INVESTIGATION OF A NOZZLE INSTABILITY ON AN F100 ENGINE EQUIPPED WITH A DIGITAL ELECTRONIC ENGINE CONTROL

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SUMMARY

An instability in the nozzle of the F100 engine, equipped with a digital electronic engine control (DEEC), was observed during a flight evaluation on an F-15 airplane. This instability occurred in the upper left hand corner (ULHC) of the flight envelope during augmentation. The instability had not been predicted by stability analyses, closed-loop simulations of the engine, or altitude testing of the engine. The instability caused stalls and augmentor blowouts. This paper will describe the nozzle instability and the altitude testing done to study the problem at the NASA Lewis Research Center (LeRC). The analysis of the test results, both from a linear analysis and a nonlinear digital simulation, will be presented. Results of software modifications on further flight tests will also be discussed.

NOZZLE INSTABILITY

A nozzle instability was noted during augmented operation in the upper left hand corner of the flight envelope during DEEC/F-15 phase 2 testing. The instability, shown in the figure on the next page, consisted of a 1 Hz to 2 Hz oscillation in the nozzle, with an amplitude up to +0.2 ft^2. This oscillation affected augmentor pressure (PAB) as shown, with each peak driving the fan toward stall, and each valley driving the augmentor toward blowout.

The stability of the engine pressure ratio (EPR) control loop that controls the nozzle had been evaluated with analytical methods during the DEEC software design. Then, the loop stability was evaluated with the engine manufacturer's dynamic simulation. Finally, the loop stability was tested on the flight engine in the altitude facility at Arnold Engineering Development Center (AEDC), but only at intermediate power. During all of these tests, the stability was determined to be adequate. Since the flight data did not show adequate stability, an investigation was conducted to determine the cause of the instability and to develop a fix.

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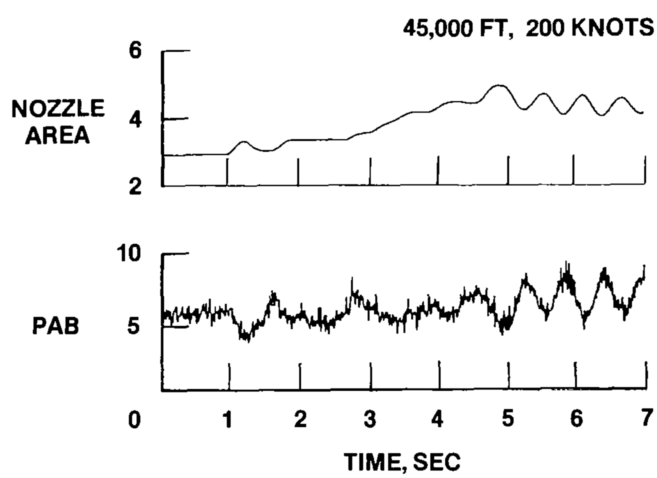
DEEC NOZZLE INSTABILITY

EPR CONTROL MODE STABILITY AT HIGH ALTITUDE - LOW AIRSPEED
- EVALUATED WITH DYNAMIC ENGINE SIMULATION - OK
- EVALUATED IN AEDC FLIGHT CLEARANCE TESTING - OK
- EVALUATED IN FLIGHT - UNSTABLE



NOZZLE INSTABILITY IN SEGMENT 1

The nozzle instability was not present during nonaugmented operation even though the EPR loop was controlling the nozzle at this condition. In the segment 1 limited part of the envelope, the instability did occur, but was limited in amplitude to $+0.1\ ft^2$ and did not cause any stalls or blowouts. As shown below, the oscillation began when the light occurred at t = 2.3 sec and then slowly damped out. The oscillations would sometimes begin, damp out, and then reoccur. Sometimes no oscillations would occur, indicating a marginal stability condition.

