Proceedings of A Workshop on

INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS

held at the

Massachusetts Institute of Technology
Cambridge, MA 02139

March 21-22, 1994

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WORKSHOP ON INTELLIGENT TURBINE ENGINES
FOR ARMY APPLICATIONS

Day 1 - Monday, March 21, 1994
7:45    Registration
8:30    Welcome and Introduction
        – A. Epstein, MIT & D. Mann, ARO

Advanced Control for Gas Turbines: Industry and Government Perspective
9:00    Army View of Rotor Craft Turbine Engine Controls - Present & Future Applications
        – V. Edwards, Aviation R&D Engineering Center
9:30    Army Ground-Based Gas Turbine Engines
        – R. McClelland, USA Tank-Automotive Center
10:00   Experience and Potential for Advanced Engine Controls
        – J. Kulberg, Pratt & Whitney, E. Hartford
10:30   Break
10:50   Advanced Engine Control
        – S. Carpenter, GE Aircraft Engines
11:20   NASA Research in Engine Control
        – W. Merrill, NASA Lewis Research Center
11:50-13:00 Lunch

Overview of Active Control in Gas Turbine Engines
13:00   The Promise of Active Control for Helicopter and Tank Engines
        – A. Sehra, Textron Lycoming
13:30   MIT Research in Active Compressor Stabilization
        – J. Paduano, MIT
14:00   GE Research in Active Control
        – A. Spang, GE Research Center
14:30   Break
14:50   Progress in Modeling & Control of Compressor Stall
        – C. Nett, UTRC
15:20   A Systems Study of the Impact of Active Compressor Stabilization
        – K. Tow, GE Aircraft Engines, Lynn
16:00   Tour of MIT Gas Turbine Laboratory, Active Control Facilities
18:30   Dinner
Day 2 - Tuesday, March 22, 1994

8:30    Panel Discussion on Intelligent Engine Control
        – Industry-Government-Academia

9:30    Change to Breakout Panels

9:45-12:00 Breakout Discussions
        a) Engine Systems & Applications
        b) Components
        c) Control Theory

12:00   Lunch

13:00   Reports from the Breakout Panels
        Open Discussion

14:30   Closing Remarks - ARO Interests in Intelligent Engines
        – D. Mann, ARO

15:00   Adjourn
Intelligent Turbine Engines for Army Applications

Professor Alan H. Epstein

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Cambridge, MA 02139-4307

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This report documents the proceedings of a workshop on Intelligent Turbine Engines for Army Applications held at the Massachusetts Institute of Technology on March 21-22, 1994. The workshop brought together experts from government, industry, and academia to explore ways in which advanced controls concepts can be used to significantly benefit Army gas turbine engines. Participants discussed Army control related requirements. Emphasis was placed on the integration of active control into helicopter and ground vehicle gas turbines.

Gas turbines, active control and control

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UL
"INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS" Workshop
March 21-22, 1994
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SUMMARY VIEWGRAPHS
OF BREAKOUT PANELS

(Parenthetical remarks are
those of the Editor)
### Vehicle Systems & Components Panel

#### SYSTEMS

<table>
<thead>
<tr>
<th>Risk</th>
<th>Potential Reward</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>• Identify active control benefit to small engines vs. large engines</td>
</tr>
<tr>
<td></td>
<td>• Diagnostics – condition-based maintenance</td>
</tr>
<tr>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>• New sensor / actuator systems</td>
</tr>
<tr>
<td></td>
<td>• Reconfigurable smart engine</td>
</tr>
<tr>
<td></td>
<td>(For battle damage component failure)</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>• Simplicity</td>
</tr>
<tr>
<td></td>
<td>(Of active control system)</td>
</tr>
<tr>
<td></td>
<td>• Passive control</td>
</tr>
<tr>
<td></td>
<td>(Same dynamic behavior without computer actuators)</td>
</tr>
<tr>
<td></td>
<td>• Totally Silent engine</td>
</tr>
<tr>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>• Active avoidance of distortion</td>
</tr>
<tr>
<td></td>
<td>(Manipulate inflow to engine)</td>
</tr>
<tr>
<td></td>
<td>• Active control of inlets</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>• Integration – adaptive propulsion control</td>
</tr>
<tr>
<td></td>
<td>(Integration of helicopter flight &amp; propulsion controls)</td>
</tr>
</tbody>
</table>

L = Low, M = Medium, H = High
Vehicle Systems & Components Panel

COMPONENTS

<table>
<thead>
<tr>
<th>Risk</th>
<th>Reward</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>H</td>
<td>• Active blade control – shape, flutter, forced vibration damping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Active combustion control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Emissions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Pattern factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Life cycle cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Tip clearance control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Now done open loop in large engines)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Active control of separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High lift / max lift airfoil</td>
</tr>
<tr>
<td>L</td>
<td>M</td>
<td>• Optimized turbine cooling / performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Control of turbine cooling)</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>• Katzmeier effect – unsteady blading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Unsteady lift would increase loading capability)</td>
</tr>
<tr>
<td>Risk</td>
<td>Reward</td>
<td>Potential</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-----------</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>- System identification (of fluid &amp; structure dynamics)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Identify low hanging fruit beyond compressor stability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Risk vs. reward</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Strategy for technology insertion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Multidisciplinary w/ in-depth teams</td>
</tr>
<tr>
<td>M</td>
<td>H</td>
<td>- Stall line prediction – accurate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Passive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- With active control</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>- Active control of flutter</td>
</tr>
<tr>
<td>L</td>
<td>M</td>
<td>- Active control as a demo tool</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>- Active control of surge only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Not including rotating stall</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>- Inverse optimization technique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Better modelling</td>
</tr>
<tr>
<td>Generic</td>
<td></td>
<td>- Closed loop control of unsteady flow</td>
</tr>
</tbody>
</table>
ENGINE CONTROL USING "CONVENTIONAL" ACTUATORS/SENSORS

- Nonlinear control (NL) techniques are needed – CONTEXT is very important

- To understand the “class” of NL systems, a standardized NL model structure for engines, similar to the flight dynamics standard
  - Must involve industry
  - Recognize noise and NL
  - Be flexible (for inclusion of new concepts)
  - Be built around experimental testbed

- Wish list – a testbed with complexity/dynamics between: a simple compressor rig and engine

- Airframe/engine integration in helicopters
  - Situation awareness/feedforward
  - Rotor aerodynamics in transient maneuvers
  - Performance seeking in new context
    - Vibration as well as fuel burn
    - Rotor speed as variable
  - Hardware/know-how is ripe
Control Panel Summary (Cont.)

• Recognition
  – Use of control theory relies on context

• Recommendations depend on context of fruitful work to be done

• Unsteady fluid mechanics
  – New system identification tools for fluid systems
    – Noise environment far worse
    – Techniques from fluid theory should be exploited
      – Length scale, time scale concepts
      – Ensemble averaging
    – Converting distributed fluids model to control form
      – Many structural dynamic, nonlinear dynamics techniques available
        – CFD to ODE \( \rightarrow \) Create low order
        – PDE to ODE \( \rightarrow \) aggregate models
  – Collaboration with experiments is vital
Control Panel Summary (Cont.)

• Other nonlinear control issues
  – Multivariable mode selection
  – Transient performance improvement through NL control
    – How to measure, insure safety during design
  – Engine companies should talk to academia about their problems
  – Disturbance rejection
    – Characterizing disturbances/uncertainty/noise

• Advanced concepts
  – Sponsoring organizations should explicitly fund control work which collaborates with experimental application
SPEAKERS' PRESENTATIONS
INTELLIGENT TURBINE ENGINES

MOTIVATION

Reduced Fuel Consumption

Example: Mechanized Infantry Division
58 M1 tanks, 21 Attack helicopters
Fuel use: 673,000 gal/day

Reduced Volume/Increased Power

Faster Deployment
Increased Range/Payload

Improved Reliability
Reconfigurable/Adaptable
INTELLIGENT TURBINE ENGINES

Application of Artificial Intelligence-based Advanced Control Strategies to Gas Turbine Engines for Improved Economy and Reliability

AI ALGORITHMS
- Fuzzy Logic
- Genetic Algorithms
- Rule-based Control
- Model-based Control
- Hybrid Systems

ENGINE MODELS
- Turboshaft
- Simple (T-800)
- Recouperated (AGT-1500)

CONTROL METHODOLOGY
- Diagnostics/Prognostics
- Adaptive Reconfiguration
- Optimization

APPLICATIONS
- Tanks
- Rotorcraft
- Civilian Aircraft
WORKSHOP ON INTELLIGENT TURBINE ENGINES

PRODUCTS

Assessment of current status

Identification of opportunities

Identification of enabling technologies

Identification of basic research requirements
A NEW RESEARCH PARADIGM

A University-Army-Industry Partnership for Research

INDUSTRY

UNIVERSITY

JOINT RESEARCH PROGRAMS

ARO WILL FACILITATE THE PARTNERSHIP WITH SUPPORT AND COORDINATION
ARMY VIEW OF ROTORCRAFT TURBINE CONTROLS PRESENT AND FUTURE CONSIDERATIONS

- CURRENT ARMY FLEET HAS DIVERSITY OF TECHNOLOGIES
  - UH-1/T53 FLY BALL GOVERNOR
  - MH-47E/T55 FULL AUTHORITY DIGITAL ELEC CONTROL
  - DIAGNOSTICS HUMAN DEPENDENT
  - HISTORY RECORDING AND VARIOUS DEGREES OF FAULT MONITORING

- ARMY'S MOST MODERN SYSTEMS
  - UH-60/T700 & AH-64/T700 HYDROMECHANICAL SUPERVISORY DIGITAL ELECTRONIC CONTROL
  - OH-58/250C30R PNEUMATIC-MECHANICAL SUPERVISORY DIGITAL ELECTRONIC CONTROL
  - MH-47E/T55 FADEC
ARMY VIEW OF ROTORCRAFT TURBINE CONTROLS PRESENT AND FUTURE CONSIDERATIONS

