Engine Monitoring and Performance Control Development at MTU Aero Engines

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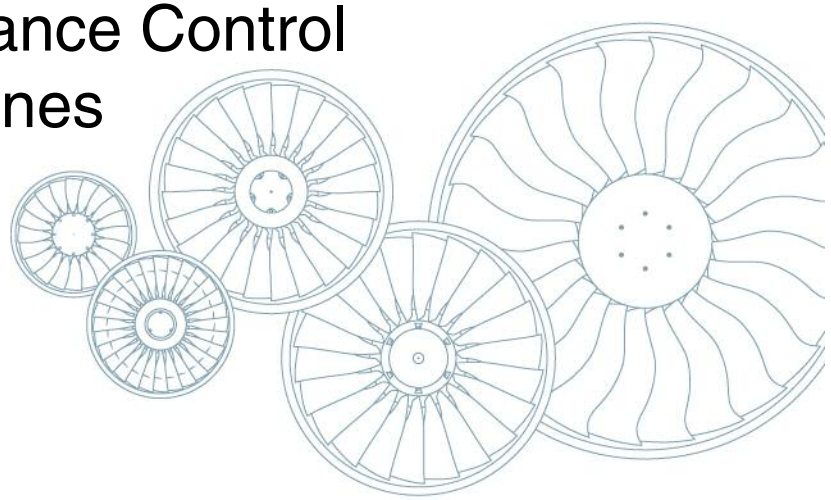

Agenda

- Introduction
- Active Systems
- Model-Based Control
- Commercial Engine Condition Monitoring

Chapter Break

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- Model-Based Control
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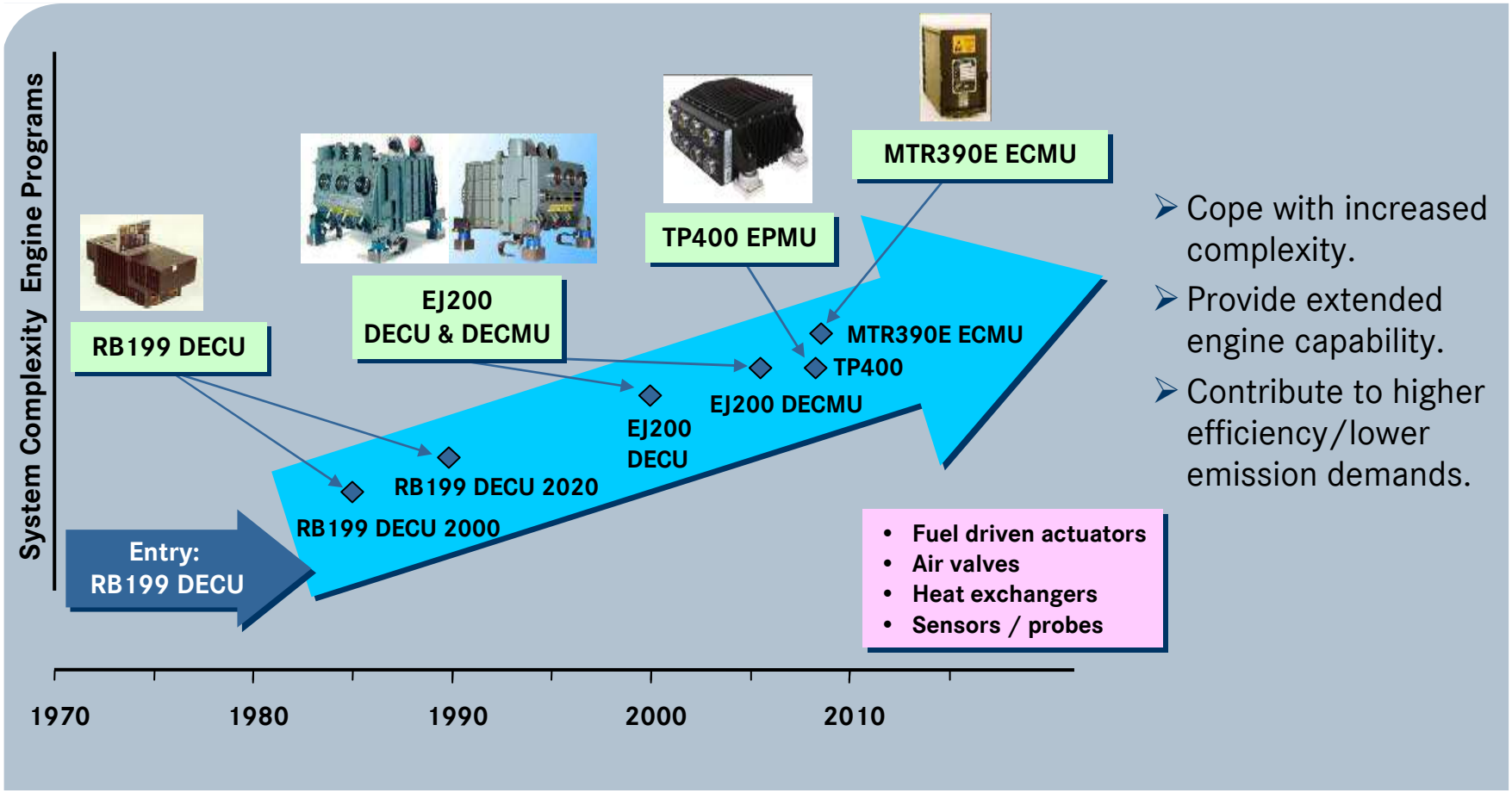
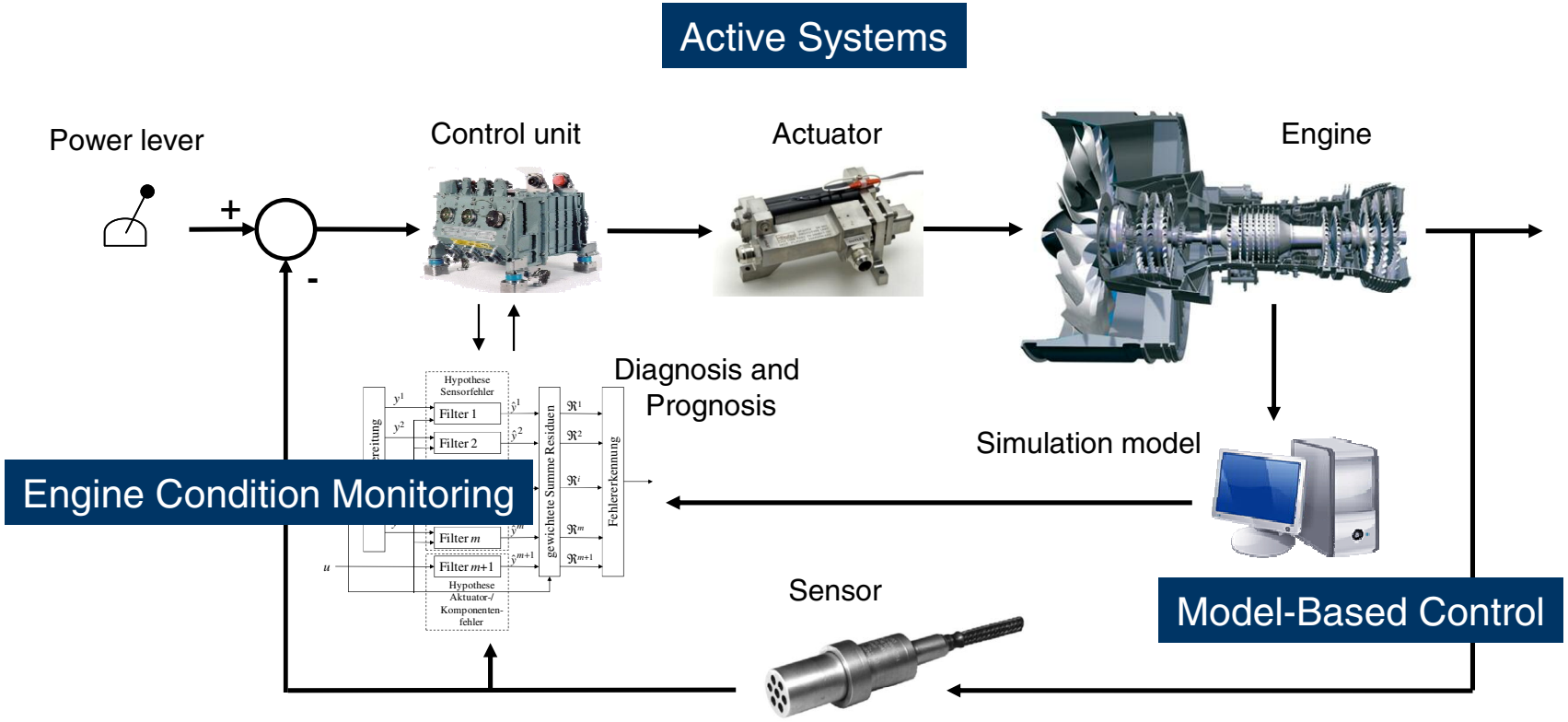
Engine Controls Heritage at MTU Aero Engines



