Is Gas Path Analysis Enough?

Some musings on the status of gas turbine engine diagnostics and where we should be headed.

Abstract

If one googles the phrase "gas turbine engine diagnostics" or a similar phrase, many, if not most of the hits describe efforts to use gas path analysis or some variant to diagnose engine problems using gas path sensors. The citations start in the early seventies and continue unabated in 2008. Is this the right emphasis? Using Google (actually Google Scholar) to determine fault frequency is not so easy (most hits describe solutions rather than problems). This presentation describes a limited review of the types of problems being referred to the OEM and suggests that more such surveys are needed to ensure that the right technologies are developed.

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Charter (What I was asked to do)

1. Challenges and opportunities in developing, selecting and qualifying sensors and processes for health assessment of industrial gas turbines burning conventional or alternative fuels.
2. Needs for research and development in this area.
3. Funding sources available for research and technology development in this area
4. Three questions for the audience to answer

My contributions will primarily address question 2 (mostly in the area of gas path analysis), and I will meet the requirement set out by item 4

An Apology

- Jeff Bird tells me you are mostly land-based gas turbine types
- I have 41 years experience with aircraft gas turbines; zero with land-based turbines
- I believe there are similarities; some of what I say may be useful
- I believe there are differences; some of what I say may not be useful
- I'm sorry
- I have eliminated items from my problem list that are obviously aircraft-specific.

Gas Path Analysis – Why do it?

- Troubleshoot an engine after an overhaul acceptance run in a test cell, especially if the engine is does not achieve target performance
  - Typically engines have limited instrumentation
    - Control system measurements + test cell sensors
  - Goal is to identify deficient component(s) to guide restoration
  - Occasionally, applied to inbound test
- Troubleshoot an engine on-wing
  - Usually applied to cruise snapshot data
  - Even more limited sensor set
    - No thrust or total engine airflow, less accurate fuel flow measurement
  - Goal is to understand a noticeable performance shift to guide borescope inspections or other troubleshooting tasks
  - Or, to begin planning work scope for an approaching shop visit
- Determine engine "health indices" as part of strategy to adapt control system algorithms to optimize fuel burn, stall margin or some other figure of merit
  - Sensor set identical to on-wing troubleshooting sensors
  - Algorithm might be optimized for the figures of merit and less concerned with the correctness of the (intermediate) health indices

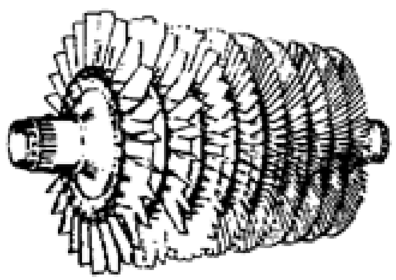
Gas Turbine Engine Diagnostics is Tough, Because

- Gas turbine engines are extremely reliable
  - In-service events such as in-flight shutdowns, unscheduled engine removals and aborted takeoffs receive individual attention to identify and correct root cause
  - Once a fault mode is understood, it will be designed out if it can
    - As a retrofit if possible
    - Else, as a change to the next upgrade
- Engine sensors are not as reliable as the engines
  - Engine designers add them to engines reluctantly
    - The designer prefers to eliminate fault modes rather than diagnose them
    - A sensor cannot be allowed to break and damage the engine (it could be the source of a fault)
    - Also, sensors are expensive and generally may deliver bad news (e.g. false alarms)
  - Most sensors are single element probes positioned where they can be accommodated
  - If they do not prove their merit, they are candidates for cost reduction
- When problems occur in the field, the emphasis is getting the engine back on line or replacing it
  - Often, just replace a suspected part and go on
  - Limited interest in diagnostic troubleshooting (Sherlock Holmes is not a mechanic)

Despite This, We Keep Plugging Away

- But only on the mathematical part of the problem
  - What can be deduced from the measurements provided?
  - No approach is untried
    - Matrix inversion when the problem can be posed as a square matrix
    - Weighted least squares or any of the associated regression / Bayesian techniques
    - Neural networks and probabilistic neural networks and . . .
    - Genetic algorithms
    - Singular value decomposition
    - Linear versus nonlinear
    - Single point versus multi point
    - If a new technique is conceived, it will be tried
- All of these address the mathematical inverse problem
  - And cannot succeed unless the sensors contain a clear indictment of the fault
    - Which may be a betrayal by one of the sensors
  - The "faults" being evaluated are mathematical artifacts
    - Efficiency, flow capacity or pumping
    - The physics behind these faults is not considered

Where Is The Compressor Efficiency, Anyway?