0 TYPICAL CURRENT TECHNOLOGY CAPABILITIES

- ISOCRONOUS POWER TURBINE GOVERNING
- TORQUE MATCHING IN MULTI-ENGINE APPLICATIONS
- TEMPERATURE LIMITING/START OVER TEMP ABORT
- OVERSPEED PROTECTION
- RUDIMENTARY SURGE RECOGNITION/AVOIDANCE
- FLIGHT CONTROL ANTICIPATION (COLLECTIVE)
- AUTOMATIC START/RELIGHT CAPABILITY
- NOTCH FILTER FOR TORSIONAL STABILITY
- TORQUE RATE ATTENUATION (UNCOMPENSATED)
TYPICAL PROBLEMS & SHORTCOMINGS

- ENGINE/DRIVE TRAIN/AIRFRAME INTERACTIONS
  - TORSIONAL MODE OSCILLATIONS
  - TRANSIENT ROTOR DROOP
  - TORQUE SPLITTING
  - TORQUE PREDICTABILITY

- UNABLE TO AUTOMATICALLY MANAGE FAILURE MODES

- NO ANTICIPATION FOR UNCOMPENSATED INPUTS

- LIMITED ADAPTIVE CAPABILITIES (ENG/OPER CONDITIONS)

- UNABLE TO SELF-DIAGNOSE ENGINE HEALTH
  NO PROGNOSTICS

- EXTENSIVE FLT TEST TO OPTIMIZE EACH INSTALLATION
**Problem Definition**

**Rotor Droop**

**Autorotation Recovery**

2 Second Pull

- 100% NR
- 85% NR
- Droop 15%

**Graph**

TIME (SECONDS)

NR %
NP %
COLL %
INTELLIGENT ENGINE & CONTROL OPPORTUNITIES

0 HI-FIDELITY TOTAL SYSTEM SIMULATION

0 RECONFIGURABLE CONTROL LOGIC

0 FAIL SMART, RAPID IDENT & AUTO SELECT BASED ON SYSTEM PARAMETERS

0 TRANSPARENT FAULT/FAILURE DETECTION/RECOVERY TO ALLOW CONTINUED MISSION CAPABILITY

0 ADAPTABILITY TO DEGRADED OPERATING CONDITIONS

0 OPTIMIZE ROTORCRAFT PERFORMANCE - SELF TUNING/PERFORMANCE SEEKING CONTROLS

0 SELF DIAGNOSIS FOR ALL ON-BOARD ENGINE SYSTEMS & INTERFACES

0 CONSIDER INTEGRATED FLIGHT & ENGINE CONTROLS
POWER LOSS SURVIVABILITY

HELO AT MAX GROSS WEIGHT
SEA LEVEL STANDARD DAY,
ONE OF TWO ENGINES FLAME
OUT AT HOVER

- PILOT REACTION - 2 SEC (CONVENTIONAL CONTROL)
- PILOT REACTION - 0.25 SEC (ADAPTIVE WITH AUTOMATIC ENGINE FAILURE DETECTOR)
- PILOT REACTION - 0.25 SEC (ADAPTIVE WITH DETECTOR AND 25% CONTINGENCY POWER)

67% REDUCTION OF DEAD MAN'S AREA
AT HOVER

- CUT REACTION TIME
- ENABLE CONTINGENCY POWER
ENGINE RELATED CONCEPTS
MINIMUM FUEL CONSUMPTION

△FUEL CONSUMPTION

%  

95  95
100  100
105  105
110  110

10,000 LBS
130 KNOTS
80°F

-10
-5
0
5
10

SEA LEVEL
5000 FT

ROTOR SPEED

% 

- OPERATE ROTOR AT OTHER THAN 100% SPEED
- SEARCH OUT OPTIMUM SPEED
SUMMARY OF EXPECTED BENEFITS

- ENHANCED FLIGHT SAFETY
- ENHANCED ROTORCRAFT SYSTEM PERFORMANCE
- REDUCED LIFE CYCLE COST
  - REDUCED ANNUAL O & S COSTS
  - IMPROVED ENGINE OPERATION
  - REDUCED ENGINE MISHAPS
- REDUCED PILOT WORK LOAD
- IMPROVED MAINTAINABILITY & DIAGNOSTIC CAPABILITY
PROPELLION SYSTEMS DIVISION

ARMY GROUND-BASED GAS TURBINE ENGINES

BY

SATYA KODALI

PROPULSION SYSTEMS DIVISION

U.S. ARMY, TACOM
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>QTY</th>
<th>N.G.</th>
<th>Engine Model</th>
<th>Manufacturer</th>
<th>HP</th>
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<tr>
<td>M60 Fam</td>
<td>1190</td>
<td>66</td>
<td>AVDS-1790</td>
<td>TCM</td>
<td>750</td>
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<tr>
<td>M728 CEV</td>
<td>728</td>
<td>89</td>
<td>AVDS-1790</td>
<td>TCM</td>
<td>750</td>
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<tr>
<td>M88 MRV</td>
<td>1560</td>
<td>697</td>
<td>AVDS-1790</td>
<td>TCM</td>
<td>750</td>
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<tr>
<td>M1</td>
<td>5841</td>
<td>2246</td>
<td>AGT-1500</td>
<td>Textron/Lycoming</td>
<td>1500</td>
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<tr>
<td>M2/3</td>
<td>5488</td>
<td>957</td>
<td>VTA-903T</td>
<td>Cummins</td>
<td>600</td>
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<td>M113</td>
<td>27,416</td>
<td>10,071</td>
<td>6V-53T</td>
<td>Detroit Diesel</td>
<td>275</td>
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<td>M9ACE</td>
<td>430</td>
<td>18</td>
<td>V - 903</td>
<td>Cummins</td>
<td>295</td>
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<td>M551</td>
<td>1070</td>
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<td>M109</td>
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<td>0</td>
<td>8V-71T</td>
<td>Detroit Diesel</td>
<td>405</td>
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**WHEELED VEHICLES**

<table>
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<th>Engine Model</th>
<th>Manufacturer</th>
<th>HP</th>
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<tr>
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<td>749</td>
<td>8V92TA</td>
<td>Detroit Diesel</td>
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<td>HEMTT</td>
<td>9663</td>
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<td>M35A2</td>
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<td>LDT-465-1D</td>
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<td>140</td>
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<td>FMTV</td>
<td>0</td>
<td>3116</td>
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<td>225</td>
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<td>M809</td>
<td>15850</td>
<td>NH 250</td>
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<td>250</td>
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<td>M939</td>
<td>11414</td>
<td>6CTA8.3</td>
<td>Cummins</td>
<td>240</td>
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<td>M880</td>
<td>2655</td>
<td>318 (Gas)</td>
<td>Chrysler</td>
<td>140</td>
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<td>HMMWV</td>
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<td>150</td>
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<td>CUCV</td>
<td>35653</td>
<td>20205</td>
<td>GM</td>
<td>150</td>
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<td>M915 Fam</td>
<td>4099</td>
<td>NTC 400</td>
<td>Cummins</td>
<td>400</td>
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<td>M915 AY2</td>
<td>3252</td>
<td>Series 60</td>
<td>Detroit Diesel</td>
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GROUND VEHICLE GAS TURBINE ENGINES

- AGT 1500
- LV 100
## AGT1500 AND LV100 FEATURES

<table>
<thead>
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<th>AGT1500</th>
<th>LV100</th>
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<tbody>
<tr>
<td>PRESSURE RATIO</td>
<td>14:1</td>
<td>12:1</td>
</tr>
<tr>
<td>AIR INDUCTION RATR(LB/SEC)</td>
<td>12.5</td>
<td>7.5</td>
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<td>BSFC (LB/BRAKE HP HR)</td>
<td>0.5</td>
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<tr>
<td>IDLE FUEL ECONOMY(LB/HR)</td>
<td>33</td>
<td>74</td>
</tr>
<tr>
<td>TIT (0 F)</td>
<td>2180</td>
<td>2470</td>
</tr>
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</table>
LV100 VERSUS AGT 1500
SFC CHARACTERISTICS

AGT-1500
LV100 WITH FIXED TURBINE NOZZLE & NO HEX
LV100 WITH FIXED TURBINE NOZZLE

NOMINAL
LV100

40 KM/HR
SR

27 KM/HR
CC

% POWER

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

TAC-1450
GROUND VEHICLE ENGINE FEATURES

- AIR FILTRATION
- MODULAR DESIGN
- RECUPERATION
- IDLE FUEL ECONOMY
REGENERATOR SCHEMATIC

AIR PASSAGE
PASSAGE
TANK ENGINE REQUIREMENTS

- POWER DENSITY
- FUEL ECONOMY
- MULTI FUEL OPERATION
- SIGNATURES
- ENVIRONMENTAL TOLERANCE
- RUGGED DESIGN- SOLDIER PROOF
ENGIN PERFORMANCE REQUIREMENTS

- QUICK ACCELERATION
- MAX SPEED CAPABILITY
- SPEED ON GRADE CAPABILITY
- POWER AT HIGH ALTITUDE
<table>
<thead>
<tr>
<th>Developer</th>
<th>Power (HP)</th>
<th>Volume (Cu.Ft)</th>
<th>Prop Sys Vol (Cu.Ft)</th>
<th>Prop Sys Wt (LB)</th>
<th>BFD Fuel (Gal)</th>
<th>Sprocket Power (HP)</th>
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<tr>
<td>AGT1500</td>
<td>1500</td>
<td>31</td>
<td>291</td>
<td>15191</td>
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<td>950</td>
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<td>1500</td>
<td>25</td>
<td>175</td>
<td>12696</td>
<td>300</td>
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<td>TANK ENGINE ELECTRONIC CONTROLLERS</td>
<td></td>
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<td>VEHICLE-ENGINE CONTROLLER</td>
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<td>ECU M1A1-AGT1500</td>
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<td>DECU M1A2-AGT1500</td>
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<tr>
<td>FADEC FUTURE-LV100</td>
<td></td>
<td></td>
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</tbody>
</table>
CONCLUSIONS