- Cope with increased complexity.
- Provide extended engine capability.
- Contribute to higher efficiency/lower emission demands.

Concept of an Intelligent Engine



➔ Optimization of the engine characteristic to the actual flight condition.

➔ Optimized engine design with enhanced operating limits.

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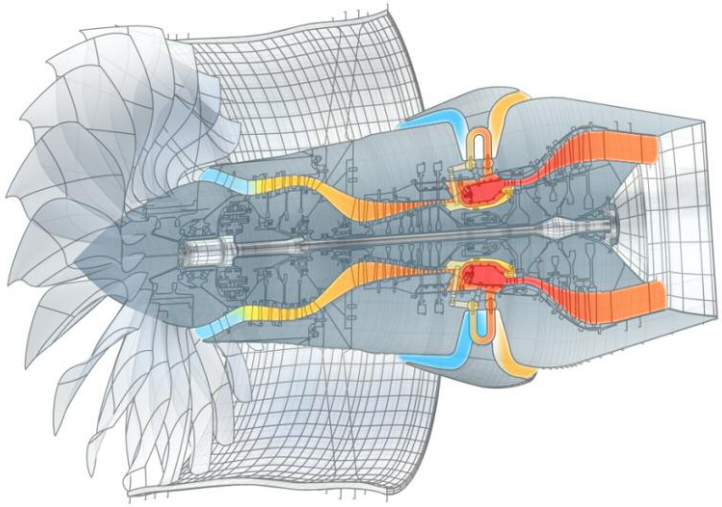