DEEC Nozzle Instability - Phase 2

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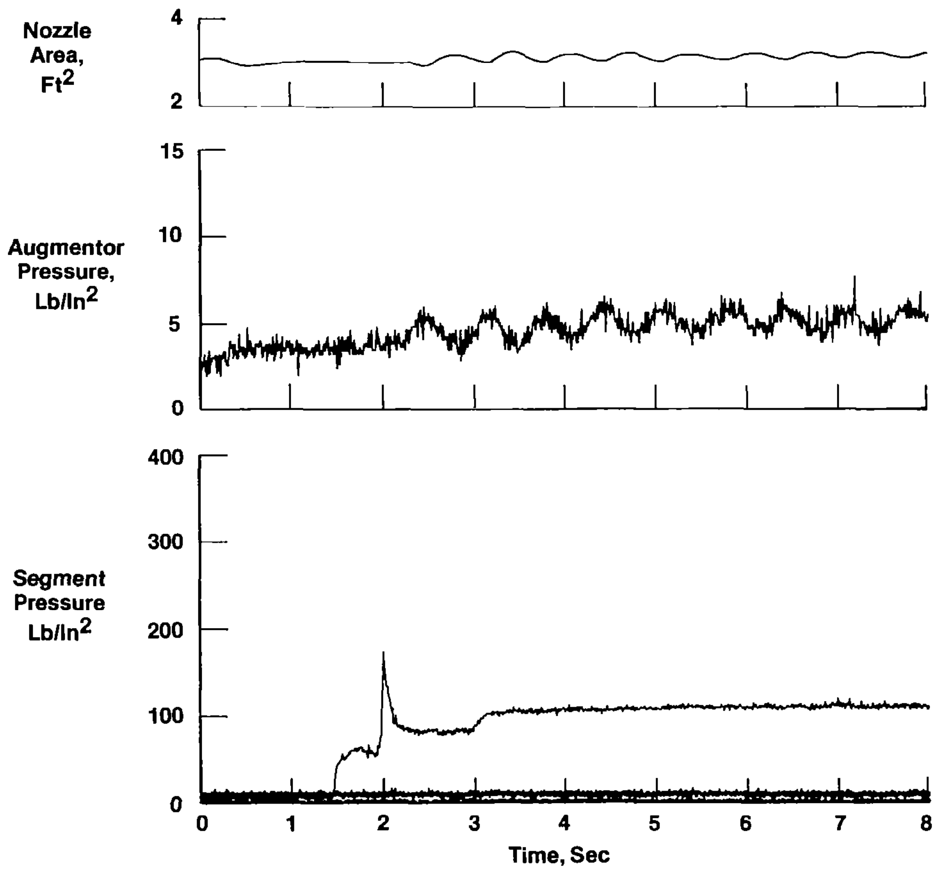
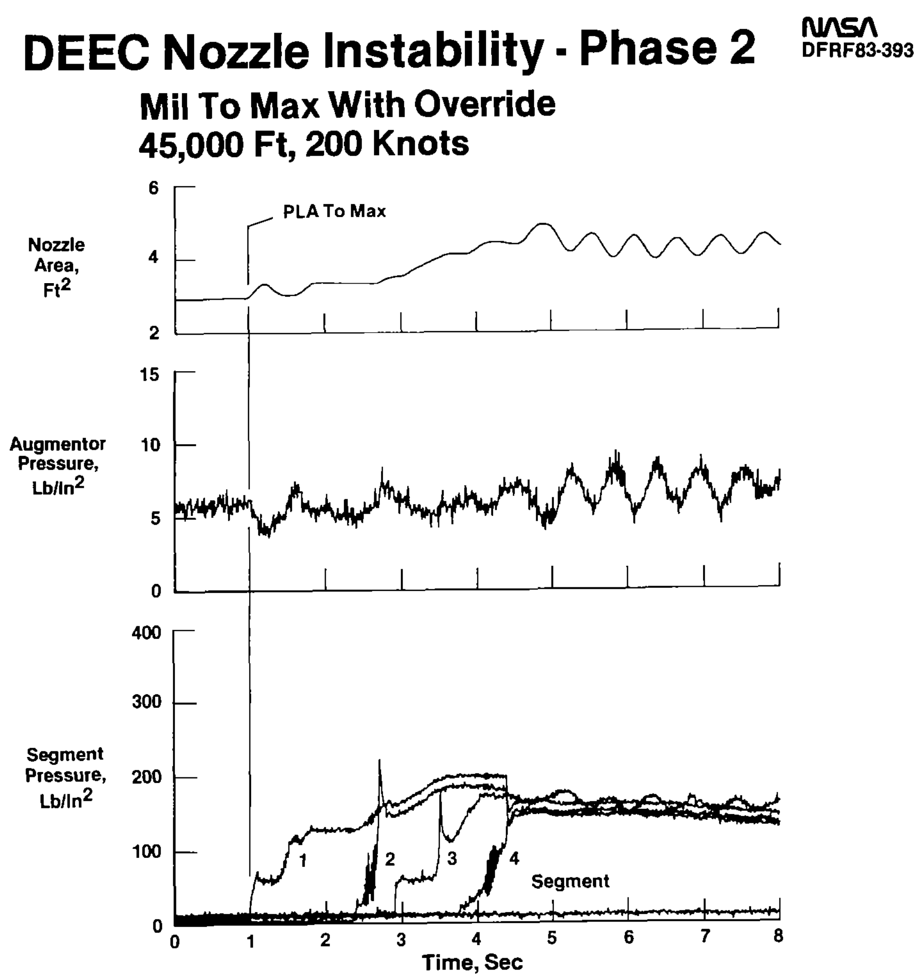
Idle To Max Segment 1 Limiting
45,000 Ft, 175 Knots



