MULTIVARIABLE NYQUEST ARRAY METHOD WITH APPLICATION TO TURBOFAN ENGINE CONTROL

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SUMMARY

Recent extensions to the multivariable Nyquist array (MNA) method are used to design a feedback control system for the General Electric-NASA Quiet Clean Shorthaul Experimental Engine (QCSEE). The results of this design are compared with those obtained from the deployment of the General Electric control system design on a full scale non-linear, real-time digital simulation. The results of this research program clearly demonstrate the utility of the MNA synthesis procedures for highly non-linear sophisticated design applications.

The QCSEE turbofan engine was developed by the General Electric Corporation under contract to the NASA Lewis Research Center during the period 1974-1978. The design incorporates performance and structural characteristics unlike those in any engine in production today and includes

1. An extremely high by-pass ratio and a high throat Mach number inlet for noise suppression

2. Reversible pitch fan blades for rapid thrust response (0.8 seconds from approach to full power)

3. Geared turbine/fan combinations for low fan speeds with a high thrust rating

4. Digital electronic engine contols

5. Extensive use of composites for drag reduction and weight considerations

To incorporate all five characteristics into a single propulsion system represents a significant breakthrough in turbofan engine technology. During 1978-1979, the QCSEE engine was successfully tested at the NASA Lewis test facility.

During this period of development and testing of the QCSEE engine, NASA developed a highly non-linear accurate real-time digital simulation of the engine at sea-level static conditions. This non-linear model was used in extensive tests at the NASA Ames in-flight simulator facility for test pilot evaluations of integrated engine airframe combinations [1].

Using the non-linear simulation, a set of transfer function matrices were generated for each of five power lever settings covering the range from approach power to full power, i.e., 62.5% to 100%. The method used to obtain the linear models is identical to that used in the F/100 study. Step response comparison of the linear models with the non-linear QCSEE simulation validated the models at each operating point.

For the QCSEE engine, there are three manipulated variables (inputs): fuel flow, nozzle area, and fan blade pitch angle. The measurable outputs for transfer function evaluation were selected to be: fan speed, inlet duct pressure (P_{12}), and combustor exit pressure (P_4). Inlet duct pressure control provides an indirect control over inlet Mach number for noise suppression while combustor exit pressure control provides a control of engine thrust response.

With the inputs and manipulated outputs identified above, an extensive control synthesis program was executed using the multivariable Nyquist array (MNA) method [2,3,4] and the recent extensions to multivariable Bode diagrams (MBD) and Nichols charts (MNC) [5,6,7]. The QCSEE design was initially performed holding nozzle area full open with fixed fan blade pitch angle at a power setting of 62.5% of full power. The control design was then evaluated at other power settings and tested in the non-linear simulation to evaluate engine performance during a power slam from 62.5% to full power (100%). Non-linear simulation transients were then compared with the full scale General Electric control time response.

The General Electric control design is based upon a series of single input, single output design evaluations with loop interactions accounted for qualitatively rather than quantitatively [8]. In the actual implementation of this control, the manipulated input variables are scheduled according to engine operating environment. In a power slam mode fuel flow is the only variable input over the 62.5% to 80% power range. At 80% power, fan pitch angle is activated and a two input situation is in operation. At the power level of 90% exit nozzle area is activated and a three input situation arises until full power is achieved. All MNA design simulations were compared with time responses resulting from this GE control.

The next phase of the MNA design program used fuel flow and fan pitch angle as inputs with fan speed and combustor exit pressure as the measured outputs. Nozzle area was again held to a fixed open position. Using the MNA method with the Bode and Nichols options, control systems were synthesized for the two input, two output models. It was established that a fixed control configuration could be used over the power lever range previously indicated. This control unit was then applied to the non-linear simulation and compared with the GE control responses. The significant result established at this point was that fan pitch angle (and fuel flow) can be used effectively at low power settings without violating the physical constraints. It provides for a rapid thrust response with a significant lower expenditure of total fuel consumption.

The results of the two input, two output case above were extended to the three input-three output system with nozzle area as the third input. This input variable is used to provide additional control over inlet Mach number with inlet duct pressure as the third output variable. System dominance was easily obtained at each power setting with closed loop system performance designed using the multivariable Bode diagrams. Non-linear simulation results of the MNA control are compared with those obtained from the GE control. A representative comparison is provided in the accompanying figures.

The dashed curve in each of the figures represents the time response of the non-linear simulation to the General Electric control under a step power demand from 62.5% of full power to 100% full power. The solid curves represent the corresponding results using the control design obtained from the multivariable Nyquist array method.

The MNA design was obtained through the following procedure:

Step 1. Determine linear state space models and system transfer functions about the steady state operating points of the non-linear simulation with the GE control and related control constraints disengaged.

Step 2. Using [7] obtain diagonal dominance. (Nominally 2 CPU minutes on a PDP 11/70)

Step 3. Evaluate performance in each control loop using [6].

Step 4. Insert MNA control into non-linear simulation to evaluate time responses.

Step 5. Overlay GE and MNA control responses.