General Benefit of Active Systems

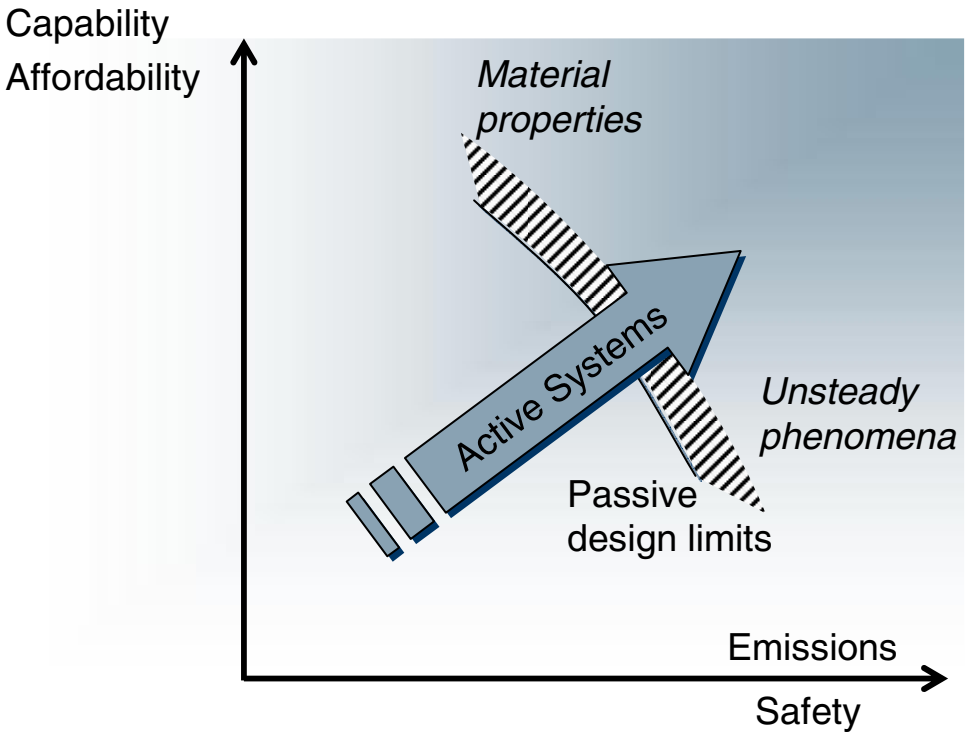
Active systems can improve the engine in two ways:

a) Direct improvement: Improving component characteristics by actuation (e.g. efficiency)

b) Indirect improvement: Extended component operating limits enable optimized engine design

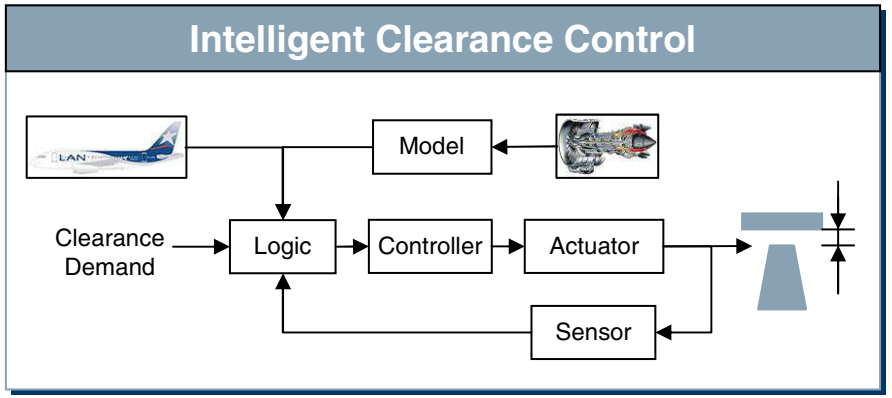
Promising technologies include:

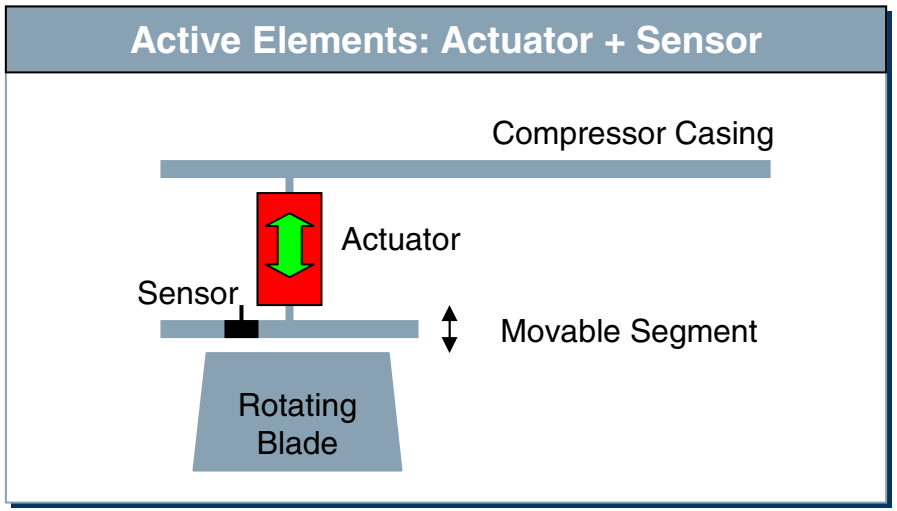
- Active flow control
- Active clearance control
- Compressor stability control
- Turbine cooling air control
- Variable nozzle



Active Clearance Control

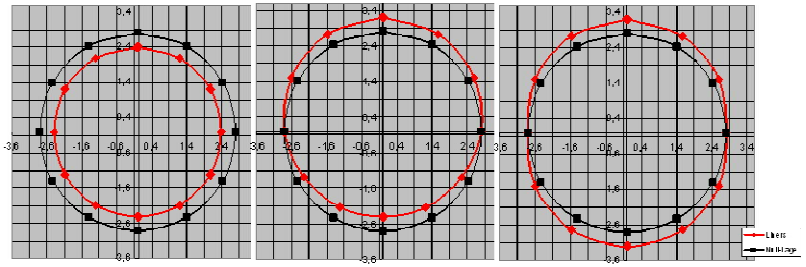
- The clearances between rotating and stationary parts are a dominant source of losses in turbomachines.
- The clearances change with
  - the operating point
  - external loads
  - component deterioration
- The concept of Active Clearance Control is
  - to identify the current condition
  - to react with clearance adjustment.
- Large potential to increase component efficiency and surge margin.