NOZZLE INSTABILITY AT MAXIMUM POWER

During maximum power operation, the nozzle oscillations were larger, as shown below. Following a military-to-maximum transient, the nozzle oscillated at a frequency of approximately 1.4 Hz with an amplitude of ± 0.2 ft^2. Large oscillations in PAB were seen, up to ± 2.5 lb/in^2; fan speed oscillations also occurred. The segment 3 augmentor pressure was also observed to oscillate in response to the changing fan duct airflow.



NOZZLE INSTABILITY CAUSES STALL

When the nozzle oscillations became large enough, the fan stalled due to the high back pressure, as shown below. Following a military-to-maximum transient at 45,000 ft and 175 knots, a divergent oscillation occurred, resulting in a stall. Stalls also occurred during sequencing when segment transfers or quickfill spikes happened to coincide with a cycle of the oscillation that raised PAB.

NOZZLE INSTABILITY CAUSES STALL

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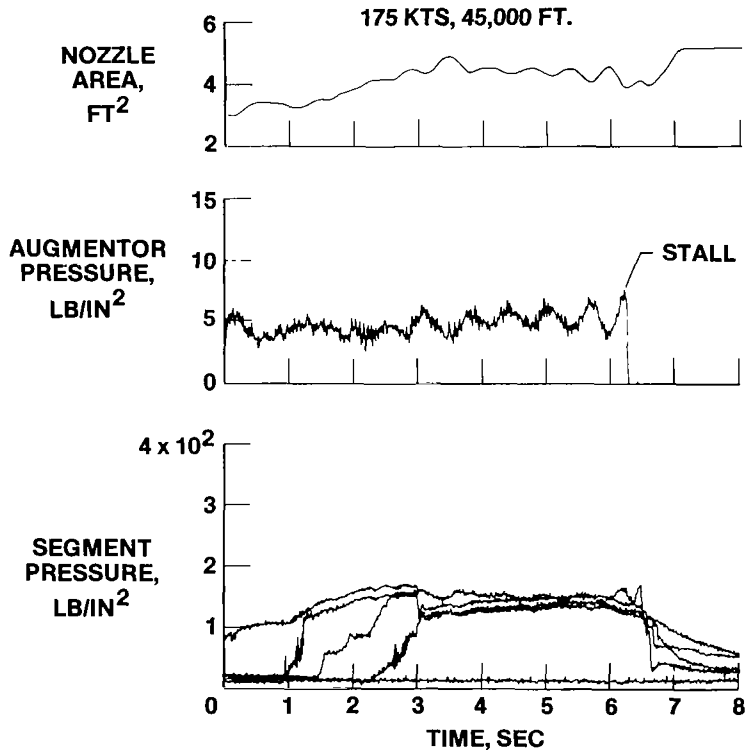
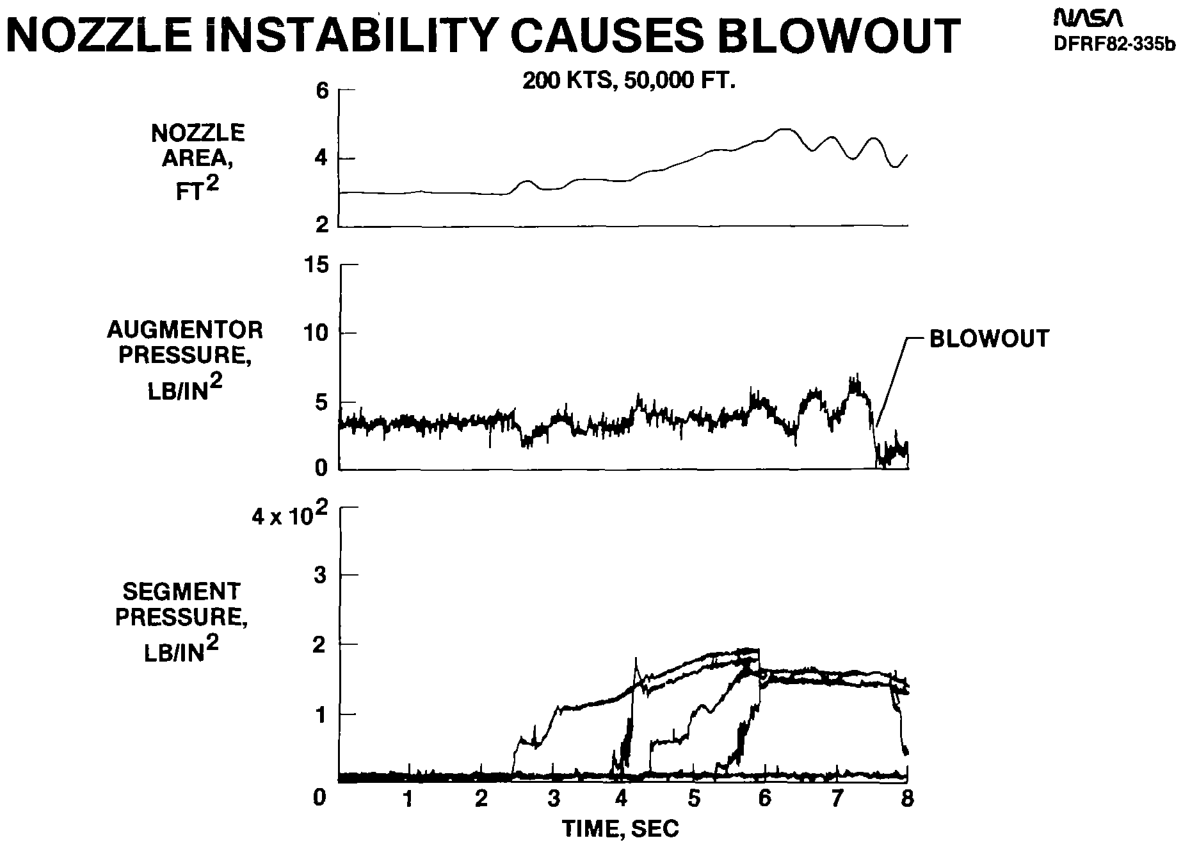