• VOLUME 40% LESS
• WEIGHT 16% LESS
• BFD FUEL 40% LESS
• SPROCKET POWER 11% MORE
• USER FRIENDLY VEHICLE
• IMPROVEMENTS IN PROGNOSTIC AND DIAGNOSTICS
• IMPROVED RAM-D 70% HIGHER
• CONTROLS PLAY A SIGNIFICANT ROLE IN ALL THESE
ELECTRONIC CONTROL SYSTEMS
FOR AIRCRAFT
TURBINE ENGINES

- EXPERIENCE
- POTENTIAL

INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MARCH 21, 1994

Joel F. Kuhlberg
CHRONOLOGY

1980 - PW2037 ENGINE
1994 - PW4084 ENGINE
2000 - ADVANCED ENGINE
ADVANTAGES OF FULL AUTHORITY ELECTRONIC ENGINE CONTROL

- REDUCTION IN FUEL BURN
- IMPROVEMENT IN CONTROL OPERATIONAL RELIABILITY
- REDUCTION IN WEIGHT
- REDUCTION IN CONTROL MAINTENANCE COSTS
- SIMPLIFIED COCKPIT PROCEDURES
ELECTRONIC ENGINE CONTROL FEATURES

- MAINTAIN FIXED ENGINE RATINGS AT UNIQUE THROTTLE POSITIONS
- PROVIDE CONSTANT IDLE SPEED CONTROL
- PROVIDE ACCELERATION AND DECELERATION CONTROL
- PROVIDE ENGINE STARTING CAPABILITY
- PROVIDE ENGINE OVERSPEED AND OVERPRESSURE LIMITING
- POSITION HIGH COMPRESSOR VARIABLE STATOR VANES
ELECTRONIC ENGINE CONTROL FEATURES (CONTINUED)

- CONTROL COMPRESSOR BLEED AIRFLOW
- PROVIDE ACTIVE CLEARANCE AIRFLOW CONTROL AND TURBINE COOLING AIR CONTROL
- MODULATE OIL COOLER AIRFLOW
- PROVIDE THRUST REVERSER CONTROL AND THROTTLE INTERLOCK
- PROVIDE ENGINE PERFORMANCE DATA TO COCKPIT DISPLAYS AND CONDITION MONITORING SYSTEMS
ELECTRONIC ENGINE CONTROL

Data entry connector

Channel A housing

Forced air heat exchanger

Shop test connection

Vibration isolator

Airframe connection

Cooling air ports

Channel B housing

Pressure ports
ELECTRONIC CONTROL SYSTEM EXPERIENCE
1984 - 1994
13 AIRPLANE MODELS
15 MILLION HOURS

HIGHS

RELIABILITY

ROBUST SOFTWARE

LOWS

WIRING

VIBRATION

NUISANCE MESSAGES
<table>
<thead>
<tr>
<th>Function</th>
<th>Current Engine</th>
<th>Growth Engine</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Wf Control</td>
<td>X</td>
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<tr>
<td>Stator Vane Control</td>
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<td>X</td>
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<tr>
<td>LPC Bleed Control</td>
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<td>HPC Bleed Control</td>
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<tr>
<td>Reverse Fn Limiting</td>
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<td>Overspeed Protection</td>
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<td>Engine Heat Management Control</td>
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<td>Turbine Case Cooling Control</td>
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<td>Nacelle Cooling Control</td>
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<td>IDG AOCV Override</td>
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<tr>
<td>TRC System</td>
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<td>TVBCA System</td>
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<tr>
<td>Modulated TCA System</td>
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<td>ARINC Receiver #1</td>
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<td>ARINC Receiver #2</td>
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<td>ARINC Transmitter #1</td>
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<td>High-Speed ARINC 429 Transmitter</td>
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<td>Reverser Control</td>
<td>A/C</td>
<td>X</td>
<td>Airframer Requirement</td>
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<td>Probe Heat Control</td>
<td>A/C</td>
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<td>Airframer Requirement</td>
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<tr>
<td>Fuel On/Off Control</td>
<td>A/C</td>
<td>X</td>
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<td>Ignition Control</td>
<td>A/C</td>
<td>X</td>
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<td>Full Autostart</td>
<td>SCU</td>
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<td>MINIMUX Features</td>
<td>SCU</td>
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<td>Power convert (115 VAC)</td>
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<td>Mass Wf Transmission</td>
<td>EBU</td>
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<td>Oil Quantity Transmission</td>
<td>EBU</td>
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<td>NAC Temperature Transmission</td>
<td>EBU</td>
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<td>Pon Transmission</td>
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<td>TIDG Oil Transmission</td>
<td>EBU</td>
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<td>Low NOX Burner System Control</td>
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<td>Oil AP Transmission</td>
<td>EBU</td>
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<td>Fuel AP Transmission</td>
<td>EBU</td>
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<td>Ram Air Turbine Deploy Signal</td>
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<td>HP Customer Bleed Valve Override</td>
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<td>Holdup Power</td>
<td>SCU</td>
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<td>PMA Health Monitor</td>
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<td>Airframer Requirement</td>
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</table>
CONTROL REQUIREMENTS GROWTH

Doubling per decade

- PW2037
- PW4000
- V2500
- C-17
- PW4168
- F119
- LoNOx
- PWC
- ADP
- STOVL
- HSCT

Product requirements adversely impact:
- Cost
- Weight/size
- Reliability
- Maintainability

System inputs and outputs

Technology transition year

1980 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
TO DATE, THE CONTROL STRATEGY HAS NOT CHANGED

• OPEN LOOP SCHEDULING
• CLOSED LOOP CONTROL
ADVANCED ENGINE CONTROLS

- GREATER ENGINE EFFICIENCY
- SIMPLIFIED EXTERNALS
- REDUCED WEIGHT
- LONGER SERVICE LIFE

[Diagram of engine controls showing various components such as active stability control, integrated ECS/stability bleeds, closed loop active clearance control, electromagnetic actuators, distributed control electronics, demand controlled fuel pump, and electromagnetic rotor bearings.]
ADVANCED ENGINE CONTROL POTENTIAL

ACTIVE CONTROL ENGINE

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>BENEFIT</th>
</tr>
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<tbody>
<tr>
<td>TOTAL SYSTEM BLEED MANAGEMENT</td>
<td>FUEL BURN</td>
</tr>
<tr>
<td>AIRCRAFT/ENGINE DRAG OPTIMIZATION</td>
<td>FUEL BURN</td>
</tr>
<tr>
<td>NACELLE BOUNDARY LAYER CONTROL</td>
<td>FUEL BURN</td>
</tr>
<tr>
<td>CLOSED LOOP CLEARANCE CONTROL</td>
<td>FUEL BURN</td>
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<tr>
<td>CLOSED LOOP TURBINE COOLING CONTROL</td>
<td>FUEL BURN</td>
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<tr>
<td>ACTIVE COMPRESSOR STABILITY CONTROL</td>
<td>FUEL BURN</td>
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</table>
ADVANCED ENGINE CONTROL POTENTIAL

MORE ELECTRIC ENGINE

<table>
<thead>
<tr>
<th>Component</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>INTEGRAL STARTER/GENERATOR</td>
<td>WEIGHT</td>
</tr>
<tr>
<td>DISTRIBUTED ELECTRONICS</td>
<td>WEIGHT</td>
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<tr>
<td>ELECTRICAL ACTUATION</td>
<td>WEIGHT</td>
</tr>
<tr>
<td>DEMAND CONTROL FUEL PUMP</td>
<td>WEIGHT</td>
</tr>
<tr>
<td>MAGNETIC BEARING</td>
<td>WEIGHT</td>
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</table>
GE Aircraft Engines
Advanced Engine Control Issues

RS Carpenter
3/21/94
Overview of Topics

- Overall Technology Base
- Technology Trends in Controls Functionality
- Design Methods
- Unique Helicopter Issues
- Unique Land Vehicle Issues
- Conclusions
GEAE CONTROLS TECHNOLOGY BASE

GE Aircraft Engines
GEAE Controls Technology

- In last decade GEAE has made major commitment to introduce “State of the Art” controls on all new product engines
- GEAE Experience on all product lines directly relates to future new product control needs
- Emphasis on appropriate application of advanced control concepts, and I&RD/ Demonstrator program spin-offs to meet real world design requirements

GEAE COMMITTED TO BE LEADER IN ENGINE CONTROL SYSTEM TECHNOLOGY
COMMERCIAL ENGINE TECHNOLOGY

- Dual Channel FADEC Red. Mgmt
  - < 2/10^6 IFSD
  - Power Management
  - Performance Seeking Control
  - Auto Starting

- 40 Million+ Hours Flight Experience on Digital Engine Controls

FITGHTER ENGINE TECHNOLOGY

- Consistent Transient Times
  - FADEC Testability/Fault Isolation
  - Integrated Flight/Propulsion Control

NEW ENGINE APPLICATION

TURBOSHAFT/TURBOPROP ENGINE TECHNOLOGY

- Engine Design for Rapid SHP Response
- Max Torque Rate Attenuator Generation and Response to Load Demand Signal
- Closed Loop Gas Generator Trans. Control

GENERIC TECHNOLOGY

- Beacon Autocode
- Multivariable Control Design Methodology
- System Design Tools
- Simulation Capability
- Technology Program Spinoffs

GE Aircraft Engines
ADVANCED CONTROL LAW TECHNOLOGIES

|------|------|------|------|------|------|------|------|------|------|------|------|------|

