Sensing for Aerospace Fuel Systems and Combustor Health Monitoring

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ABSTRACT

Novel fuel systems, as required for lean burn combustion, can carry a high risk failure modes, particularly through their control valves. The rapid detection of these failure modes, such as valve sticking or impending sticking would reduce this risk. However, sensing valve state is challenging due to hot environmental temperatures, which result in a low reliability for conventional position sensing. Whilst conventional sensing may be feasible within a test cell, the constraints of aerospace in-service operation may necessitate more novel alternatives, as outlined in this paper.

Starting with the business needs elicited from stakeholders, a Quality Functional Deployment (QFD) process is performed to derive sensing system requirements. The process acknowledges the difference between test-bed and in-service aerospace needs through weightings on requirements, and maps these customer requirements to systems performance metrics. The design of the system must therefore optimise the sensor suite, on- and off-board signal processing and acquisition strategy.

Against this systems engineering process, two sensing strategies are outlined which illustrate the span of solutions, from conventional gas path sensing with advanced signal processing to novel non-invasive sensing concepts. Acoustic emission (detecting very high frequency surface vibration waves) sensing technology is evaluated to provide a non-invasive, remote and high temperature tolerant solution. Through this comparison the considerations for the end-to-end system design are highlighted to be critical to sensor deployment success in-service.

1.0 INTRODUCTION

1.1 Fuel System Health Monitoring Problem

Lean premixing of fuel and air is needed for a step change emissions reduction in oxides of nitrogen (NOx) and smoke performance for high power combustion applications, such as large aerospace gas turbines [1]. It is necessary to apply fuel staging for combustor operability: a rich pilot for low power stability; and a lean main zone for minimised NOx and smoke. To realise this advanced combustion process, the fuel system must independently meter fuel into the pilot and main injectors, including several flight cycle operational points where mains fuel is switched on and off. When in off-state, the mains lines need to remain primed with fuel, to allow satisfactory thrust response times, and allow the fuel to circulate to prevent thermal degradation. One potential solution is to include injector check valves, marked as nodes 'V' in the example lean burn architecture shown in Figure 1, that prevent flow into the combustor at low pressures needed for the fuel recycling, but open at higher pressures to allow mains flow. A sticking fault in any one valve has implications of combustor temperature profile on engine performance and life. In particular, should any one of these valves fail open, the recycling fuel could enter the combustor raising the local temperature to an unacceptable level causing significantly increased degradation rates. Detection of this event is beneficial to realising this architecture, providing that system constraints on weight, volume, and reliability can be respected.

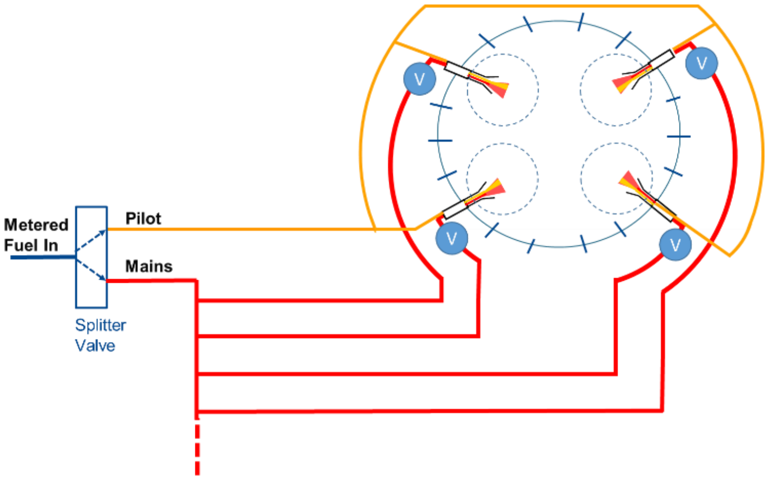

Figure 1: Example staged fuel system architecture shown with four combustion cans and independently controlled pilot and mains fuel manifolds.

The local operating environment imposes challenges to sensing the state of valves or flow in the injector lines. The local temperature, in excess of 700°C, is significantly greater than conventional sensor solutions, which imposes reliability challenges as well as sensor drift and noise inaccuracies, which are explored in the literature review of available solutions. However, the solutions must be evaluated against a multitude of requirements of the end-to-end monitoring system as described in Section 2.

The potential solutions to the problem are described in Section 3, using both existing sensor technology and a novel concept for passive acoustic sensing. In Section 4, the sense, acquire, transfer and analyse functions are described and compared for two example monitoring solutions.