NOZZLE INSTABILITY CAUSES BLOWOUT

Numerous augmentor blowouts were caused by the nozzle oscillation. An example is shown below, at an altitude of 50,000 ft at 200 knots. The low pressure in the augmentor, when the nozzle opened farther than normal, caused the blowout. Blowouts also occurred during augmentor sequencing. Fortunately, the DEEC logic successfully detected the blowouts and turned off the augmentor fuel quickly, thus avoiding any relight stalls.



OBSERVATIONS OF NOZZLE INSTABILITY

At the conclusion of the DEEC phase 2 flight evaluation, there were some observations made concerning the nozzle instability. First, the instability had never been observed at intermediate power, even though the EPR loop was controlling the nozzle. At segment 1 limited conditions, the oscillation occurred; it was limited in amplitude to the point where it was a nuisance, but not a threat to operability. At maximum power, the amplitude of the oscillation was large enough to cause numerous stalls and blowouts. At all times, the occurrence of the oscillation was very sensitive to conditions, often beginning at steady conditions and then damping out later at the same conditions.

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DEEC NOZZLE INSTABILITY

OBSERVATIONS

- NO INSTABILITY AT INTERMEDIATE POWER
- LOW AMPLITUDE LIMIT CYCLE AT SEG 1
- HIGH AMPLITUDE LIMIT CYCLE AT MAX POWER
- SENSITIVE TO CONDITIONS

NASA LEWIS NOZZLE INSTABILITY TESTING

Because the DEEC/F100 dynamic simulation did not indicate the nozzle instability, it was necessary to perform some actual engine tests to determine the cause of the instability. It was not practical to get the flight engine into an altitude facility because of the long lead time required. However, a test engine, XD11, was running at the NASA Lewis Research Center (LeRC) in the Propulsion System Laboratory (PSL) altitude facility. The XD11 engine had been modified to the F100 Engine Model Derivative (EMD) configuration but was thought to be close enough to the flight engine configuration to provide useful data.

The XD11 engine was controlled by a breadboard DEEC that could be reprogrammed easily. LeRC agreed to provide time to conduct nozzle stability tests and assist in the testing and analysis. The flight software was loaded and augmentor transients were performed at Mach 0.6 and 45,000 ft. No instability was noted. Gains in the EPR loop were increased until nozzle oscillations were observed.

As shown in the figure below, when the integral gain was increased by a factor of 2.5, nozzle oscillations occurred. No sustained limit cycle oscillations occurred, but the frequency was similar to that seen in flight. In order to gain additional insight into the EPR loop stability, further tests were performed to acquire dynamic characteristics of the engine and control system. Forced sine and step functions were introduced into the nozzle through the DEEC breadboard control, and the resulting data were used to generate transfer functions. These transfer functions were then used to update the engine simulation.