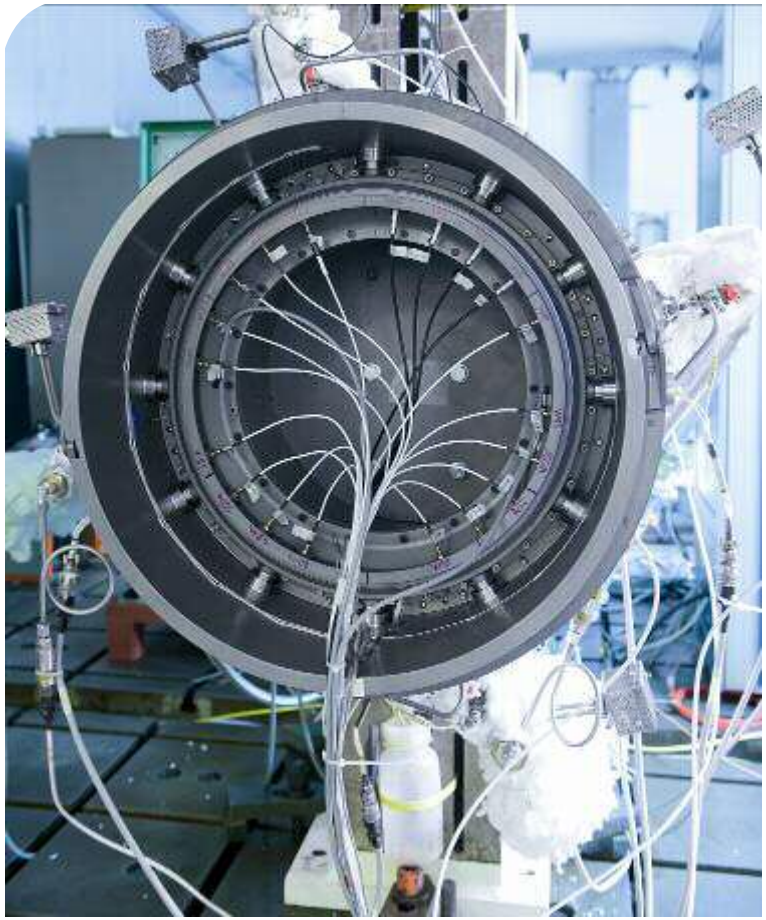


The ACC Functionality has been Demonstrated in Closed Loop

- Test campaign on conceptual rig
- Closed loop control of various steady state and transient clearance distributions.
- Simulation of transient tip clearance changes during a typical flight mission and due to maneuver loads etc.



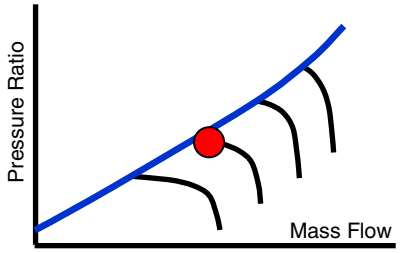
centric eccentric oval



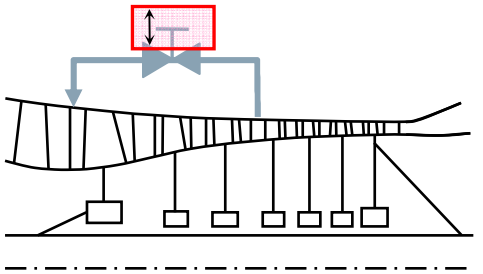
Active Compressor Stability Control

- An upcoming instability can be detected by fast response sensors or surge margin models.
- As a reaction, a recirculation valve is opened.
- The recirculation valve is controlled in closed loop or by a surge margin model.
- The injected air stabilizes the flow.
- The compressor can be operated in a range which is instable without control.