**Army**
- LV100
  - Multivariable Control

**Navy**
- ARTERI
  - Component Tracking Filter, Component Level Model, Fault Detection, Fault Isolation, Fault Accommodation
- DMICS
  - Functional Partitioning & Specification

**USAF**
- PSC
  - On-Line Performance Optimization
- SUBEC
  - Battle Damage Reconfiguration
- IEC
  - Model Based Direct Power Controls
- NASA
  - US/Canada STOVL
  - IFPC: Functional Design/Handling Qualities
- ICLE
  - VMS Physical Integration
- ASTEC
  - Redundant, Parallel Processing
- PROLIFIC
  - IFPC: Redundant Hardware

**Technologies Which Can Impact Future Systems Based on Customer Requirements**

GE Aircraft Engines
# Glossary of Terms

**Contracts**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARTERI</td>
<td>Analytical Redundancy Technology for Engine Reliability Improvement</td>
</tr>
<tr>
<td>ASTEC</td>
<td>Advanced Simulation Technology for Engine Control</td>
</tr>
<tr>
<td>DMICS</td>
<td>Design Methods for Integrated Control Systems</td>
</tr>
<tr>
<td>FOCSI</td>
<td>Fiber Optic Control System Integration</td>
</tr>
<tr>
<td>ICLE</td>
<td>Integrated Control Law Evaluation</td>
</tr>
<tr>
<td>IEC</td>
<td>Intelligent Engine Control</td>
</tr>
<tr>
<td>INTERFACE</td>
<td>Integrated, Reliable, Fault Tolerant Control for Large Engines</td>
</tr>
<tr>
<td>PROLIFIC</td>
<td>Propulsion Critical Integrated Control</td>
</tr>
<tr>
<td>PSC</td>
<td>Performance Seeking Control</td>
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<tr>
<td>SUBEC</td>
<td>Survivability Based Engine Control</td>
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**Other Terms**

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>PMC</td>
<td>Power Management Control</td>
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</table>
Control Technology Trends

Capability for "Intelligent" Control

Facilitating Factors

Control Architecture

- Control I.Q.
- and Authority

Time

Processor capability
Memory Affordability
Design Methodology
System & S/W process

- 16 Bit > 32 Bit > Fast 32 Bit floating point with CACHE
- >16 X growth in digital control memory capacity
- Great advances in multivariable design methods, simulation capability, computer horsepower, and smorgasboard of "intelligent" concepts
- Integrated control law design/analysis with pictures to code system allows affordable usage of complex control laws

- Great advances in ability to develop/incorporate intelligent engine control features

- Dual FADEC
- FADEC & Backup
- Supervisory Digital
- Supervisory Analog
- Hydromechanical
EVOLUTION OF INTELLIGENCE

- NATURAL EVOLUTION OF CONTROL FUNCTIONALITY TO RELY ON INTELLIGENT CONTROL TECHNIQUES TO HELP MEET EVER TIGHTER PERFORMANCE REQUIREMENTS
**GOVERNOR LOOP DESIGN**

**INTELLIGENCE**

- **HIGH PERFORMANCE DIGITAL MIMO W/GAIN SCHEDULING**
- **SOPHISTICATED GAIN SCHEDULING**
- **DIGITAL ELECTRONIC ISOCRONOUS**
- **ANALOG ELECTRONIC ISOCRONOUS**
- **HYDROMECHANICAL DROOP (PROPORTIONAL)**

**TIME**

---

**BENEFITS**

- Consistent high performance over operating regime, SS SFC
- Consistent high performance over operating regime
- Improved accuracy/performance
- Improved accuracy/performance
- No EMI or electrical power loss issues

**COMMENT**

- Current approach on dev/demo programs
- Current approach when MIMO N/A
- Added flexibility for gain/dynamics tailoring

---
CONTROL SCHEDULING

**BENEFITS**

- Optimized system SFC,
  EN, NOISE,
  EMISSIONS

- Higher performance,
  W/MARGIN, W/O
  EXTRA SENSORS

- Exploit engine perf
  while holding
  STALL/SFC MARGIN

- Set required
  power for
  mission phases
  automatically

- Improved
  flexibility
  to tailor
  scheduling

- Allowed
  scheduling to
  non-constant
  limits

**COMMENT**

- Part of IFPC study
- On GE CERTIFIED ENGINES
- Control cycle param
  beyond just sensor set
- GE commercial production
TRANSIENT CONTROL STRATEGY

WEIGHT

COLLECTIVE

PEDALS

CYCLIC

AIRMSPD

LOAD

MODEL

INTEGRATED LOAD FACTOR FOR TURBOSHAFT

OPTIMIZED TRANS YG/AIRFLOW CONTROL

DIRECT RATE OR TRAJECTORY CONT OF N, TORQUE, ETC

BASIC CORE NDOT CONTROL

SIMPLE COLLECTIVE BASED FEEDFORWARD FOR TURBOSHAFT

WF/PS3 CONTROL

ACCEL

DECEL

\( N/3 \)

\( N/5 \)

ACCEL

DECEL

COLLECTIVE

\( N_6 \)

\( N_6 \)

WF/PS3

CONTROL

TIME

MORE RAPID

POWER RESPONSE/

DISTURBANCE

REJECTION

SHORTER FF

REDUCES

"UNCOMPENSATED"

MANEUVERS

IN PRODUCTION.

OPTIMIZED

PERFORMANCE,

LIMIT PROTECT,

HANDLING

QUALITIES

STALL MARGIN,

LIFE, TRANSIENT

CONSISTENCY

EFFECTIVE LOAD

ANTICIPATION FOR

MOST COLLECTIVE

TYPE MANEUVERS

GOOD BASIC

STALL/ BLOWOUT

PROTECTION AND

TRANSIENT

HANDLING

COMMENT

COMBINED W/ ALL BELOW FOR MIXED MODE TRANS CONTROL THAT FULLY EXPLOITS ENGINE CYCLE CAPABILITY
ENGINE OPERABILITY CONTROL

<table>
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<tr>
<th>BENEFITS</th>
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<tr>
<td>ACTIVE COMPRESSOR STABILIZATION</td>
<td>RESEARCH PHASE</td>
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<tr>
<td>ACTIVE STALL RECOVERY</td>
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<tr>
<td>INTELLIGENT INLET BUZZ PREVENTION</td>
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<tr>
<td>HIGH-BANDWIDTH PRESSURE RATIO CONTROL</td>
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<tr>
<td>UNIQUE TRANSIENT VG SCHEDULING</td>
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</tr>
<tr>
<td>GE MIXED MODE TRANSIENT CONTROL, W/NDOT</td>
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<tr>
<td>WF/PS3 ACCEL/DECEL AND SIMPLE VG SCHEDULING</td>
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</tr>
<tr>
<td>ENHANCED STALL RECOVERY</td>
<td>UNIQUE DETECTION AND CONTROL SCHEDULING</td>
</tr>
<tr>
<td>FASTER SUPersonic DECELS</td>
<td>SUPersonic APPLICATIONS ONLY!!!</td>
</tr>
<tr>
<td>LIGHT OF-LINE CONTROL FOR REDUCED STALL MARGIN LOSS</td>
<td>ENGINES WITH VARIABLE EXHAUST NOZZLE</td>
</tr>
<tr>
<td>BUYS TRANSIENT STALL MARGIN, ALLOWS USING FULL CYCLE ACCEL/DECEL CAPABILITY</td>
<td>INDEPENDENT BLEED ON AXI-CENTRIF MACHINES</td>
</tr>
<tr>
<td>SAME AS ABOVE</td>
<td>BLEND OF WF/PS3,NDOT, TRAJECTORY AS APPROPRIATE</td>
</tr>
<tr>
<td>BASIC OPERABILITY, STALL RECOVERY, BLOWOUT PROTECTION</td>
<td></td>
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</tbody>
</table>
STARTING

- BENEFITS
  - HANDLES BROAD RANGE OF FUEL TYPES, NATURAL GAS FOR M&I
  - FULLY HANDS OFF, EYES OUT OF COCKPIT
  - SUCCESSFUL START FOR WEAK STARTER, LEAN FUEL SCHEDULE
  - COOL, CONSISTENT, RELIABLE STARTS OVER ENHANCED START ENVELOPE
  - HOT PARTS PROTECTION
  - RAPID RECOVERY FROM FLAMEOUT
  - GOOD BASIC AUTOMATIC START FUEL SCHEDULING

- COMMENT

- FULLY AUTOMATIC STARTING
- SUCCESSFUL START FOR WEAK STARTER, LEAN FUEL SCHEDULE
- COOL, CONSISTENT, RELIABLE STARTS OVER ENHANCED START ENVELOPE
- HOT PARTS PROTECTION
- RAPID RECOVERY FROM FLAMEOUT
- GOOD BASIC AUTOMATIC START FUEL SCHEDULING

- ADAPTIVE START FLOW SCHEDULING
- HUNG START PREVENTION
- NOT STARTING AND VARIABLE MIN FLOW
- AUTO RESTART/RELIGHT
- FIXED MIN FLOW PLUS WF/PS3 SCHEDULE

INTELLIGENCE
<table>
<thead>
<tr>
<th>TIME</th>
<th>FAULT DETECTION AND RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>BENEFITS</strong></td>
</tr>
<tr>
<td></td>
<td><strong>COMMENT</strong></td>
</tr>
<tr>
<td></td>
<td>FUZZY-LOGIC IN- RANGE FAULT ACCOMMODATION</td>
</tr>
<tr>
<td></td>
<td>ANALYTIC REDUNDANCY</td>
</tr>
<tr>
<td></td>
<td>PHYSICAL REDUNDANCY</td>
</tr>
<tr>
<td></td>
<td>SOPHISTICATED SYSTEM LEVEL ERROR CHECKING</td>
</tr>
<tr>
<td></td>
<td>BASIC BIT: CPU TESTS, RANGE TESTS</td>
</tr>
<tr>
<td></td>
<td>SIMPLE FAILSAFE RESPONSE</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit</td>
<td>Comment</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Isolates To Faulty Component (WRA) Or SRA</td>
<td>Processes Raw BIT Info, INITs Added Tests And Applies &quot;Knowledge&quot; Based Type Reasoning</td>
</tr>
<tr>
<td>Records What Was Happening In Vicinity Of Fault Events</td>
<td></td>
</tr>
<tr>
<td>Integration W/ Cockpit Display, Ground Based Diag System</td>
<td></td>
</tr>
<tr>
<td>Communicate Results Of BIT For Troubleshooting</td>
<td>Electro-Mechanical Balls</td>
</tr>
<tr>
<td>Measure Control Params w/ or without Dissassembly Controls</td>
<td></td>
</tr>
</tbody>
</table>
Simulation of an F404 engine upon receiving combat damage to the high pressure compressor case shows capabilities of advanced controls in maximizing performance. Here, SuBEC control algorithms actuate most of the thrust loss that would result with usual control laws.