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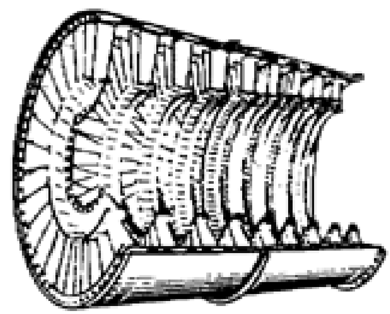
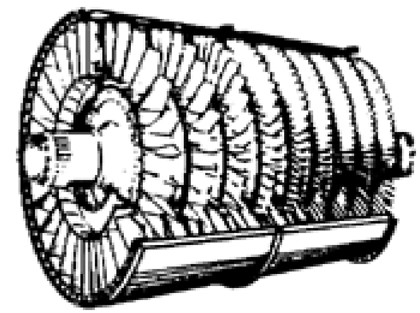


Stator Case



Full Assembly

- We have a single element temperature and pressure behind and a single thermocouple in front from which to determine efficiency
  - On rare occasions there may also be a single element inlet pressure
  - Statistical algorithms also evaluate the loss in overall performance to confirm that an indicated efficiency loss isn’t just a measurement problem
- A mechanic, told that the compressor efficiency is down three points, must attempt to find the defect in the hardware
  - Many places to look
  - Not all easily recognized: clearances or chord length may not be recognized
  - And a clever measurement error in T3 can have her looking in the wrong part of the engine

Where have we already done enough?

- We've done enough work nitpicking at gas path analysis mathematical algorithms (at least until we have a better definition of the problem)
  - Linear / non-linear, single-point / multi-point, neural network, Bayesian algorithm, genetic algorithm, . . . you name it, someone has tried it
  - Also, enough of evaluating artificially generated test cases (e.g., OBIDICOTE)
    - These also focus on"fictional parameters" such as efficiency
  - If someone wants to describe in-service experience using one of these gas path analysis tools, that <u>is</u> of interest

- **If the only tool you have is a hammer, you tend to see every problem as a nail.**
  - **Abraham Maslow**

What Should Come Next for Gas Path Analysis?

- 3-D models are used everywhere to design gas turbine engines
  - Leading to more sophisticated airfoil shapes (no longer rely on NACA airfoils, etc.)
- Gas Path Analysis algorithms still use 1-D models
  - And mathematical "fictions" to describe faults (efficiency, flow capacity)
  - These fictional faults are extrapolated to different power settings and flight conditions as if they were chiseled in the engine hardware
    - Are shocks always there?
    - Do clearances generate the same efficiency loss at all conditions?
    - If the component is choked at high power, is it choked everywhere?
    - Do the sensor outputs retain the same relationship to plane average?
  - The users are asked to infer the real hardware problems from the fictional faults
- True progress requires better modeling of component faults and of the sensors used to diagnose them
  - Progress can likely be made by applying the same mathematical techniques to more sophisticated physical models
- I know it won't be easy!
  - But, this is the key to understanding where new sensors can be more effective
  - And it also increases the ability to express results in the "maintenance language"

- **In theory, theory and practice are the same. In practice, they are not**
  - **Lawrence Peter (Yogi) Berra**