In addition to the control design for the QCSEE engine the MNA method has also been successfully applied to the F 100 turbofan engine [4].

REFERENCES

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3. Leininger, G. G., "Diagonal Dominance for Multivariable Nyquist Array Method Using Function Minimization," Automatica, May 1979.

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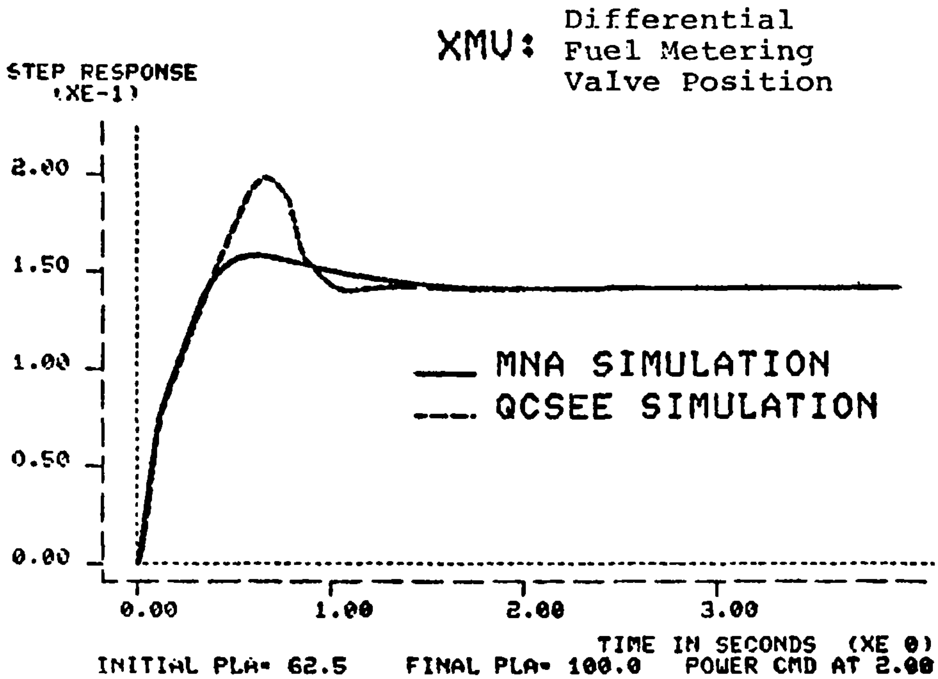
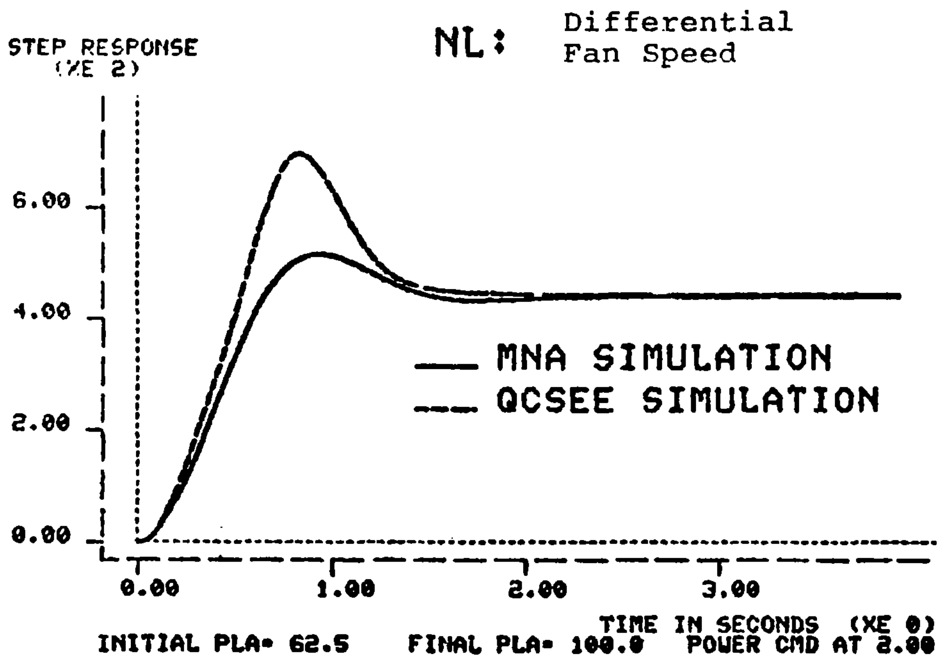
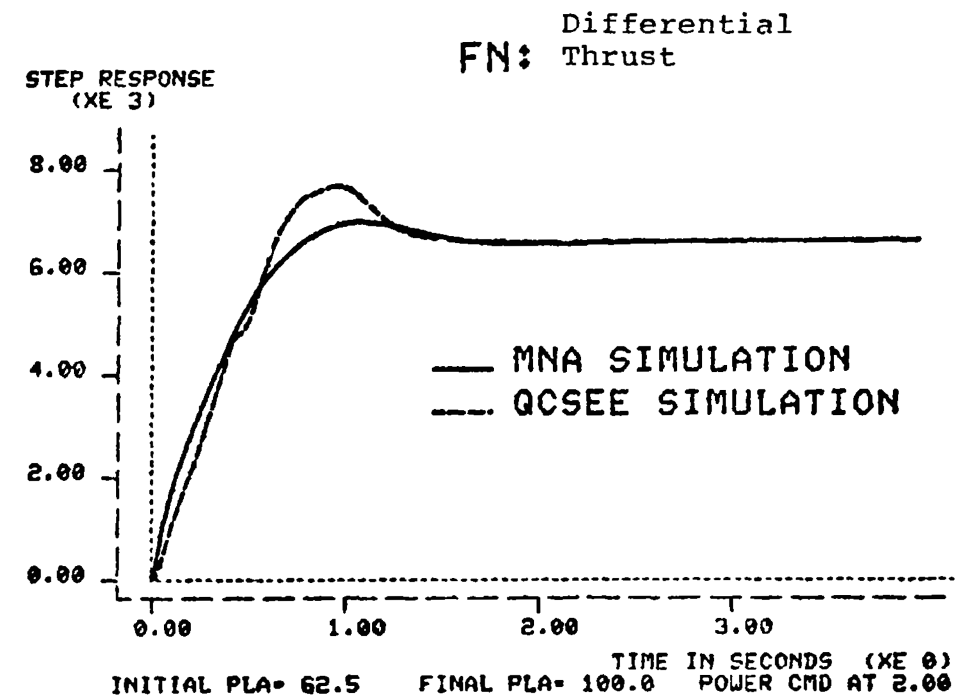
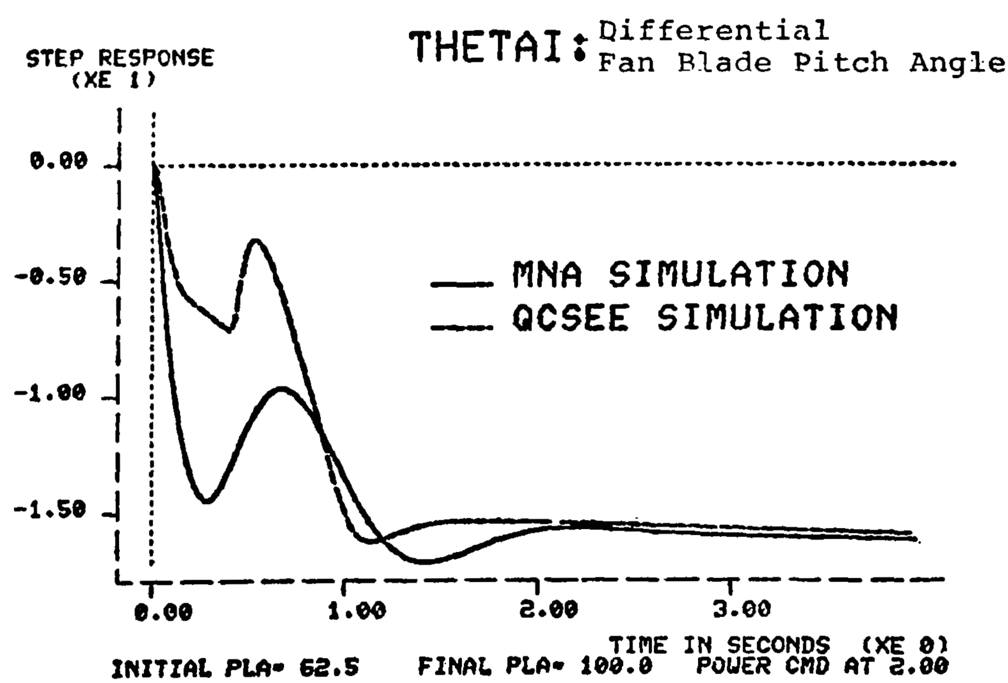

XMU: Differential Fuel Metering Valve Position
STEP RESPONSE
(XE-1)
2.00
1.50
1.00
0.50
0.00
MNA SIMULATION
QCSEE SIMULATION
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
INITIAL PLA= 62.5 FINAL PLA= 100.0 POWER CMD AT 2.00


NL: Differential Fan Speed
STEP RESPONSE
(XE 2)
6.00
4.00
2.00
0.00
MNA SIMULATION
QCSEE SIMULATION
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
INITIAL PLA= 62.5 FINAL PLA= 100.0 POWER CMD AT 2.00


FN: Differential Thrust
STEP RESPONSE (XE 3)
8.00
6.00
4.00
2.00
0.00
MNA SIMULATION
QCSEE SIMULATION
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
INITIAL PLA= 62.5 FINAL PLA= 100.0 POWER CMD AT 2.00


THETAI: Differential Fan Blade Pitch Angle
STEP RESPONSE (XE 1)
0.00
-0.50
-1.00
-1.50
MNA SIMULATION
QCSEE SIMULATION
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
INITIAL PLA= 62.5 FINAL PLA= 100.0 POWER CMD AT 2.00