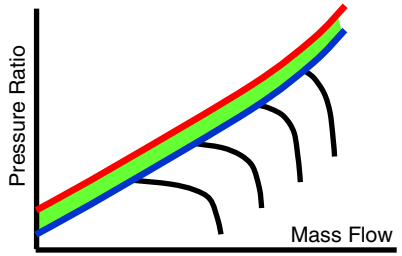
Detection of Upcoming Instability



Bleed Valve Opening, Fluid Re-Injection

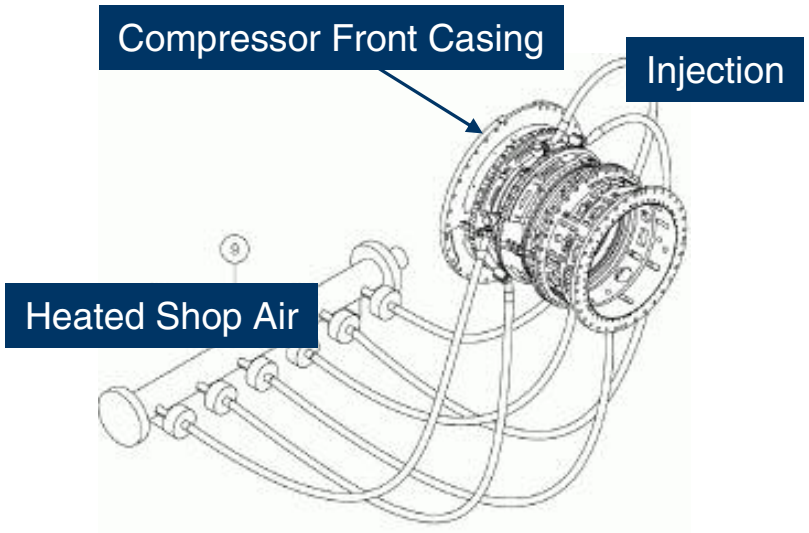


Surge Line Extension

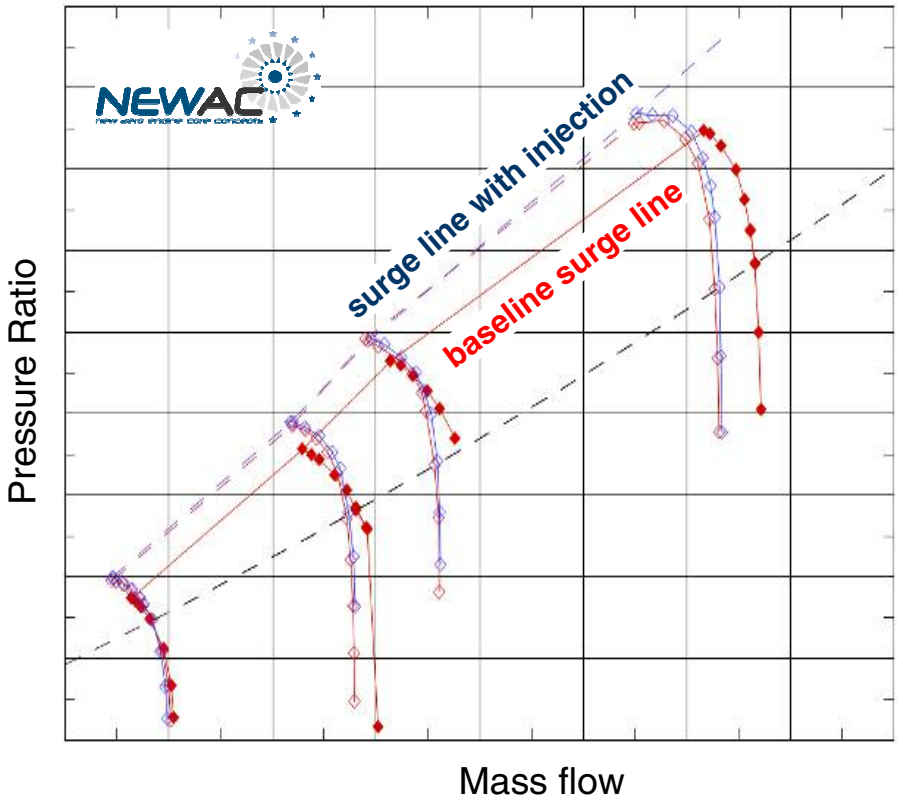


The Potential of Active Stability Control has been Demonstrated

- Multi-stage high pressure compressor
- Controlled injection and bleed flows
- Exchangeable injection geometries
- Extensive instrumentation

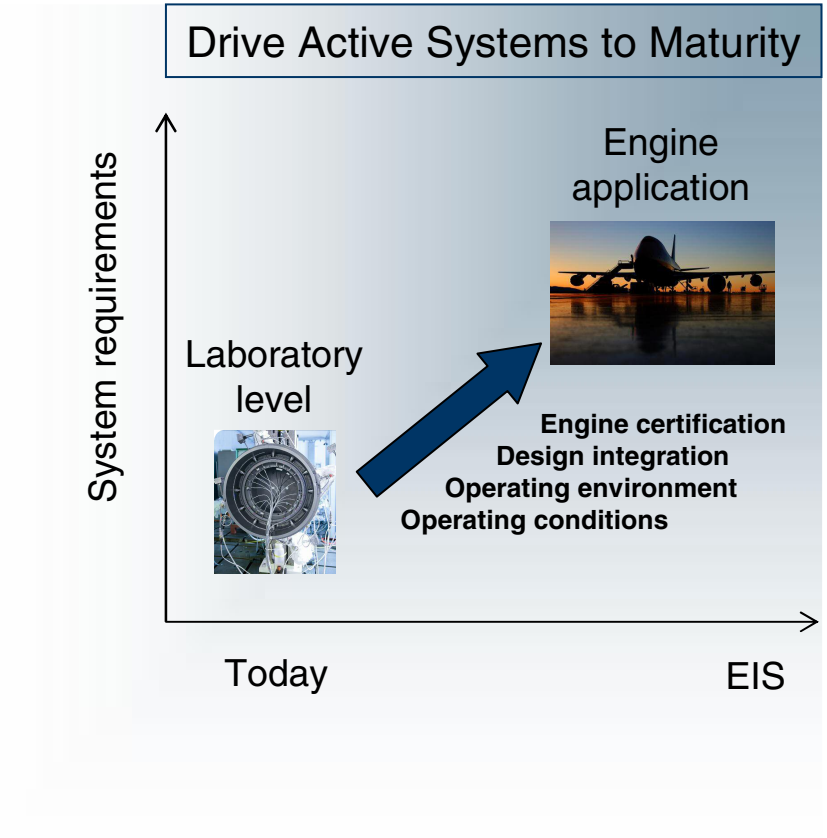


Compressor Map with Fluid Injection



Challenges for Active Systems

- Active systems rely on a multi-disciplinary approach.
- Profound understanding of the underlying physical process is required.
- Sensors have to operate in high temperature environment at high reliability.
- Actuators have to be light and small at high durability.
- Control system has to be robust and reliable under all operating conditions.