Fault Models

- Many simpler types of faults have already been modeled in 3D tools
  - Clearance, chord erosion, leading edge shape, surface finish, leaks, . . .
  - We just need to take advantage of these models
- Damage caused by fatigue failures, FOD, DOD, etc. are “random” and far more difficult to model
- Prediction of sensor responses may also be difficult
- Ignoring these harder problems doesn’t solve anything!
  - If we can’t develop ways to perfectly localize a fault to the appropriate component, we can at least quantify the uncertainty in our solutions
- I’m convinced these uncertainties dwarf any possible benefits of multipoint versus single-point, nonlinear versus linear, neural net versus Kalman filter, versus genetic algorithm, etc.
  - And a multi-point algorithm, in particular, must be based on an understanding of the physical changes that occur at different conditions

GE Gas Path Analysis Experience (TEMPER)

- Originally developed in mid-1970s
  - To replace a square matrix inversion algorithm
  - Target: overhaul acceptance runs
    - Weighted least squares was chosen to simultaneously estimate health indices and sensor errors
  - Originally included hand-tailored baselines and standard deviations
    - Derived from prior acceptance test data
    - Labor intensive (to put it mildly)
- An on-wing version using cruise data was created in the late-1970s
  - As an ingredient in GE's GEM engine monitoring package
  - Baselines were developed from cruise data
    - Even more labor intensive
- After an initial "honeymoon," most communications from customers were squawks
- Meanwhile, GE sought to reduce the development cost (and address the question of how to create baselines for a newly developed engine model)
  - Evolved to using production baselines and cell correlations for overhaul test cells
    - Which shortchanged gas path temperatures and pressures (not addressed by the cell correlations)
- Recent programs are generally less effective as a result
  - Meaning those developed during the last twenty years
- Now, nearly all requests come not from airlines but from the shops (who provide a TEMPER output with their overhauled engine)
  - Several new engine types do not have TEMPER versions

Holistic Health Monitoring

- Other engine systems have their own measurements and diagnostic algorithms
- Vibrations used to identify fan or core imbalance
  - But sometimes can help to explain a sudden performance change
  - Probably need to more completely analyze the frequency content
- Oil sensors: hard to see a link, but maybe someone who understands them better can find one
- Control sensors are already part of the gas path diagnosis, but much of the control "smarts" is overlooked
- Fault messages are part of the control smarts being overlooked
- Some work in this area has been done but reporting of methods has been sparse (other than some of the mathematics)

Some Other Service Issues Worthy of Attention

- Water Wash
  - Water wash is used to extend the performance life of an engine.
    - Restores EGT margin and helps operability
  - When should it be done?
    - On a fixed schedule? Seasonal?
    - Condition based?
      - Using visual inspections?
      - Overall performance measures?
      - Estimated component performance?
  - How should it be done?
    - Cold water, warm water, detergent?
    - Various competing apparatuses
- Engine performance deterioration modeling
  - Projected life for an engine family or a specific engine
    - Derived using experience data (for aircraft engines EGT margin is the figure of merit)
  - Engines are removed for various reasons; the high-time engines are the "survivors"
  - Developing projections based upon survivors yields a favorably biased estimate
  - Need an approach that properly uses "censored" data
  - The math may already have been developed by insurance mathematicians (actuaries)
    - A nice alternate project for the GPA math-types

Ideas about Land-Based Turbines from an Outsider

- I suspect emissions are more significant for you than for us (so far)
  - Are you required to predict/estimate kind and amount of emissions?
  - A good gas path analysis algorithm coupled to a good model might help
- Alternate fuels
  - Current fuels can introduce problems (coking for example)
  - What "gotchas" do alternate fuels offer?
  - How will we recognize that they are happening?
  - How can we anticipate their possibility?
- What opportunities does a ground environment as opposed to aircraft environment offer? Any liabilities?

My Three Questions

- What gas turbine engine field support problems should be added to the technologists' "job jar?"
- Can we find a way to create more realistic exercises to test diagnostic tools, especially gas path analysis (e.g., drawn from real examples)?
- Does anyone have results from applying a gas path analysis tool in service: qualitative or, better yet, quantitative? (I don't, beyond my earlier confessions)