NASA LEWIS NOZZLE INSTABILITY TESTING

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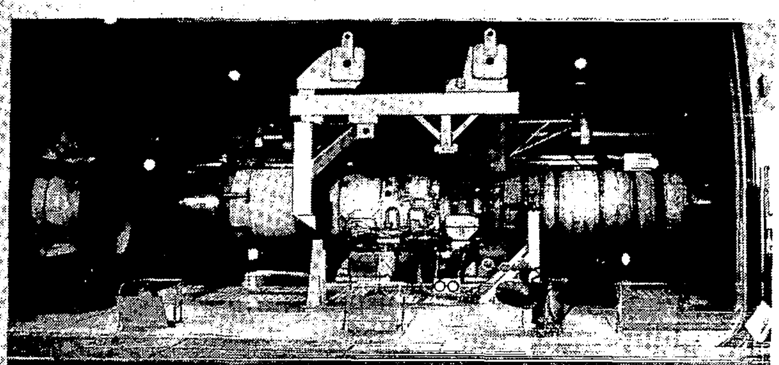
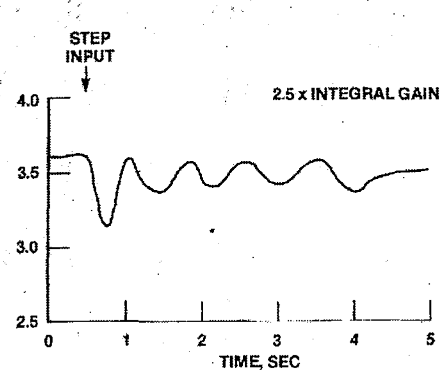


- F100 ENGINE XD-11
- DEEC BREAD BOARD
- M = 0.6, 45,000 FT
- FLIGHT SOFTWARE-
  NO INSTABILITY



SOFTWARE CHANGES

- GAINS INCREASED
  NOZZLE OSCILLATIONS
  MATCHED FLIGHT FREQUENCY
  DID NOT MATCH FLIGHT AMPLITUDE
- FORCED SINE & STEP NOZZLE INPUTS
  TRANSFER FUNCTIONS TO
  IMPROVE ENGINE SIMULATION
- EVALUATED PROPOSED LOGIC CHANGES

ERP LOOP LINEAR ANALYSIS

The engine manufacturer, Pratt and Whitney Aircraft, took the transfer function data from the LeRC tests and conducted a linear analysis of the EPR loop. A block diagram of the system is shown on the next page. It models the part of the EPR control mode that was enclosed in the dashed lines of the nozzle control figure of Paper 11. The EPR request was multiplied by integral and proportional gains and by the nozzle base gain to generate the nozzle request. The nozzle request was passed to the nozzle dynamics block - which models the servo loop dynamics - the air motor that drives the actuators, and the actuators themselves. The nozzle output was used to generate the appropriate EPR dynamics, the jet primary nozzle area (AJ)/EPR transfer function having been determined from the LeRC tests. The resulting EPR was fed back to the DEEC pressure sensors, the DEEC filter, and the DEEC computational cycle to generate the EPR feedback. Another feedback loop was also modeled. As the nozzle area and EPR changed, the fan speed also changed, as modeled in the AJ/fan rotor speed (N1) dynamics block, determined from the LeRC test data. The N1 to EPR constant was the slope of the N1 to EPR request table in the DEEC logic. That was then fed back to the EPR request to complete the generation of the EPR error.

This linear simulation of the EPR control loop was reduced to a single transfer function and a stability analysis was conducted. At the upper left hand corner flight condition, the gain and phase margins were very small, indicating a marginal stability condition. The stability analysis was also conducted at two other flight conditions - sea level static, and Mach 0.9 at 30,000 ft - where the engine dynamics were well documented, and the results were consistent with test data. Based on these results, the engine manufacturer recommended reducing the gain in the upper left hand corner by a factor of 2. In addition, a deadband between the EPR error and the proportional and integral gains that had been very small (0.001), was to be increased by a factor of 30 to 0.03. These proposed logic changes were then evaluated on the test engine at LeRC and were found to stabilize the EPR loop.

In comparing the engine dynamics derived from the LeRC test and the dynamics that had been used in the engine manufacturer's nonlinear simulation, no major differences were seen. Rather, there appeared to be a number of relatively small effects, which, when combined, caused a significant difference in dynamic characteristics to occur.