**Survivability Based Engine Control**
- Maintain safe engine thrust for engine damage
- Fail operational with control failures
- Reduced fire hazard
- Reduced control component vulnerability

**Control Fault Tolerance and Redundancy**
- Damage detection & adaptive/model-based control
- Minimize/control damage caused leaks

**Fuel System Design**
- Control component placement

**Time**
<table>
<thead>
<tr>
<th>FEATURE</th>
<th>BENEFITS</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Annular Combustor, Active Flame Temp Ctrl</td>
<td>Controlled NOx and CO w/o Steam</td>
<td>Applicable to M&amp;I &amp; Aircraft</td>
</tr>
<tr>
<td>Steam Injection</td>
<td>Reduced Nitrous Oxide Emissions</td>
<td>Applicable to M&amp;I only</td>
</tr>
<tr>
<td>Afterburner Vapor Puff Prevention</td>
<td>Reduced Incidence of Visible Vapor Puff during A/B Start/Shutdown</td>
<td></td>
</tr>
<tr>
<td>Fuel Recycle Unit</td>
<td>Addresses Liquid Fuel Discharge During Shutdown</td>
<td></td>
</tr>
<tr>
<td>Smokeless Combustor</td>
<td>Burns Clean w/o No Visible Smoke (Control Engineers Dream) Strategies!</td>
<td></td>
</tr>
</tbody>
</table>
MODEL BASED CONTROL

- CRITICAL PART OF TODAY'S DESIGNS... SOME EXAMPLES:

  MODELS USED TO ACHIEVE SENSOR TIME CONSTANT CORRECTION, AFTERBURNER FUEL SCHEDULING, AND LOW EMISSIONS BY CONTROLLING PREDICTED FLAME TEMPERATURE

  INPUT SENSOR AND SERVO LOOP FAILURE DETECTION, SENSOR VOTING, AND SENSOR SUBSTITUTION

  IMPLIED T41 AND STALL MARGIN BUILT INTO SMART REFERENCE SCHEDULES

  SIMPLE MAP MODELS OR MORE COMPLEX COMPONENT LEVEL EMBEDDED MODELS USED DEPENDING ON ACCURACY REQUIREMENTS

- INCREASING ROLE IN THE FUTURE:

  INCREASED EMPHASIS ON DESIGN FOR SURVIVABILITY (DETECTION AND RECONFIGURATION FOR BATTLE DAMAGE)

  INTEGRAL PART OF PERFORMANCE SEEKING CONTROL

  DIRECT CONTROL TO MODEL BASED PARAMETERS

  GREATER USE OF ANALYTIC REDUNDANCY

  TREND MONITORING AND DIAGNOSTICS

  INCREASED VEHICLE SYSTEM INTEGRATION/OPTIMIZATION
CONCLUSIONS ON EVOLUTION

- SUBSTANTIAL EVOLUTION IN CONTROL STRATEGIES HAS BEEN OCCURRING, WITH ASPECTS OF INTELLIGENT CONTROL PHASING INTO PRODUCT AND NEAR TERM DEVELOPMENT PROGRAMS

- GENERALLY DRIVEN BY SPECIFIC PROGRAM NEEDS AS CUSTOMERS CONTINUE TO ASK FOR MORE FROM THEIR ENGINES
REGARDING TOOLS

- COMPREHENSIVE TOOLS FOR DESIGN, ANALYSIS, AND SIMULATION HELP MAKE INTELLIGENT CONTROL MANAGEABLE
<table>
<thead>
<tr>
<th>Component Level</th>
<th>Benefit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Model</td>
<td><strong>Full Control System H/W in the Loop Facility</strong></td>
<td><strong>Comprehensive Control System Simulation Capability</strong></td>
</tr>
<tr>
<td></td>
<td>Highly Frequency Modelling: Fuel System/Engine</td>
<td>Allows greatest non-linear, performance in today's highly coupled systems</td>
</tr>
<tr>
<td></td>
<td><strong>Auto-Generated Complete Control Model</strong></td>
<td>Rapid availability of error free complete control model</td>
</tr>
<tr>
<td></td>
<td><strong>Closed Loop FADEC Test With Real-Time Model</strong></td>
<td>Verification of control law implementation prior to engine</td>
</tr>
<tr>
<td></td>
<td><strong>Integrated Engine/Vehicle System Model</strong></td>
<td>Vehicle/Engine interactions, and prediction of handling and qualities</td>
</tr>
<tr>
<td></td>
<td><strong>Component Level Engine Model</strong></td>
<td><strong>Vital for helicopter, tiltrotor, VSTOL, and land vehicles</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Piece-Wise Linear Engine Model</strong></td>
<td>Most accurate for optimization/GE's CWS, cycle work-station sys</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compact, dynamically accurate simulations</td>
</tr>
</tbody>
</table>
GE'S BEACON SYSTEM:
PROVIDES INTEGRATED CONTROL LAW DESIGN, IMPLEMENTATION, AND TEST,
WITH DRAMATIC TOTAL PROCESS COST AND CYCLE TIME REDUCTION,
QUALITY ENHANCEMENT, AND SIGNIFICANT REDUCTION IN MANUAL STEPS

Simplified Process Diagram

OLD PROCESS

ENGINEER HAND SKETCHES DESIGN

MANUALLY CODE SIMULATION

RUN SIMULATION TO ASSESS DESIGN

CAD SYSTEM TO DRAW DIAGRAMS

TYPE IN SPEC TEXT, TABLES, I/O LIST

DETAILED FADEC CODE DESIGN

GENERATE FADEC CODE

GENERATE TEST VECTORS

EXPECTED TEST RESULTS

ACTUAL S/W TEST (AUTOMATED)

BENCH, ENGINE, VEHICLE TEST

BEACON OUTPUTS

ENGINEER CREATES BEACON DIAGRAM

* RUN SIMULATION TO ASSESS DESIGN

* GENERATE TEST VECTORS

* EXPECTED TEST RESULTS

* ACTUAL S/W TEST (AUTOMATED)

BENCH, ENGINE, VEHICLE TEST

* = AUTOMATED COMPUTER UTILITIES AND BEACON OUTPUT USED TO ACCOMPLISH THIS TASK

NOTE: FOR CLARITY, DESIGN ITERATION IS NOT SHOWN, NOR ARE ALL DETAILED PROCESS STEPS
LINEAR ISSUES:

NEED TOOLS THAT ALLOW CONSTRAINED STRUCTURE CONTROL LAW SYNTHESIS.

Currently, most multivariable designs are done using Model Matching (KQ) because company developed software allow controller structure constraints to be entered before optimization. Other toolboxes such as H Infinity do not provide this capability.

Linear analysis tools such as Structured Singular Values are well developed and meet our needs better than the linear design tools.

NONLINEAR ISSUES:

NEED A MORE ANALYTICAL APPROACH TO NONLINEAR DESIGN

Currently depend solely on transient simulations to evaluate nonlinear stability.

Multivariable/Multimode Selection Logic (Limit Protection, Stability).

How to guarantee that approaching a linear governor from a new direction will not cause limit cycling due to nonlinearities such as gain kickers.
Unique Helicopter Issues

- **Background**
  - Extensive GE Experience on Helicopter applications through T58/T64/T700 product line
  - Numerous military/commercial applications, including single/dual/triple engines

- **Unique Issues**
  - Helicopter applications inherently a challenging load disturbance rejection problem
  - Increasingly aggressive maneuvers, low rotor inertia, low transmission torque limit, and eyes out of cockpit flying result in increased performance demands on engine/ control and drive control law complexity
  - Multiple engines coupled through rotor system drivetrain drives need for load share function & good OEI strategies
  - New VSTOL designs require mode transition
  - Difficult to specify aircraft handling qualities drivers on engine system performance
• Past Approach
  - Highly refined supervisory electrical control architecture cost effectively meets today’s performance demands
  - NP and load share loops spectrally separated
  - Collective based load anticipation signal
  - NP governor adapts gains based on rotor coupled/decoupled, and NP error/rate conditions
  - Torque trajectory shaping employed to control rate of torque rise at power

• Relevant Technologies For Future Application
  - FADEC for stringent performance requirements, cockpit integration, and fail operational capability
  - Higher bandwidth NP governing (with combustive damping) for load rejection in light of continued trend of aggressive maneuvers and low rotor inertias
  - True NP/Q mimo design with optimized gain scheduling for tight loadshare and torque trajectory performance
  - Intelligent load factor allowing compensation for pedal and cyclic inputs
  - Multi-mode transient control for fastest/consistent accel
  - VG overclosure during autorotation to enhance axi-centrif machine power vs. NG characteristic
  - Integrated vehicle management allowing interchange of limits and other info for optimal vehicle system control
  - Integrated vehicle/engine PSC for optimizing total system (E.G. tailor Nr for best cruise fuel burn, noise,maneuver load capability, etc.)