2.0 SYSTEMS PERSPECTIVE ON SENSORS FOR HEALTH MANAGEMENT

It is well understood that requirements for a sensor depend on its use case. Aerospace propulsion testbeds might accommodate sensors in an off-engine installation, higher unit weight and cost, and manage reliability with more frequent maintenance. It is also important to consider that fault modes are far less well understood, and that testing to the extremes of operation may introduce different monitoring requirements. The ability to acquire and transfer data in test cells is far less constrained that in today’s in-service infrastructure. This section introduces the in-service monitoring environment and outlines a lightweight process for incorporating these resulting constraints into a systems engineering process.

2.1 Monitoring Architecture

In contrast to test bed application, fleet monitoring requires thousands of engines to be monitored in real time to identify emerging fault modes and trend degradation, thus the modelling and monitoring need to be computationally efficient and compact. Equipment Health Monitoring (EHM) systems are typically architected to collect and concentrate data on-board an asset. However, the difficulty to provide trustworthy autonomous health decisions, as well as the on-board constraints, often results in much analysis and final decision making taking place at a centralised location where expertise and fleet comparisons can be more readily made. Limited communications between an asset and operating stations is typical of industries with remote and geographically diverse assets, e.g. rail, marine, agriculture and aerospace. Despite the prevalence of this architecture across industries [2]–[6] the joint design of data transfer and analytics are not well considered in the literature; algorithms are often designed for optimality rather than considering trades in cost and difficulty of transferring data to a decision maker.

This process must be compatible with a fleet management computing architecture, such as that illustrated in Figure 2. Data for monitoring is selected and compressed on-board into a report that is designed to carry sufficient information to perform health monitoring on a cloud platform (e.g. Microsoft Azure), shown in Figure 2. On-ground, the cloud platform receives data and instantiates the EHM processes, this initially trains a profile model until enough data is collected and thereafter the model is executed to generate the residuals used for operational decision making. The Data Handling and Compression involves on-board collection of a rich subset of measurements that are compressed, transmitted to ground and decoded back into measurements in the Azure Cloud.

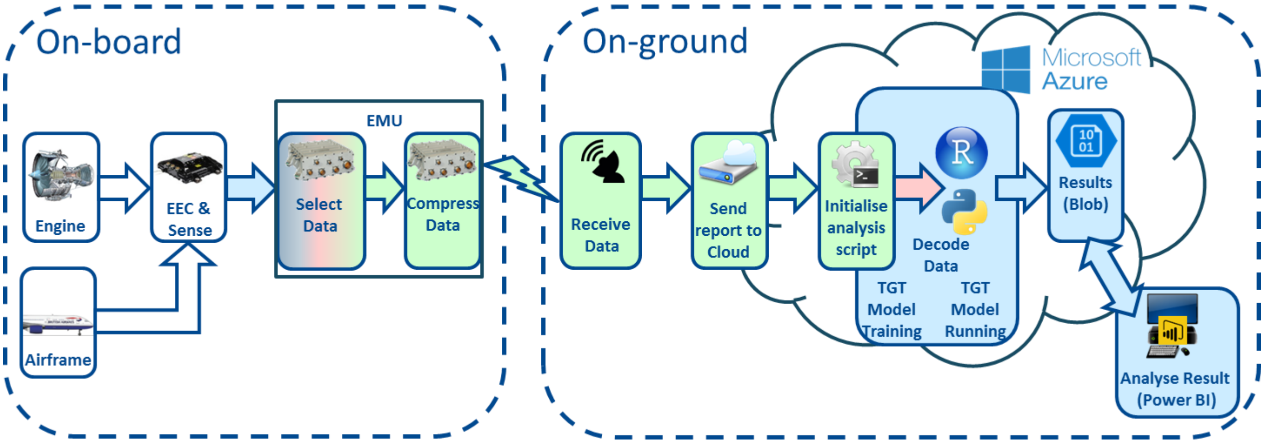

Figure 2: Schematic representation of lean burn EHM system

2.2 Systems Engineering Process

Many large organisations have their own favoured system engineering processes, but these are often broadly aligned to standards such as ISO/IEC/IEEE 24748. The process of transitioning from design intent to a physical system contains the key design activities of eliciting stakeholder goals, deriving functional and non-function requirements, and the means (the technical solutions) to fulfil the functions. In complex systems, such as an EHM system, the solution evolves and there is a need for iteration and spirals of development. A traditional V-model must therefore be extended to incorporate the iteration.