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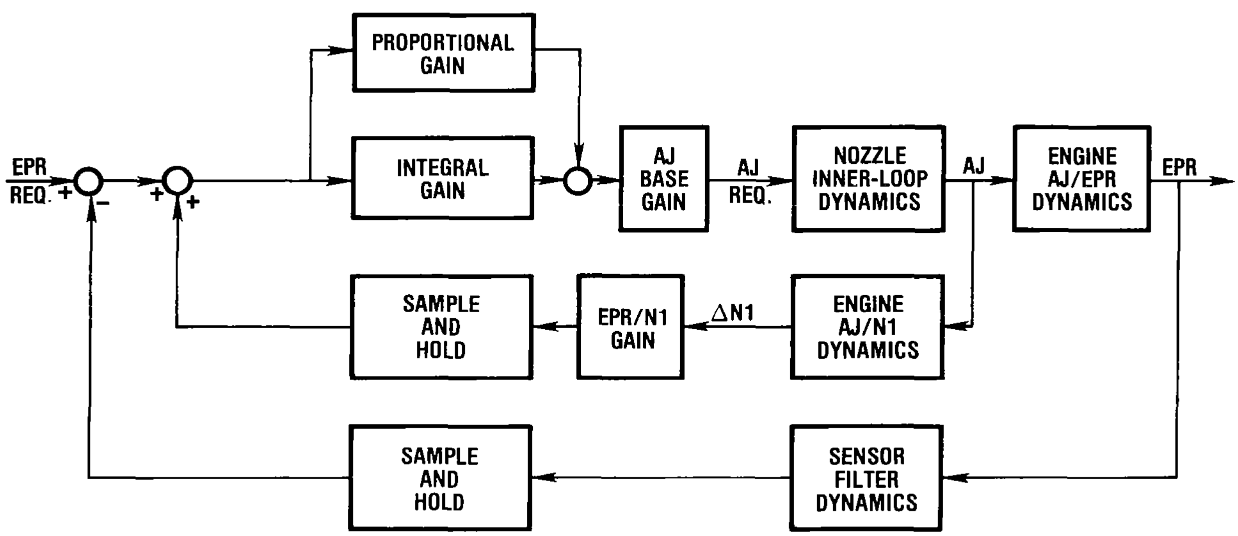
PWA EPR/NOZZLE LOOP LINEAR ANALYSIS



DRYDEN NONLINEAR EPR LOOP SIMULATION

In order to study the nozzle instability further, NASA Ames Research Center's Dryden Flight Research Facility (DFRF) developed a nonlinear digital simulation of the EPR loop. The basic block diagram of the linear analysis was modified by the addition of the deadband, nonlinearities in the nozzle, and more accurate modeling of the DEEC cycle times. The simulation was mechanized in the time domain using Z transform techniques. The digital computer program used an integration interval of 0.005 sec and modeled the DEEC computational minor cycle time of 0.02 sec. A step input in EPR request was used to evaluate the EPR loop stability. Variations in proportional and integral gains, deadband, and nozzle hysteresis were investigated.