GE will continue to draw on Experience across product lines and appropriate advanced technologies to provide cost effective helicopter controls that meet operational needs
Unique Land Vehicle Issues

- **Background**
  - LV100 Demonstrator program ongoing since early 80’s sponsored by US ARMY Tank-Automotive Command
  - Technology Demonstration of Electric Actuation/Fuel pump and multivariable control

- **Unique Issues**
  - Minimizing idle fuel flow and attaining great SFC are key
  - Engine cycle utilizes recuperator to help achieve above
  - Variable area turbine nozzle (VATN) allows greatest realization of recuperator benefits
  - Multivariable control of core speed and turbine discharge temperature allow near minimum SFC over power range
  - Normal control operation is analogous to turboprop control, throttle controls engine power, “load” controls power turbine speed
Comparison of Engine Cycles; Benefit of Recuperator and VATN. The sfc of a recuperated turboshaft is significantly lower than that of a standard turboshaft.
Hydro-Kinetic Transmission

Transmission Shifts Gears

Vehicle speed

Electric Drive Train

Np Topping

Np Bottoming

Np Topping

Np Set for optimal power pack Performance

Np Bottoming

Vehicle speed

Output load varies at constant Np, as in aircraft applications
• **Unique issues (cont’d)**
  - Low cost another key requirement, drives reduced sensor set
  - Adaptive starting and decel control for range of fuel types and recuperator heat soak conditions
  - Multi-mode transient control with varying recuperator heat input back into cycle
  - Load loss/management impact on overspeed potential with recuperator
  - Engine dynamics with recuperator
  - Transient VATN control (opening VATN quickly accels gas generator, but can cause power dip)
  - Control of auxiliary functions (e.g. blowers)
  - Reflected vehicle inertias impact on Np governor design

• **Potential Future Relevant Technologies**
  - PSC for optimal engine performance over life with reduced sensor set
Conclusions

- Advances in methodology and computer horsepower have placed plethora of intelligent control possibilities at disposal of control system developers.
- Digital control processor power can be available as needed, but costs $'s and weight... advanced features generally need to buy their way onto engine through life cycle cost savings or addressing stringent performance requirements.
- Increased dependency on model based approaches for enhanced performance, better SFC, reduced emissions, and enhanced fault tolerance.
- Fuzzy logic concepts providing benefits in area of soft fault tolerance.
- Performance seeking control holds promise for turbofan/turboprop SFC/thrust benefits, and helicopter cruise fuel burn/noise reduction.
- Integrated system design and control/engine/vehicle simulation tools help make complexity manageable.
- Additional work needed on multivariable design techniques to better address real world constraints.

"Intelligent" Control Concepts will continue to play a vital role in meeting ever more demanding performance requirements.
THE PROMISE OF ACTIVE CONTROL FOR HELICOPTER AND TANK ENGINES

ARUN K. SEHRA
MANAGER, COMPRESSOR AERODYNAMICS
TEXTRON LYCOMING, STRATFORD, CT 06468

WORKSHOP ON INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATION
MARCH 21-22, 1994
M.I.T., CAMBRIDGE, MASS
CONCLUDING MESSAGE

ISSUES & CONCERNS

- TANK ENGINE APPLICATION
- HELICOPTER ENGINE APPLICATION
- ACTIVE STABILIZATION - PAYOFFS & OPERABILITY ENHANCEMENT
- COMPRESSOR/ENGINE OPERABILITY

AGENDA
COMPRESSOR OPERATING ENVELOPE

- Pressure Ratio
- Unstable
- Surge Initiated by Rear Stages
- Surge Line
- Operating Envelope
- Choke Line
- Limiting Flow
- Set by Front Stages
- 100% Nr
- Rotating Stall
- Windmilling Line
- Inlet Referred Flow
STABILITY AUDIT

- Manufacturing Tolerance
- Inlet Distortion
- Compressor Deterioration
- Reynolds Number

- Nominal Surge Line
- Remaining Surge Margin
- State Operating Line
- Nominal Steady
- Corrected Speed

- Engine Tolerance Transients

COMPRESSOR REFERRED FLOW

COMPRESSOR PRESSURE RATIO
# SURGE MARGIN ENHANCEMENTS

<table>
<thead>
<tr>
<th>SM ENHANCEMENT DEVICE</th>
<th>ENGINE</th>
<th>IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add More Stage(s)</td>
<td></td>
<td>Inc. Size, Wt., &amp; Complexity, Reduced Reliability</td>
</tr>
<tr>
<td>Increased Speed</td>
<td></td>
<td>Inc. Wt., Reduced Eff.</td>
</tr>
<tr>
<td>Variable Geometry *</td>
<td>AGT1500 &amp; T53</td>
<td>Inc. Wt. &amp; Complexity, Reduced Eff.</td>
</tr>
<tr>
<td>Bleeds *</td>
<td>All Engines</td>
<td>Inc. Wt. &amp; Complexity, Reduced Eff. &amp; Power</td>
</tr>
<tr>
<td>Casing Treatment *</td>
<td></td>
<td>Reduced Eff.</td>
</tr>
<tr>
<td>Dual Spooling *</td>
<td>AGT1500</td>
<td>Inc. Wt., Size, &amp; Complexity</td>
</tr>
<tr>
<td>Other Devices</td>
<td>LTS101</td>
<td></td>
</tr>
</tbody>
</table>

* Primarily for part speed surge margin
ACTIVE STABILIZATION

PAYOFFS

- IMPROVED OPERABILITY RANGE
- IMPROVED SPECIFIC FUEL CONSUMPTION
  - HIGHER CYCLE PRESSURE RATIO
  - HIGHER EFFICIENCY
ACTIVE STABILIZATION
APPLICATION TO HELICOPTER & VEHICULAR ENGINES

Results of an In-house study corresponding to a 10% reduction of surge margin requirement for the following Lycoming engines:

- T55
- COMMON CORE (T55 DERIVATIVE)
- LTS101
- AGT1500
ACTIVE SURGE CONTROL PAYOFFS

T55

DESIGN PT. SFC REDUCTION: 4.0%

IDLE FUEL CONSUMPTION REDUCTION: 5.6%

OPERABILITY FROM 25 K TO 39 K FEET ALTITUDE

STEADY STATE INLET PRESSURE DISTORTION
CAPABILITY DI FROM 0.03 TO 0.23

where DI = \( \frac{P_{\text{mean}} - P_{\text{low mean}}}{P_{\text{mean}}} \) \times KP

KP = Factor to account for shape, extent, & radial content
    = \sqrt{MER}
ACTIVE STABILIZATION OF T55 ENGINE

TEST RIG
ACTIVE STABILIZATION OF T55 ENGINE

OBJECTIVE: DEVELOP AN A.S. SYSTEM FOR LOW/HIGH SPEED APPLICATION ON AN ENGINE USING AXIAL-CENT. COMPRESSOR

PROGRAM STATUS:

• RIG TESTING WITH DYNAMIC INSTRUMENTATION COMPLETED (AVPD/NASA T55 STRAT-UP STALL PROGRAM)
• DYNAMIC MODELING UNDERWAY AT MIT
• PROPOSALS SENT TO NAVY/NASA FOR A.S. SYSTEM DEVELOPMENT
ACTIVE SURGE CONTROL PAYOFFS

COMMON CORE

DESIGN POINT SFC REDUCTION: 3.3%

MAX. CRUISE SFC REDUCTION: 2.4%

IDLE FUEL CONSUMPTION = -6.6%

OPERABILITY: FROM 30 K TO 50 K FEET ALTITUDE
ACTIVE STABILIZATION OF LTS101 ENGINE

(JOINTLY SPONSORED BY NAVY)

OBJECTIVE: DEVELOP AN A.S. SYSTEM FOR HIGH SPEED OPERATION ON AN ENGINE HAVING A HIGH PRESSURE RATIO CENTRIFUGAL STAGE

PROGRAM STATUS:

- MODIFIED AN LTS101 ENGINE FOR ACTIVE STABILIZATION APPLICATION
- DYNAMIC MODELING COMPLETED
- FORCED RESPONSE TESTING USING INBLEED AT ROTOR INLET COMPLETED
- FORCED RESPONSE TESTING USING THROAT INBLEED UNDERWAY
LTS101 COMPRESSOR
4.0% SAVING IN IDLE FUEL CONSUMPTION
3.7% INCREASE IN SPECIFIC POWER

PRESSURE RATIO

(4.2% SFC REDUCTION)

DESIGN POINT

105% Nr

97.5% Nr 100% Nr

INLET REFERRED FLOW
ACTIVE STABILIZATION OF LTS101 ENGINE

TEST RIG
AGT 1500 HIGH PRESSURE COMPRESSOR

2.6% SAVING IN IDLE FUEL CONSUMPTION

(POTENTIAL UPTO 10%)

PRESSURE RATIO

INLET REFERRED FLOW
ACTIVE STABILIZATION
ISSUES AND CONCERNS

SEVERAL UNKNOWNs ABOUT ACTIVE STABILIZATION SYSTEM:

- EFFECTIVENESS IN ENGINE ENVIRONMENT
- RELIABILITY
- ACTUATOR DEVELOPMENT SCHEDULE
- DEVELOPMENT COST AND SCHEDULE
- PRODUCTION COST
- WEIGHT
CONCLUDING MESSAGE

AN EARLY CONCEPT DEMO ON AN ENGINE IS VERY IMPORTANT PRIOR TO A MAJOR INVESTMENT BY ENGINE COMPANIES

AND

BASIC RESEARCH MUST CONTINUE
MIT RESEARCH IN
ACTIVE COMPRESSOR STABILIZATION

Presented to the Workshop on
Intelligent Turbine Engines for Army Applications
March 21-22, 1994