From the many tools to support this process [7], a powerful qualitative model is Quality Function Deployment (QFD). The QFD method is used to transform desired product behaviour (e.g. what is required by the customer) into implementable functions (how the requirement is achieved). Requirements and their interactions are captured as rows in a table and a weight of importance is assigned to the requirement. A set of top-level functions for the monitoring system are derived to meet these requirements. The quality of the functions at meeting the requirements is assessed qualitatively, allowing their selection and evaluation. The QFD process is hierarchical, as shown Figure 3. The system requirement derived to meet customer goals can become the functional requirements for the next stage QFD; the how becomes the what for the next stage.

The ‘means’ define the solution space which must be investigated through a research and development programme to understand the attributes of each technology against the requirements weighted by stakeholder needs for each different target environments. Knowledge of the means quality against attributes related to the functional requirements allows a solution efficacy to be assessed, with weighting to reflect the importance of different application requirements determining the optimal solution.

This process has informed the discussion presented in Section 3 and 4 though results from the QFD are not explicitly presented.

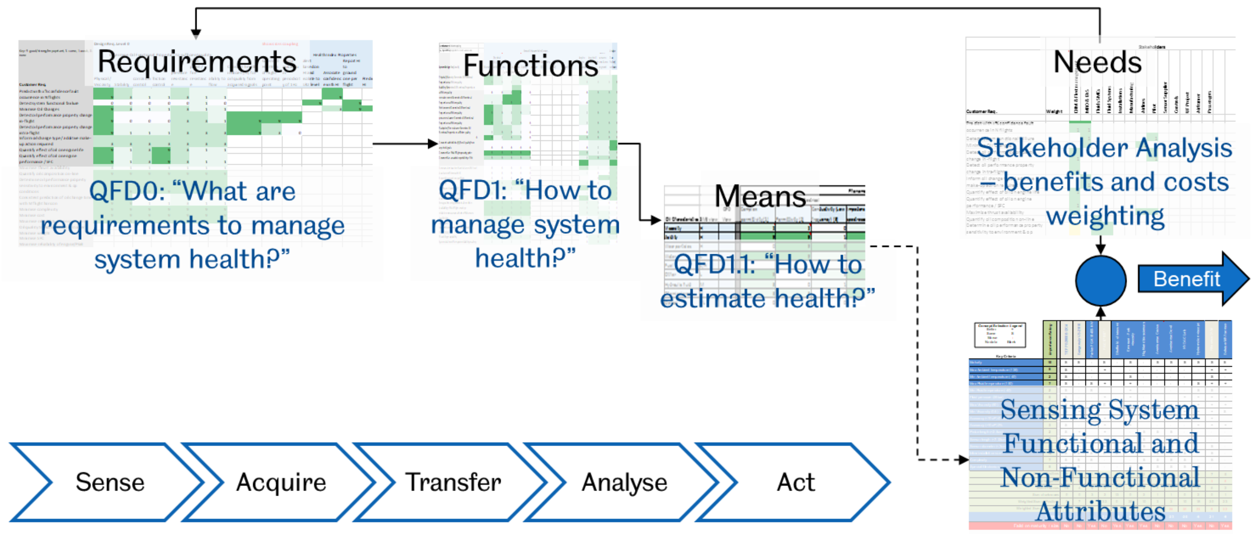

Figure 3: Systems engineering tools can be applied in a lightweight fashion to understand requirements and perform functional means analysis weighted by the application to test-bed or in-service.

3.0 OVERVIEW OF SOLUTION SPACE

3.1 Solution Approaches

Either the cause, i.e. the check valve sticking, or the effect, combustor temperature profile anomaly, can be monitored. The below literature evaluates the principle means to sense this cause and effect through valve state and liquid flow rate, along with combustor exit temperature sensing. Prior work to employ sensing in a non-invasive manner is reviewed and suggests that the prior reported successes in acoustic monitoring of flow may be exploited to solve the challenge of check valve fault detection. The effect sensing illustrates the potential for existing sensing to be used, with enhanced data analysis, to infer fault conditions.

3.2 Effect Monitoring

Engines with fully annular combustors have a uniform exit temperature during normal operation. Temperature near combustor exit deviating from nominal values is a direct indication of combustion anomalies. Conventionally, constraints on sensing techniques means, due to extreme high temperatures, mean only a limited number of temperature measurements downstream of combustion system are feasible in production engine. The sensor apparatus, consisting of multiple thermocouple probes, is arranged at the Low Pressure Turbine (LPT) Nozzle Guide Vanes (NGVs), circumferentially around LPT inlet. The multiple turbine gas temperature (TGT) sensor harness system may be designed to provide either individual or a quadrant measures of the circumferential temperature distribution of the turbine gas flow, i.e. the TGT profile. A difference for in-service operation is the drive to reduce the number of harnesses to save weight – thus demanding more signal processing to attempt to compensate for lower spatial resolution in temperature measures.