DEEC EPR/NOZZLE LOOP SIMULATION

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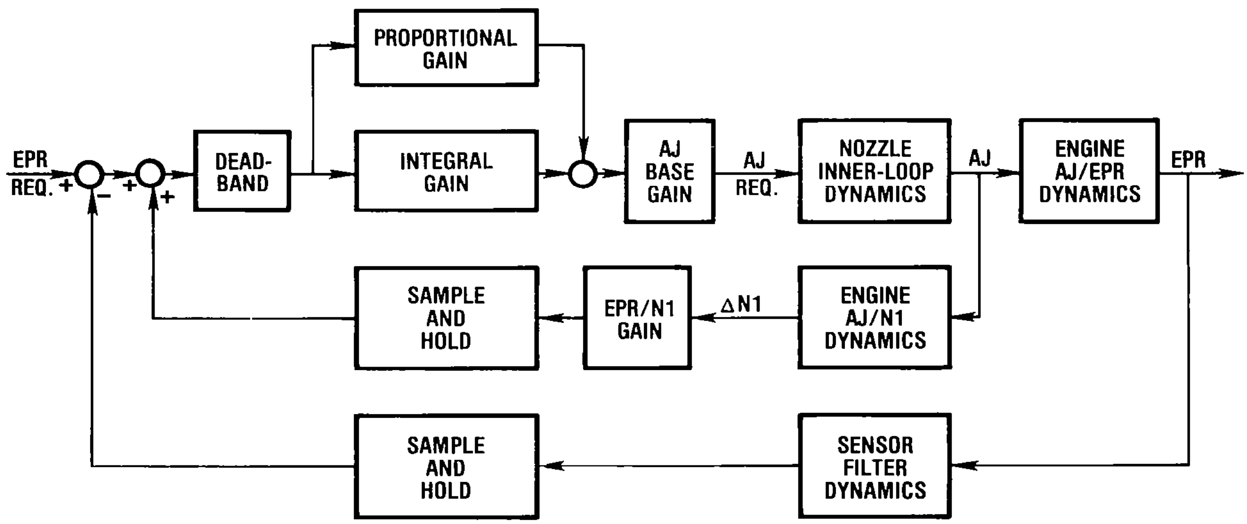
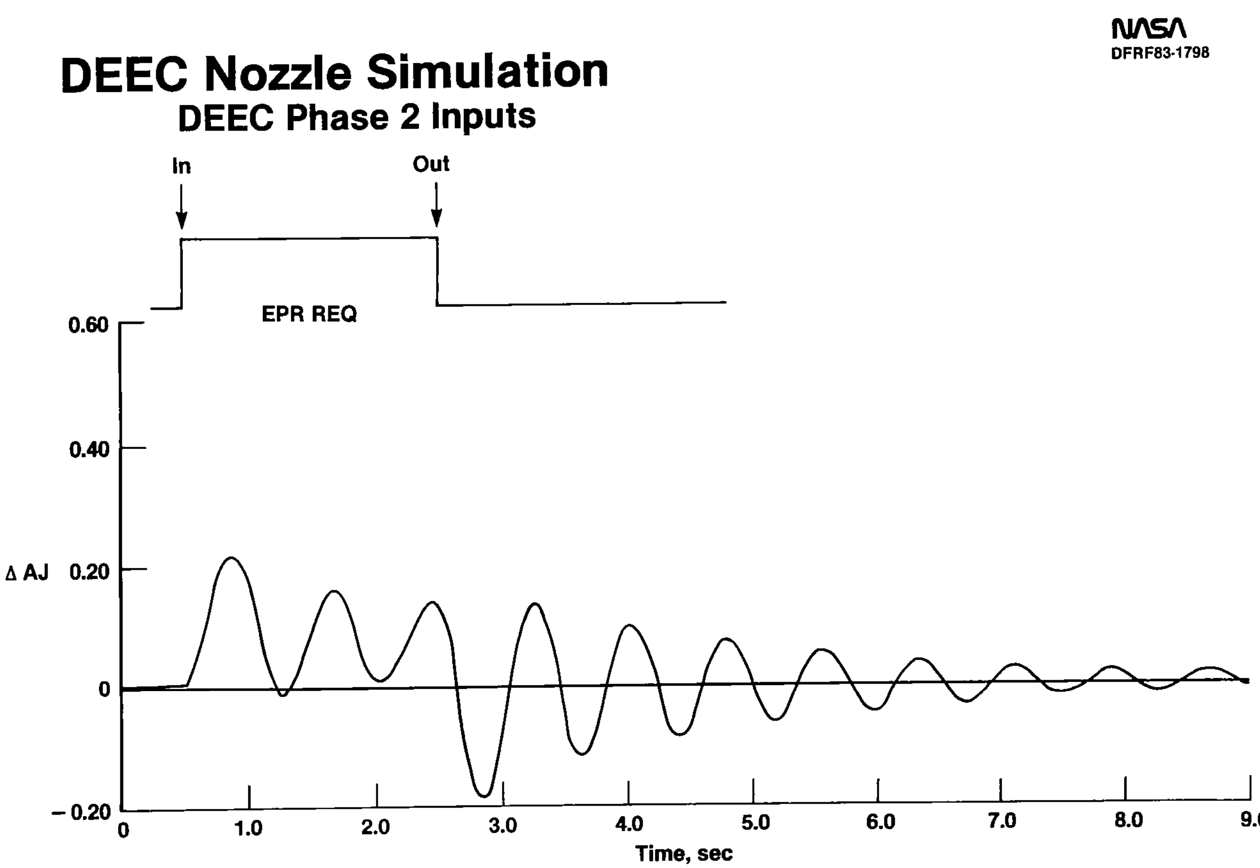


