents the maximum angle of attack at the compressor vanes.

Especially the last limitation causes major problems for engine operation. Most engine-types have to bleed air from the high-pressure compressor during acceleration and even in low speed steady-state operation to guarantee safe operation. The surge line also limits the additional fuel flow needed for acceleration. So, to increase thrust as fast as possible the engine has to operate close to this line.

A Linear Multivariable Control Structure From Literature

Froriep, Joos and Kreisselmeier (1978) proposed a turbofan engine control structure based on an optimal linear open loop compensator combined with a Riccati-feedback. In our opinion this appears to be a concept of great promise for future designs. For that reason it has been used as starting-point of our own investigations.

The control structure from this literature is shown in figure 2. The design has been divided into two steps:

- The design of a precompensator by an optimization method to realize the demanded time response,

- The Riccati design to achieve sensitivity reduction.

The precompensator designed in the first step is a state-variable filter given by

$$\underline{\dot{x}} = \underline{A}\ \underline{x} + \underline{b}u^*$$

$$\underline{u}_N = \underline{K}\ \underline{x}$$

where u^* is the power lever input, and $\underline{u}_N$ is the open loop control generated. The turbofan engine with nominal parameters is given by a set of linear state-equations in this literature. Thus the optimal open loop compensator can be obtained by minimizing a given algebraic performance index using an explicit formula for the calculation of the parameters to be optimized. In this design concept the matrix $\underline{K}$ has been chosen as subject to optimization, whereas the poles of the precompensator have been chosen to be the engines poles. The input matrix $\underline{b}$ was calculated for a steady-state gain of one for $\underline{x} / u^*$.

If the open loop control is applied to a plant in real world, the actual behaviour is perturbed by engine parameter variations. Therefore, a Riccati-feedback has been proposed to reduce parameter sensitivity. The gains of the Riccati-feedback also were obtained from an explicit formula by minimizing a cost functional.

Nonlinear Design of the Model-following Control System

In order to obtain a structurized design process and a properly organized modular structure of software the system is splitted into several parts, which can be designed successively. So the design process can be divided into the following steps:

1. Definition of the cost functionals

2. Design of the precompensator
   2.1. Layout of the precompensator structure
   2.2 Optimization of the steady-state gain
   2.3 Optimization of the small signal dynamic
   2.4 Optimization of the large signal dynamic

3. Design of the model-following control
   3.1 Layout of the control-structure
   3.2 Optimization of the parameters

The turbofan simulation and optimization program used for this purpose is based on the program DYNGEN (Daniele, Sellers, 1975). Figure 3 shows the structure of the advanced version of this program, developed at the TU Braunschweig (Sölter, 1984), which uses the minimum searching program EXTREM (Jacob, 1982).

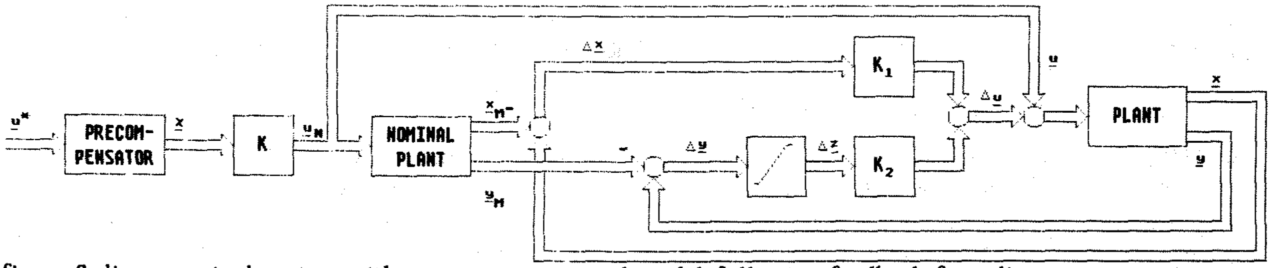


figure 2: linear control system with precompensator and model-following feedback from literature