A. H. Epstein  E. M. Greitzer  G. R. Guennette  J. D. Paduano  C. S. Tan

OUTLINE

- Background
  - Goal of Active Control
  - Surge and Rotating Stall in Compressors

- Surge Control
  - Results - High-Speed Centrifugal Turbocharger
  - Current Research - Centrifugal Gas Turbine Surge Control

- Rotating Stall Control
  - Results in Low Speed Axial Compressors
  - Modeling and Detection in High Speed Compressors
  - Current Research in Control of R/S in High Speed Compressors
GOAL OF ACTIVE STABILIZATION
- Safe Operation at Higher Performance Levels -

- System study projects 8% reduction in GTOW or 11% longer range

NATURAL OSCILLATORY MODES OF COMPRESSORS

Lowest Order

Higher Order

Surge

Rotating Stall
SURGE AND ROTATING STALL IN GAS TURBINES

- Rotating Stall Generally Precedes Surge
  - Often eventually leads to surge

- Depending on Machine, May Choose to Control Surge and Not R/S
  - Centrifugals, axicentrifugals: surge control alone may pay off
    rugged compressors
    'progressive', recoverable rotating stall
    surge is first debilitating instability

  - Axial, multistage compressors - R/S control required
    rotating stall is abrupt, debilitating
    control surge alone ⇒ deep, nonrecoverable stall

COMPARISON OF RECOVERABLE AND DEEP ROTATING STALL

--- Compressor test, no surge
----- Unstable axisymmetric map, no rotating stall
---------- Rotating stall

![Graph of Pressure Rise vs Mass Flow](image)

Centrifugal Compressors, Fans, and Blowers

Axial Compressors
EARLY SURGE CONTROL RESULTS

- Rig Demonstration (Pinsely et al., 1988)
  - High speed (90,000 Rpm) centrifugal supercharger
  - 100 Hz valve actuating downstream or plenum bleed
  - Demonstrated 20-25% operating range extension

- Dynamic Control Through Tailored Structures (Gysling, 1991)
  - Movable plenum wall w/ tailored structural dynamics
  - Tuned to act as passive damper for surge oscillations
  - Demonstrated 25% operating range extension

- Detailed Sensor/Actuator Placement Studies (Simon, 1991)
  - Sensor and actuator type, placement are pivotal
  - Close-coupled actuation is a key to success
  - Highly multidisciplinary endeavor

STUDYING ALTERNATE IMPLEMENTATION STRATEGIES

Integrates control theory, engine design, fluid mechanics, experimentation, aeroelastics
CURRENT EFFORTS - ACTIVE SURGE STABILIZATION IN SMALL GAS TURBINES

- Two 650 HP engines on test stands
  - Textron LTS-101 gas producer (turbojet w/ variable area nozzle)
  - Allison 250-C30 turboshift (power turbine and water break)

- Surge Model Extended to Include:
  - Combustor energy dynamics
  - Compressor/turbo shaft dynamics
  - Compressibility
  - Candidate actuation strategies

- Sensor/Actuator Effectiveness Study Complete
  - Diffuser throat injection very promising
  - Fuel modulation least effective

- LTS-101 Modified for Diffuser Throat Injection

LTS-101 INSTRUMENTATION LAYOUT
LTS-101 INSTRUMENTATION LAYOUT

GAS TURBINE PRESENTS NEW CHALLENGES TO ACTIVE CONTROL DESIGN/MODELLING

Turbocharger System
- $\pi_C \sim 2$, $M_T \sim 0.8$
- Simple compact geometry
- "Shallow" characteristics
- Low Helmholtz frequency

G.T. Helicopter Engine
- $\pi_C \sim 8$, $M_T > 1.0$
- Complex geometry
- "Steep" characteristics
- High Helmholtz frequency
- Combustion
- Shaft dynamics
- Very noisy
**ROTATING STALL**  
A Distributed Fluid-Mechanical Instability

Small amplitude circumferential traveling waves:

Large amplitude nonlinear 'rotating stall' cell:

- Rotating Stall Causes Damage, Leads to Surge
- Engine Performance Compromised to Avoid Stall/Surge

**ROTATING STALL STABILIZATION**  
"Distributed" Sensors and Actuators

- stator vanes (IGVs) individually servo-controlled
- wave stabilization increases compressor operating range
ROTATING STALL CONTROL DEMONSTRATIONS
- Low Speed Compressors -

- Single-Stage Axial
  - Original demonstration
  - Modeling, identification, and control concepts & techniques developed

- Three-Stage Axial
  - Verification of 1-stage results on Pratt-designed rig
  - Detailed identification, refinement of fluids models
  - Testbed for advanced modeling and control

- Dynamic Control Using Aeromechanical Feedback
  - Tailored structures coupled to fluid mechanics
  - Proof of passive control concept
  - Close-coupled actuation concept tested

SINGLE-STAGE DEMONSTRATION
18% Operating Range Increase with Active Control

- Control Circumferential Harmonics Independently
  Moore-Greitzer dynamics borne out

- Additional Range For Each Add'l Harmonic
ACTIVELY STABILIZED THREE-STAGE COMPRESSOR

Design Characteristics:
Low Speed $\omega = 2400$ RPM $\phi = C_x/U = 0.6$
High Reaction $R = 0.74$
No Surge $B = 0.16$

PARAMETER IDENTIFICATION RESULTS
and
Refined Theoretical Predictions

rotation rate

$$\omega$$

Experiment
Refined Theory

growth rate

$$\sigma$$

Experiment
Refined Theory
NONLINEAR MODEL VALIDATED AGAINST STALL INCEPTION DATA

AEROMECHANICAL CONTROL OF ROTATING STALL

- 'Passive' system
  - Feedback through dynamic coupling between unsteady flow and structure
- Deflection of structure causes flow injection into annulus
- Circumferential array of 24 reed valves control injection
- Phase of injection set by interaction between stall precursors (pressure perturbations) and reed dynamics
- 10% change in stall point
DYNAMIC CONTROL OF ROTATING STALL USING AEROMECHANICAL FEEDBACK

High Pressure Air

Flexible Cantilever Reed Valve

Rotor

Stator

Air Injection

\[ C_L \]

RANGE INCREASE DUE TO AEROMECHANICAL FEEDBACK

Stall point with unsteady blowing (aeromechanical feedback)

Stall point with no control

Stall point with steady blowing (reeds fixed)

\[ \text{Pressure Rise Coefficient (}\gamma\text{)} \]

\[ \text{Stalling Flow Coefficient} \]

\[ \text{Mass Flow Coefficient (}\Phi\text{)} \]

- Baseline
- Rigid Reed
- Optimized

10% 6%
HIGH SPEED COMPRESSOR STALL CONTROL RESEARCH

- Modeling
  - Compressible 2D Hydrodynamic Stability Model in Place
  - Applied to Industrial Compressor Test Rig Geometries
  - Compressible Modes Explain Experimental Results
  - Control, Sensor/Actuator Studies Underway

- Detection
  - Data from 10 high speed compressors reduced
  - Pre-stall traveling wave energy present in all cases
  - 'Compressible mode' important to stall inception

- Actuation
  - Mass injection currently the most promising
  - Valve hardware designed (Moog and NASA Lewis)
  - Currently investigating fluid mechanics of unsteady blowing

- Initial Control Design Studies Underway

COMPRESSIBLE MODELING OF ROTATING STALL

- 1D Compressible Flow in Blade Passages
- 2D Compressible Flow in Gaps
- Boundary Conditions Link Volumes
- Result - Hydrodynamic Model for Circumferential Harmonics
- Actuation and Sensing Added to Study Control
MODEL PREDICTS
COMPRESSIBLE MODE AT ROTOR FREQUENCY
- this mode can limit operating range -

HIGH SPEED COMPRESSOR PRE-STALL SPECTRA
CURRENT EFFORTS - ACTIVE CONTROL OF ROTATING STALL

• Control With Inlet Distortion on 3-Stage Rig
  - High priority for implementation
  - Modeling, control much more complicated
  - We will 'close the loop' with distortion this Spring

• Mass Flow Injection on 3-Stage Rig
  - Replace inlet guide vanes with injectors
  - Significant performance improvement predicted by 2D modeling
  - Details of implementation will effect performance achieved

• Application of Advanced Control Techniques
  - Robust controller design and implementation
    demonstrated on 3-stage
    developing techniques for use at NASA Lewis
  - Nonlinear analysis and control law design
    goal: enhance large disturbance stability
    applying Lyapunov, absolute stability theory

CURRENT EFFORTS - ACTIVE CONTROL OF ROTATING STALL
- NASA Lewis Project -

• Industrial scale compressor stages
  - Stage 37 - High speed compressor stage \((u_{tip} = 454 \text{ m/s, } h/t = .7)\)
  - Stage 67 - Low hub/tip fan stage \((u_{tip} = 430 \text{ m/s, } h/t = .36)\)

• Mass flow injection, high-bandwidth actuation (300-500 Hz)
  - NASA Lewis & Moog designing linear actuators
  - MIT designing valves and injectors
  - Scale wind tunnel tests \((M=0.5)\) of injection underway

• 3D hydrodynamic stability analysis of rotating stall

• System procedures for eigenvector identification

• Testing at NASA to begin Late 1994
SUMMARY
Stall and Surge Control are Maturing Rapidly

- Evolution of apparatus complexity
  Surge control concept → surge rig → small engines
  R/S control concept → 1 stage → 3 stage → high speed/industrial

- Evolution of maturity of understanding
  - Surge control:
    Lumped model → model w/ actuation → engine scale, environment
  - Rotating stall control:
    Moore-Greitzer → unsteady losses → distortion → high speed, 3D, nonlinear

- Each evolutionary stage has been successful to date
  - Still much to do, but confidence is high