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Approach of Model-Based Control

Current situation:

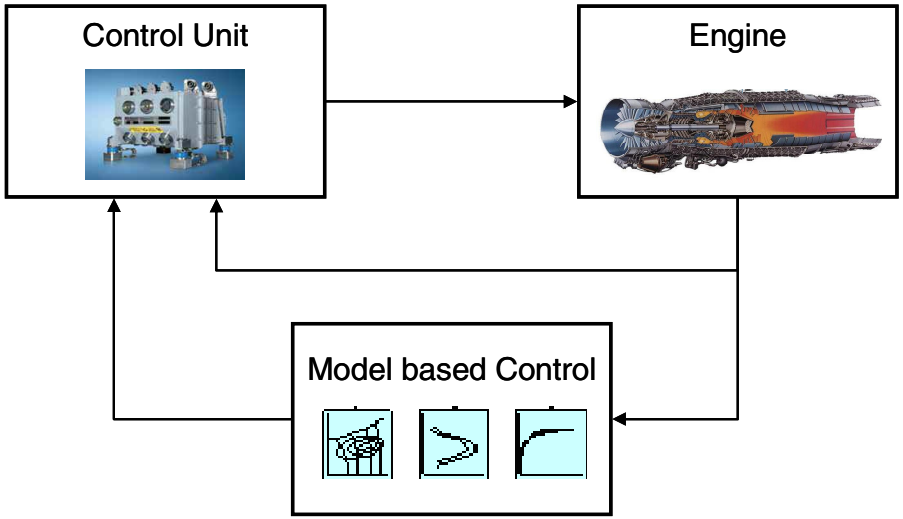
- Engine control schedules respect worst case scenarios
- Control schedules not adapted to the individual state of the engine

➔ Design is conservative for most engines and operating conditions

Approach of model-based control:

- Identify the actual state of the individual engine:
- production scatter, deterioration, steady-state/transient condition

➔ Better exploitation of existing margins



Benefits …

Integrated control & monitoring system

➢ Improved Engine Control

- enables on-line adaptive control depending on the state of the individual engine

➢ Improved Engine Operation Monitoring

- allows improved fault detection & isolation concepts

➢ Improved Engine Health Monitoring

- Evaluation
- Trending
- Prognosis

of engine / module health condition

… and Remaining Challenges

- Availability of adequate controller hardware (processing power)
- Limited number of sensors to secure reliable adaptive engine control
- Advanced algorithms for adaptation of model-based control
- Certification of control system with model-based elements
- Integration of engine control and aircraft control

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Motivation for Engine Condition Monitoring

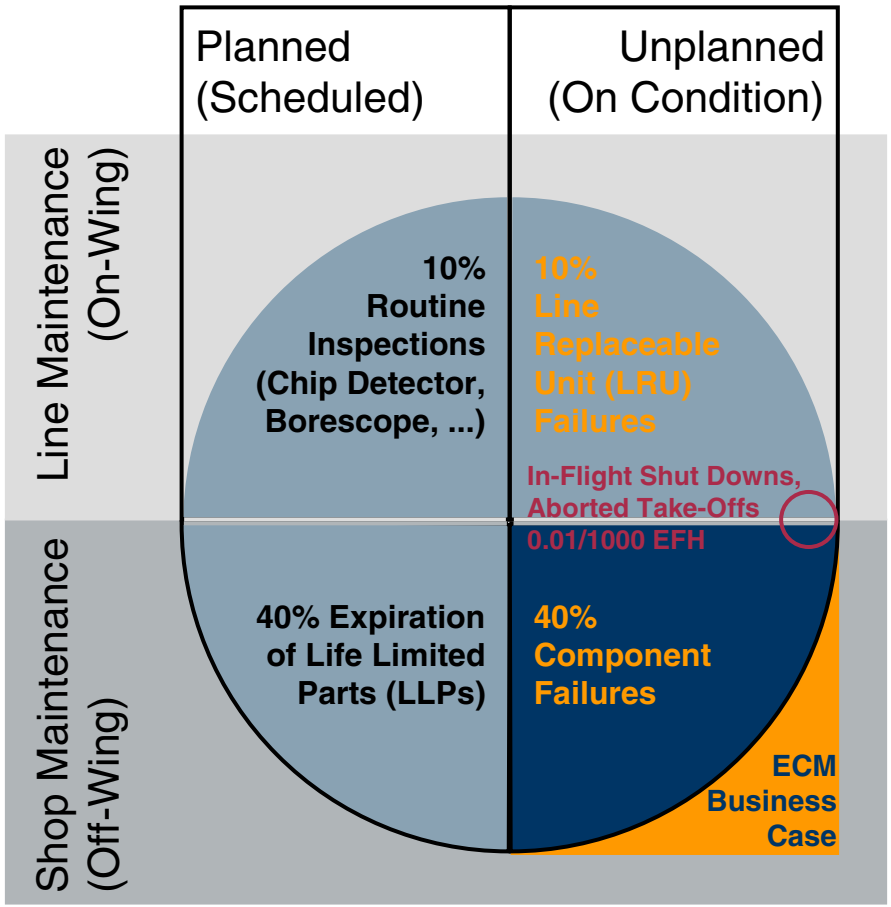
- Mitigation of risks and costs from engine operator to maintenance provider through contract design (Fly-by-Hour)