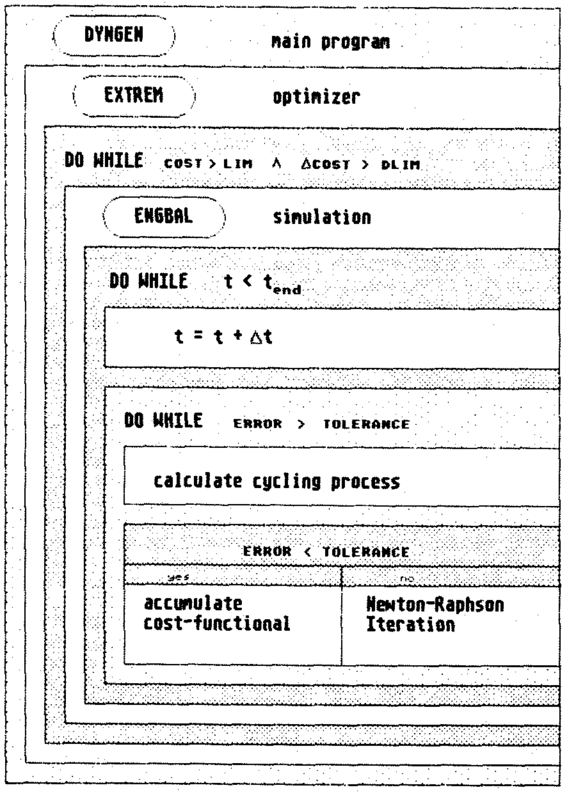


figure 3: Structure of the Simulation-Program

Cost Functionals

Two different cost functionals are needed for optimization. One optimization criterion must be defined for computing the optimal combination of fuel flow and nozzle area in steady-state operation, and another must be used for the optimization of the dynamic part of the precompensator and the model-following control.

The optimal steady-state characteristic of the controller can be derived from two operational demands. During full power operation, either maximum thrust or minimum thrust-specific fuel flow is required at a given rotor speed. In idle operation thrust and absolute fuel flow should be as small as possible. Therefore the specific fuel flow has been chosen as optimization criterion to be minimized at high rotor speeds. This also meets the demand for maximum thrust in most cases. In the range of low rotor speeds the absolute fuel flow is minimized for each rotor speed.

The cost functional for the optimization of acceleration and deceleration is a numerical expression of the specifications given by the Federal Aviation Agency as mentioned in the introduction. The explicit formula is:

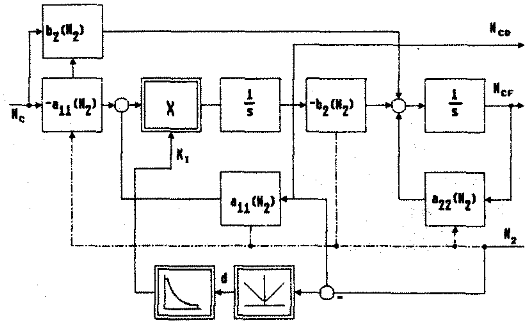
$$
\begin{aligned}
G = \; & Q_1 t \, (N_c - N_2)^2 \\
& + \max(0,\, Q_2 (N_c - N_2)^2 (t - 4)) \\
& + \max(0,\, Q_3 (ZC - 0.95)) \\
& + \max(0,\, Q_3 (ZF - 0.95)) \\
& + \max(0,\, Q_4 (T_4 - 1403.)),
\end{aligned}
$$

where Q_1, Q_2, Q_3, and Q_4 are weighting factors, T_4 is the turbine-inlet temperature, and ZC and ZF are the stall margins of the fan and of the high-pressure compressor. One of the values of ZC or ZF becomes one, when the surge limit is reached. The first term of this formula is a simple time weighted quadratic cost index. Although its weight has been chosen quite small, it ensures, that the calculated optimum is the fastest possible response. The second term increases the cost functional, if the desired rotor speed is not reached after four seconds. The other terms increase the cost functional, if the engine gets too close to one of the operation limits. If the engine overshoots the stall limit, the simulation is stopped, and the cost functional is set to a very high value. During normal operation, however, the optimization program tries to find a compromise between providing a safe stall margin and speeding up the time response.

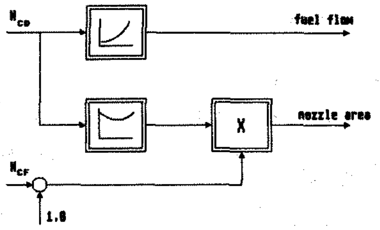
Structure of the open loop control

The main control variable of a turbofan engine is the speed of the high-pressure rotor N_2, called rotor speed in the following chapters. The rotor speed is normalized by takeoff rotor speed to values between 0.0 and 1.0.

The structure of the open loop control, as shown in figure 5 consists of two modules: a state-variable filter, that computes a delayed desired rotor speed n_{cd} and a transient nozzle correction factor N_{cf} from the commanded rotor speed N_c, and a steady-state gain map, that calculates the demanded fuel flow nad nozzle area from N_{cd} and N_{cf}. This allows to split the optimization into one part for steady-state operation and one part for transient states. The results of optimization of the precompensation have been discussed earlier.



module 1: adjusted state-variable filter



module 2: steady-state gain map

figure 5: Structure of the Nonlinear Open-Loop Compensator

Summarizing, the optimized precompensation meets the demands made on speed and safe operation as long as the parameters of the process don't differ from those, used to optimize the precompensator.