- New multidisciplinary concepts are emerging out of necessity:
  'Close-coupled' actuation
  System identification of fluid processes
  Passive aeromechanical control
  Wave energy for detection
  Interaction of compressible and acoustic modes
Progress in Modeling & Control of Compressor Stall

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Dynamic Systems & Controls

PW Joint Program Subelement Manager,
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Intelligent Turbine Engines for Army Applications
Cambridge, MA (MIT)
March 21, 1994
Key UTRC Contributors

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Obstacles and Related Issues

- Highly nonlinear phenomena characterized by bifurcations
  - relevancy of linear perspective
- 3D distributed unsteady compressible flow phenomena
  - model uncertainty (unknown physics and parameters)
  - model complexity
  - number, locations, and types of actuators and sensors
- Relatively high frequency phenomena
  - sensor and actuator bandwidths
  - digital processor throughput
- Inherently noisy and hostile operating environment
  - sensing and actuation constraints
- Complex interactions with overall system and operating environment
Stability Enhancing Control Concepts

- 2D HF Actuation, 2D HF Sensing
  - Active Linear Feedback Stabilization
  - Extend stable operating range

- Clearance Sensors, Clearance Actuators
  - Dynamic Closed-Loop Active Clearance Control

- 1D HF Actuation, 2D HF Sensing
  - Dynamic Closed-Loop Active Stall Margin Control

- Reduce line / margin variability
  - Coordinated Multivariable Dynamic Control
  - Existing Engine Hardware

- "Soften" stall: eliminate "jump" & hysteresis
  - Active Nonlinear Stability Augmentation
  - 1D HF Actuation, 2D HF Sensing
Active Control Proof-of-Concept Demos
Active Surge Control Demo: 2-Way Actuation

Plenum Pressure

Compressor Inlet Pressure (q = 20 deg)

Actuator Position

Disturbance Control
  On
  Off
  On
  Off

1 sec
Active Surge Control Demo: 1-Way Actuation

- Plenum Pressure
- Compressor Inlet Pressure \((q = 20 \text{ deg})\)
- Actuator Position

Disturbance: On, On, On
Control: Off, On, Off
Active Surge Control Demos

- Stable surge
- Previously unstable equilibrium stabilized
- Disturbance on
- Control off

\[ |SFC_1| \]

- Disturbance Throttle Position

- Control on
Active Rotating Stall Control Demo

- Disturbance off
- Control off

<table>
<thead>
<tr>
<th></th>
<th>Disturbance Throttle Position</th>
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<tbody>
<tr>
<td></td>
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- Limit cycles
- Control on

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<tr>
<th></th>
<th>Disturbance Throttle Position</th>
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<tr>
<td></td>
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Integrated Control Proof-of-Concept Demo

UTC Proprietary

Sensing Strategy → Signal Processing → Integrated Rotating Stall / Surge Controller

Patent Pending

no rotating stall phase information
Active Rotating Stall / Surge Control Demo

Plenum Pressure

Compressor Inlet Pressure (q = 20 deg)

Actuator Position

Disturbance: Off, On, Off, Off, On, On, On
Control: Off, Off, Off, Off, On, On, Off

2 sec
Active Rotating Stall / Surge Control Demo

coexistent stable surge

$|SFC_1|$ vs. Disturbance Throttle Position

$|SFC_1|$ vs. Disturbance Throttle Position

disturbance off

disturbance on

control off

control on
Stall Inception Models

Span-wise Uniform, Long Wavelength Inception

Part-span, Short Wavelength Inception
Pressure and Velocity Perturbations During Stall Inception

Filtered @ 6*Rotor Frequency

Velocity at HUB

Velocity at TIP

Time (Rotor Revolutions)
Model-Based Surge Controllers

Proportional Feedback Controller

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<th>Model</th>
<th>Experiment</th>
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<td>Gain</td>
<td>+ 6.6 dB</td>
<td>+ 5.6 dB</td>
</tr>
<tr>
<td>Margins</td>
<td>- 2.0 dB</td>
<td>- 4.4 dB</td>
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Dynamic Feedback Controller

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<th>Model</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>+ 7.3 dB</td>
<td>+ 5.5 dB</td>
</tr>
<tr>
<td>Margins</td>
<td>- 4.0 dB</td>
<td>- 6.3 dB</td>
</tr>
</tbody>
</table>
Required Extensions

- Low speed to high speed (compressibility effects)
- Few stage to many stage
- Single spool to multiple spool
- Compressors to cores to engines
- Low pressure ratio to high pressure ratio

Extensions required for both models and controls
Parting Comments...

Nonlinear perspective provides a real edge

Much fruitful work can yet be accomplished in low speed environments

Carry out parallel efforts in high speed environments

Deployable hardware issues yet to be considered
A Systems Study of the Impact of Active Compressor Stabilization

3/21/94

Kevin R. Tow
General Electric Aircraft Engines
Lynn, MA.
A Systems Study of the Impact of Active Compressor Stabilization

- Overview of Assumptions
- Potential Benefits of Active Stabilization
- Engine System Level Benefits
- Aircraft System Level Benefits
- Summary of Design Options
Overview of Assumptions

- Active control provides assumed levels of additional stability margin.
- The specific method of active control is not studied.
- Potential effects of the active control hardware on efficiency or weight are not included.
- Active stabilization is used as an upgrade to both existing configurations and entirely new designs.

The systems level study assesses the bottom line benefit of having more stall margin
Advantages of Active Control Stabilization

- Current advanced control technologies are designed to avoid stall.
- Active stabilization suppresses the initiation of stall and increases the acceptable region of compressor operation.
- Active control has the potential for more widespread application over stall avoidance technologies.

Active stabilization includes and potentially exceeds the performance benefits of stall avoidance control technologies.
Active Control Provides Potential Benefits on Different Levels

- Compressor Component Level
  Improved adiabatic efficiency
  Higher pressure ratio capability
  Weight reduction

- Engine System Level
  Improved cycle thermal efficiencies
  Improved steady state and transient performance
  Improved hardware durability

- Aircraft System Level
  Improved distortion tolerance capability
  Reduced installed drag
  Increased aircraft range
Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

**Design Scenario**

- Low, bypass ratio afterburning turbofan typical for military fighter applications.
- Additional 5%-20% stall margin available
- Other cycle limits (temperatures, pressures, rotor speeds, physical geometries) remain constant
Typical Engine Design Limits

Parameters other than stall margin may limit cycle performance.
Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

Method of Implementation

- Additional stall margin used by raising the compressor pressure ratio at constant corrected speed.
- High pressure compressor is actively controlled; the fan is not.

![Diagram showing pressure ratio and corrected flow with points A and B labeled as Baseline Cycle Design Point and Final Cycle Design Point respectively.](image-url)
Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

**Engine Performance Figures of Merit**

- **Specific Fuel Consumption (SFC)**
  \[ SFC = \frac{\text{Fuel Flow}}{\text{Net Thrust}} \]

- **Specific Ideal Gross Thrust**
  \[ FG = (\text{airflow})(\text{exhaust velocity}) \]
  \[ FG/\text{airflow} = \text{function (exhaust total temperature, exhaust total pressure, gas properties)} \]

---

The steady state systems performance improves if the additional stall margin results in lower fuel flow, higher exhaust temperature and/or higher exhaust pressure.
Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

Results

- Cruise Operation
  Significant fuel consumption benefits

- High Power Operation
  Higher pressure ratio results in lower turbine exhaust temperature due to temperature limits.
  Intermediate Rated Power: thrust penalty at all flight conditions
  Max AB: thrust benefit/penalty depending on the flight condition.

For this application, performance benefits and penalties are associated with the higher pressure ratio.
Specific Fuel Consumption Benefit for Cruise Operation
35,000 ft/ .85 MN

Net Thrust Normalized to a Reference Point
High Power Thrust Penalty Driven by Temperature Limits

The presence of existing cycle constraints may compromise potential active control benefits on existing configurations.
T3 Limited Operation Covers a Larger Portion of the Flight Envelope as Core Pressure Ratio is Raised

The severity of the performance penalty depends on the location of the aircraft’s critical flight conditions.
Summary of Results:
Benefits of 5% Additional Stall Margin on an Existing Configuration

- Raise core pressure ratio
  Cruise SFC improves by -.74% to -.82%
  Max AB thrust changes from -4.3 % to +.8% depending on the flight condition.

- Raise fan pressure ratio
  Max AB thrust improves from 0.0 % to 5.4% depending on the flight condition.
  No impact on cruise performance.

- Optimize efficiency using variable stators
  Cruise SFC improves by -0.21% to -0.41%

Additional stability margin above 5% could not effectively be utilized on the existing configuration.
Active Stabilization Incorporated on a New Engine Design
(J. C. Seymour- MIT MS Thesis)

Design scenario
- Configuration: low bypass, mixed flow afterburning turbofan
- Implementation: higher pressure ratio operation
- 20% available stall margin

Results:
- 11.2% increase in mission radius
- 8.3% decrease in takeoff gross weight
- 7.3% decrease in aircraft operating weight

The benefits of 20% additional stall margin are maximized when active stabilization is incorporated early in the engine design process.
Aircraft System Benefit:
Active Stabilization on a New Aircraft Design
(Northrop)

**Design Scenario**
- Configuration: high performance fighter aircraft
- Implementation: Higher compressor stall margin can accommodate larger inlet flow distortion.

**Results**
- Inlet capture area reduction
- Reduced spillage drag
- Increased aircraft range
Aircraft System Benefit: Larger Inlet Distortion Tolerance Allows Reductions in the Inlet Capture Area

The reduction in inlet area results in significant improvements in range.
Design Options for Implementing Active Control

- Performance improvements must be compared to the associated penalties. Higher stall margin capability is not simply a win-win situation.

- The presence of other cycle design constraints limits the benefits of additional stall margin on existing configurations.

- Active stabilization is likely to provide the greatest benefits on new aircraft/engine designs.

- The manner of implementation of active control is dependent on the particular aircraft application.