  ➔ Keeping the engine “in the air” key interest of maintenance provider

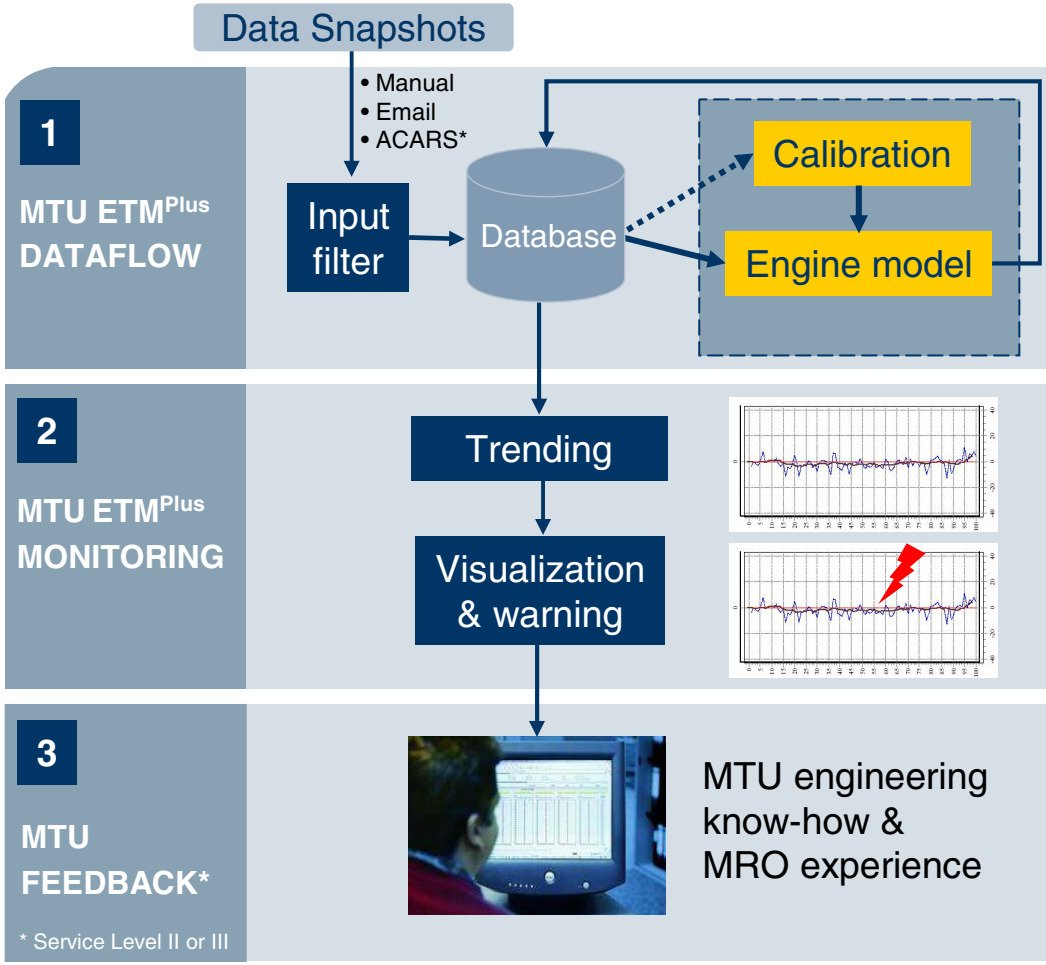
- Intelligent life and fuel saving services increasingly valuable product/capability for maintenance provider

- State of the art ECM allows for detection of incipient failures

  ➔ Avoiding secondary damage yields cost savings in engine operation and maintenance



MTU ETM^{Plus} – MTU's ECM Tool for Off-Wing On-Line Monitoring



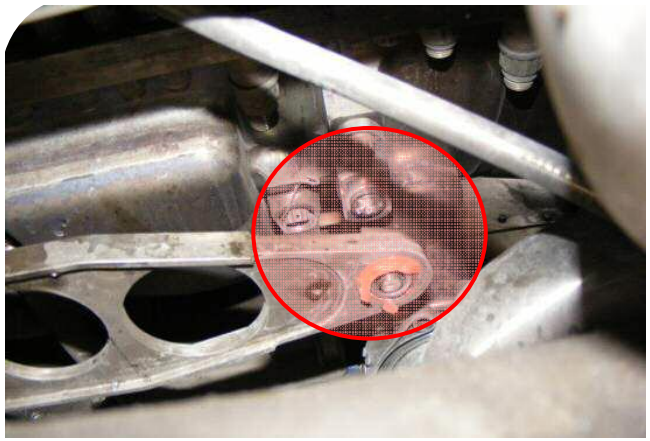
- TAKO / Cruise snapshots
- Engine specific models
- Trends calculated by proprietary non-linear engine performance model