Design of the Model following Control

In case of parameter variation of the process or disturbance, however, the open loop control will not work properly. Therefore a closed loop control has to be added. Traditionally a single loop control for the high-pressure-rotor speed N_2 is used for this objective. In improved control systems using multi-variable-control, set values for the supplementary control-variables have to be supplied, because they have non-zero steady state values. This is done by using a model-following control concept.

Desired Function of the following control

The task of the closed-loop model-following control is to compensate parameter deviations of the engine and the effect ofexternal disturbances. A turbo jet-process can be disturbed by the following effects:

- non-symmetric airflow because of
    - side-wind,
    - fast-flight-maneuvres
    - gun-smoke
- varying demands of electric and hydraulic power by the energy-systems of the plane
- varying demands of bleed-air by the air-condition system of the plane

The process parameters, that may vary, are the efficiencies and pressure ratios of the compressors, the combuster and the turbines. Whereas the parameters change their values very slowly, the disturbances may occur fast and suddenly. So the demands on the dynamic of the controller are given by these disturbances.

As the open loop control commands the maximum fuel flow, which is permitted for safe operation, in order to accelerate the engine as fast as possible, the model-following Riccati feedback must not supply additional fuel to compensate disturbances or parameter deviations. On the contrary, in this case the feedback control has to reduce the increase of fuel flow during an acceleration in order to avoid a violation of the stall limit. So, the task of the model-following feedback is not, to maintain the nominal performance in spite of disturbances, but to guarantee safe operation under all circumstances. Because of that reason, the weighting factors Q_3 and Q_4 of the cost-functional have to be increased for the optimization of the feedback gains.

Design of the Model Following Control

In the linear model-following control concept from literature the nominal turbofan process was used as reference-model. In nonlinear application a more complex model has to be used. Nonlinear real-time simulations of turbo-engines generally are programmed as state-variable models with variable coefficients. These coefficients depend on the operating point and must be read from maps (Klotz,1987). These programs are developed for medium-scale computers. A real-time capability cannot be obtained with microcomputers as used in state-of-the-art engine controls, considering, that about 80 percent of the computation time are consumed by memory checks and CPU-tests etc. .

Because of this reason the reference model must be simplified. Most of the computation-time is consumed by the numeric integration of the state-equations of the engine. So, if the dynamic simulation is replaced by a set of maps, containing the steady-state relations of the nominal process, the computation time can be reduced. This model, however, neglects the time-constants of the process and would cause large control deviations during transients. As speeding up the process is not realistic and, therefore, is not desired, a certain margin of control deviations has to be permitted, without causing a controller output.

For that reason dead-zones have to be introduced into the feedbacks for each control-variable, except the high-pressure-rotor speed N_2, whose set value is given by the N_{CD}-signal of the precompensator. The upper limits of these dead-zones are the acceleration lines of the nominal process. Only, if a control-variable violates this limitation, the corresponding feedback-lane generates a controller output to conteract this overshoot. Figure 6 shows the dead-zone for the fan-speed N_1. The pressure at the compressor-exit and the fan-speed are delayed by the dynamic of the rotors. So, if the set values of this control-variables is generated from maps, whose input is the commanded fuel flow, the dead-zones for this feedback-lanes has to be very large. This also means a lack of information for the controller.

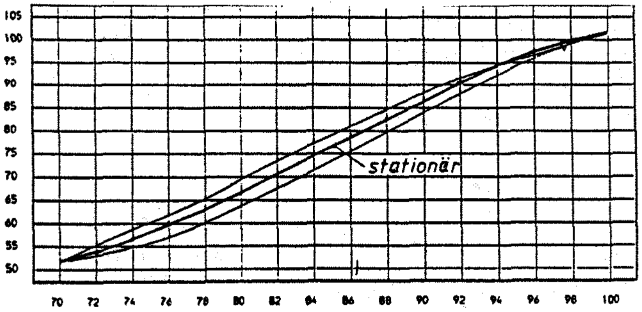


figure 7: dead-zone of the fan-speed N_1 feedback lane

In order to improve the generation of set values for these control-variables, the time lag needed here is "borrowed" from the process. As the rotor speed N_2 is taken as map-input signal, the dead-zones can be shrinked substantially. The structure of the control derived from this idea is shown in figure 7. The main control-variable N_2 is compared with N_{CD} , the delayed set value . This feedback-lane includes an integral part to achieve steady-state accuracy. The turbine-inlet temperature T_4 , which changes very fast according to the fuel flow is compared with a set value, generated with the input signal N_{CD}, which also generates the fuel flow, commanded by the precompensator. the set values of the other control-variables are generated by