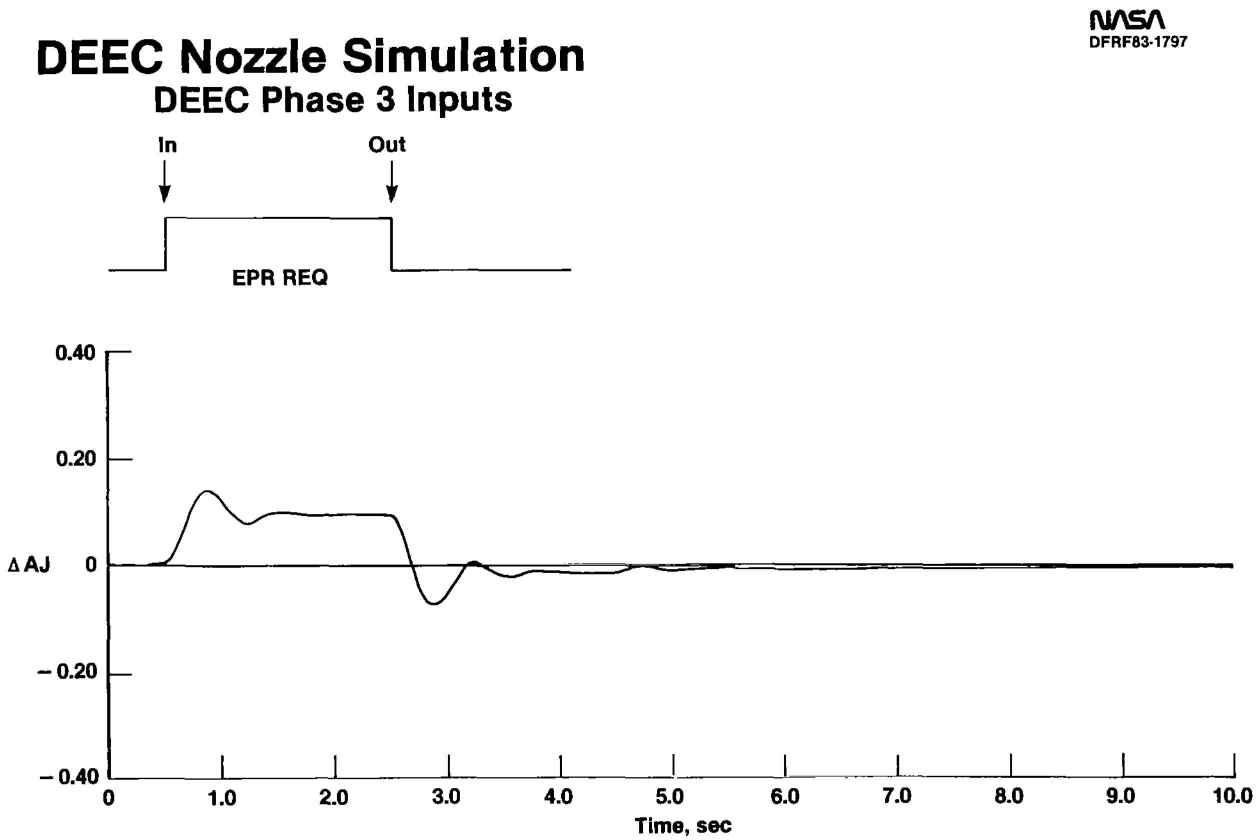
RESULTS OF NONLINEAR EPR LOOP SIMULATION

Results of the DFRF nonlinear simulation of the EPR loop at Mach 0.6 and 45,000 ft are shown below. The deadband, proportional, and integral gains from the DEEC phase 2 logic are incorporated. As shown, the step input in EPR request initiates a very lightly damped limit cycle oscillation with a frequency and amplitude similar to that observed in flight. This nonlinear simulation, which incorporated LeRC test results, essentially duplicated the flight results - whereas the engine manufacturer's full nonlinear simulation did not predict the oscillation. This points out the importance of having very high quality engine modeling data.



NONLINEAR SIMULATION OF PROPOSED SOFTWARE CHANGES

The proposed logic changes for the phase 3 software were evaluated on the DFRF simulation and were again verified. As shown below, when the deadband was increased and the integral gain was cut in half, the response to the same step input in EPR request produced only a small overshoot that rapidly damped. This response was judged to be acceptable. The phase 3 flight results showed that the nozzle instability had been effectively eliminated. During phase 4 testing at very high altitudes and low airspeeds, some tendency for nozzle overshoots was observed, but this did not cause any stalls or blowouts.



LESSONS LEARNED ON AUGMENTOR INSTABILITY

The augmentor instability investigation on the DEEC-equipped F100 engine has provided several lessons for future engine developments. First, it was shown that engine dynamic models must be very accurate to reveal instabilities, particularly for operation in the upper left hand corner of the flight envelope. It was also found that loop stability testing should be performed at augmented power if possible, since the DEEC flight clearance testing at intermediate power did not reveal the instability. It was also found that a nonlinear simulation could essentially duplicate the observed engine behavior in flight if accurate engine test data were included.

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Augmentor Instability
Lessons Learned

- **Models must be very accurate to reveal instabilities in ULHC**
- **Flight clearance testing should have been done at augmented power**
- **Non-linear digital simulation with test data did duplicate flight results**