- Trend plotting
- Warning logic
  - standard
  - customized

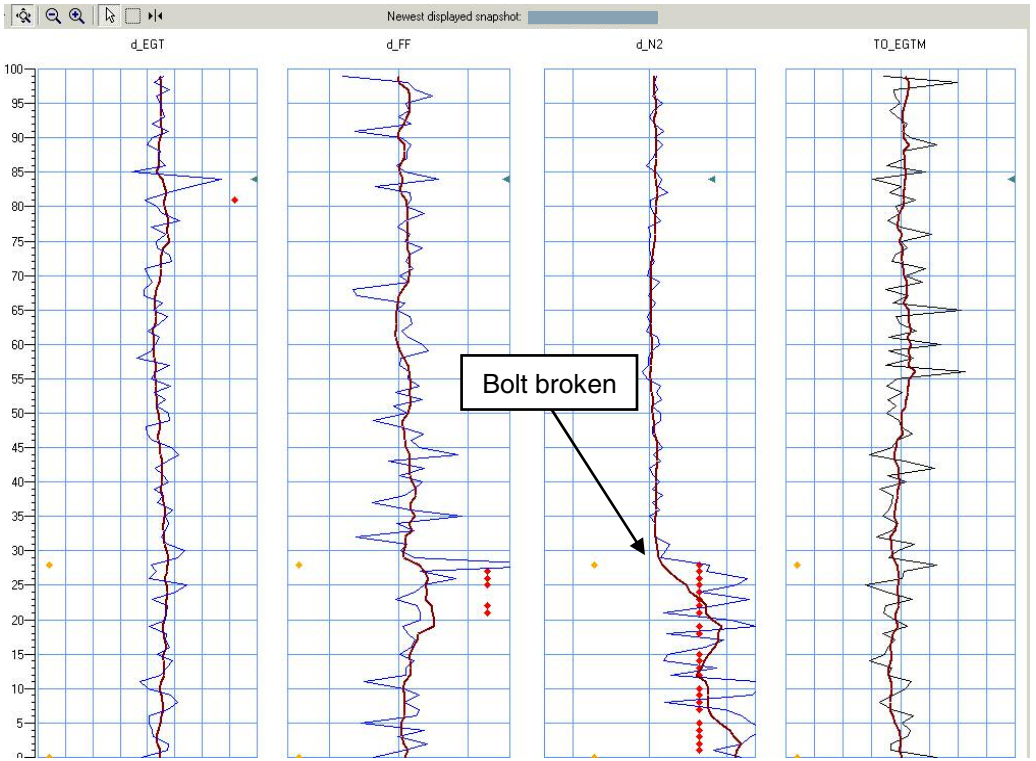
- Analyzing
- Communication with customer
  - Recommendations
  - Corrective actions

*ACARS: Aircraft Communication Addressing and Reporting System (digital datalink system via radio and satellite)

MTU ETM^{Plus} Findings:
CF6-80C2 - L/H Core VSV Master Beam Aft Hinge Bolt Broken



- L/H core VSV master beam aft hinge bolt broken
- Engine visually inspected
- Returned to service after bolt replacement



Future Trends are Driven by Customer Requirements

- Automated on-line diagnosis of engine performance on module/part level
  - Location of incipient damages
  - Contribution of module to overall performance deterioration (EGT-Margin, SFC, ...)

- EGT Margin and SFC/fuel burn analysis:
  - Optimum time for engine wash
  - Remaining useful time-on-wing prognosis
  - Fleet ranking/advanced maintenance scheduling

Major customers
MTU Maintenance:

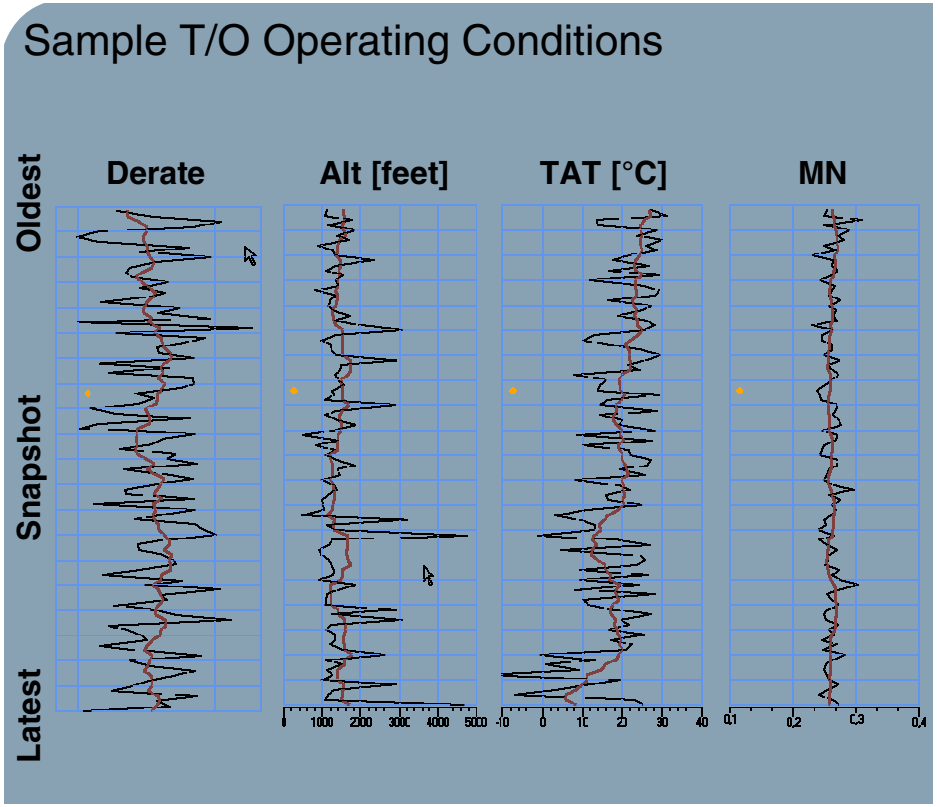
U.S. AIR FORCE
AMC KC-10 Fleet

ATLAS AIR

U·S AIRWAYS

Challenges for Engine Condition Monitoring

- Limited instrumentation and transmission of data (1 to max 5 snapshots/flight)
  ➔ Successor to ACARS with higher bandwidth desirable
- Non-stabilized operating conditions @ T/O ➔ To be adressed by snapshot-logic
- General high measurement uncertainty vs. small measureable effects
  ➔ Sophisticated filtering required
- Impact of local operating conditions: natural/man-made aerosols, ...
  ➔ Adaptive deterioration analysis needed
- Missing information from aircraft operator
  ➔ Better networking required



Conclusion

- Enhanced engine performance controls and diagnostics offer the opportunity to
  - improve engine operation
  - improve engine design
  - improve maintenance action.

- Diagnostic algorithms still have development potential with benefits for manufacturers and customers.

- Technologies for active systems and model-based control have been identified and developed on a laboratory level.
- Technology enhancements for the transition to certifiable engines will be required.