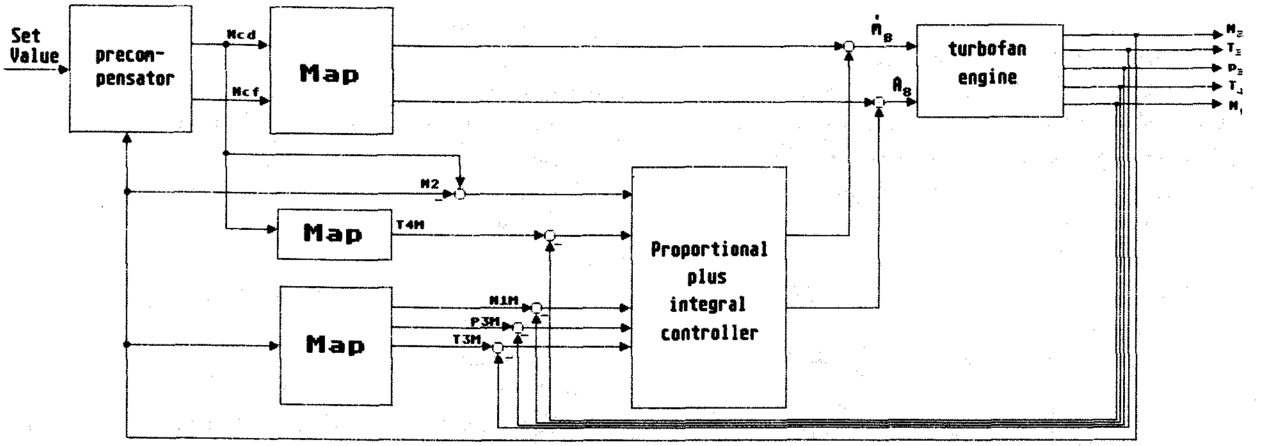


figure 7: structure of the control structure including the Riccati-feedback with steady-state-model

maps, using the rotor speed N_2 as input signal. Thus the compressor exit temperature and pressure, whose actual values, related to the actual rotor speed N_2 give the best available information about the stall margin , are interpreted as good as possible.

This control structure has been optimized for several disturbances.
figure 8 gives an example of an acceleration from idle to full power, while the engine is disturbed by an additional power extraction. Input signals are a jump of the commanded rotor speed N_C from 70 percent to 100 percent and a jump of the power extraction from zero to 50 kW at the same time.

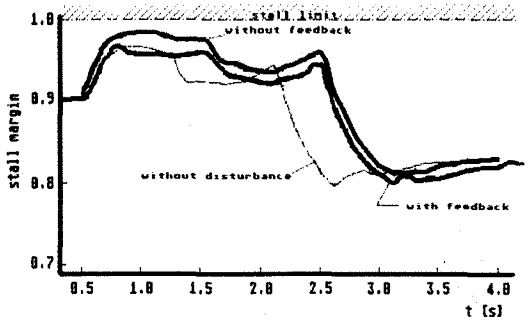


figure 8: Acceleration from Idle to Full Power with Power Extraction

The transient response of the stall margin using an additional feedback-control shows a much less critical value compared with the open loop control only. Instead, there is no deterioration of the stall margin compared with the nominal process.

Figure 9 shows the transient response of the stall margin of the fan. Input signal is a sudden disturbance of the inlet air-flow. Disturbances like these cannot be compensated by control structures as discussed above, so that in unfavourable situations the stall limit may be violated. To avoid a damage of the engine in this case, either the control has to be able to recover the engine to normal operation, or it must get additional information from the air-data-computer of the plane to avoid critical operation.

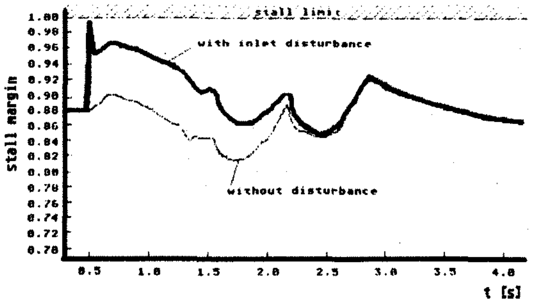


figure 9: Response of the Stall Margin of the Fan with Disturbance of the Inlet Airflow during an Acceleration

Conclusion

A model-following Riccati-feedback combined with a nonlinear precompensator has been designed, based on a linear concept from literature. After the application of the nonlinear precompensator to a nonlinear simulation program and optimizing this open loop control the model-following feedback has been added. Considering the limitations of computation time, the reference model has been reduced to a set of maps, containing the steady state values of the control-variables of the nominal process. In order to regard the dynamic of the process, some of this maps use the high-pressure rotor speed N_2 as input signal. The results of the optimization of the parameters of the controller show, that this concept meets the demands , made on speed and safe operation even, if substantial disturbances occur. Some disturbances, however, cannot be compensated by controllers without additional information. For that reason , the interchange of information between engine control-device and air-data-computer will have to be improved in the future.

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