Being downstream of the combustor exit plane, means airflow swirl and temperature diffusion make detection and isolation of local temperature anomalies difficult to detect without analysis of the data. Rather than directly discriminate distorted from normal exhaust gas temperature pattern (c.f. Allegorico & Mantini 2014) [8], we propose the generation of residuals between a prediction model and measurements [9]. This method does not require historical fault data and is more interpretable. In contrast to Tarassenko et al. who proposed training a neural network (NN) predictor of fault-free temperature reading from a set of measured variables [10], we avoid the complexity of dealing with the convergence issues of such nonlinear models with no loss of performance [11]. This is applicable to an in-service environment where the trends in behaviour are key, but may be less suited to a test environment – as discussed in Section 4. Thus the application drives changes to the whole signal chain.

Alternative combustor temperature sensing methods are described in Von Moll et al. (2014) [12], which allow increased temperature measurements avoiding the complexity of compensation for gas path effects. Of these, pyrometer technology is probably the most mature in gas turbine application, with various real-world applications including EJ200. The cost, installation weight and reliability for commercial application prevents their use currently, despite higher temperature capability. Whilst gas spectroscopy methods are regularly used in combustion rigs in aerospace, they require complex mechanical arrangements to provide temperature profile measurements.

3.3 Cause Monitoring

In gas turbines, LVDTs are typically used to measure actuator and valve position by physical connection to the moving component, i.e. the valve spool. Operation within temperature environments in excess of 500°C, and beyond with integrated fuel cooling, are possible with bespoke design, but come with sealing challenges due to need for physical interfacing with the valve spool. Non-contact position sensing, such as magneto-resistive or hall effect, ultrasonic and eddy current methods avoid the complications of mechanical linkage to the valve but must still be installed in the extreme temperature environment local to the combustor. In a test environment the increased risks may be more acceptable, given the lower cost of maintenance, or the on-ground location allows a higher weight budget and permits the inclusion of cooling or shielding.

An alternative is to measure the downstream flow rate in the individual injector feed pipes, since a relative change in flow rate in one part of the fuel manifold indicates a stuck position of a valve. Mechanical meters (piston, gear, turbine, etc.) or force-based variable area meters placed in the flow path are a proven but high weight method. Measuring the pressure disruption to flow by a mechanical feature is used in orifice plate meters or those exploiting Venturi effect of restrictions. Turbulent flow disruptions are exploited by vortex shedding meters, which use physical correlation between shedding frequency and flow rate. Potentially less invasive are reflectometry methods that detect flow suspended particles with laser or ultrasonic Doppler measurement. Ultrasonic transducers are also used to measure the effect the movement of the liquid has on time of flight, once temperature sensitivities have been rejected. Thermal mass flow meters, measuring heat transfer rate from source to thermal sensor, these are also called hot wire sensors due to the constant heat flux heating element used to transfer heat into the transport path of the flow. All flow measures suffer from the need to install individual sensors on each line thus presenting recurring cost, increased weight and maintenance burdened on the system – particularly in a production environment.

One route to reducing the system impacts is to exploit these concepts but to implement them in a passive fashion, with minimal alteration to the system architecture. In our application, the fuel system geometry is designed to transport the commanded metered fuel to each combustor can. The fluid mechanics effects of the piping geometry can be exploited to identify mains fuel flow into the combustor, this is particularly attractive as the acoustics associated with flow into the combustor might propagate to a single point potentially requiring only one sensor. Depending on the frequency of the acoustics a number of sensing principles and transducer types may be applied: condenser or dynamic microphones, fibre-optics, and various MEMS approaches. At higher frequencies solid pieces of piezo-electric materials maybe used and these provide very high temperature ranges, commercially in excess of 650 °C [13], [14]. The application of acoustic sensing is explored in the next section.

3.4 Summary of Solution Candidates

In summary, five different approaches can be envisaged:

- Conventional valve position
- Conventional flow sensing
- Passive flow sensing
- TGT profile monitoring
- Extreme temperature gas path monitoring

Each approach has different trades in terms of weight, installation complexity, technology risk, reliability and signal processing complexity. The next section selects the examples of passive flow sensing and TGT profile monitoring as illustration of the considerations for an end-to-end monitoring system.

4.0 ENGINE HEALTH MONITORING – END-TO-END SYSTEM

4.1 Cause Monitoring – Non-Invasive Flow Sensing

4.1.1 Sense

The overarching process for the passive acoustic measurement of flows is shown in Figure 4. The kinetic energy contained in flow is converted into acoustic energy by its interaction with the geometry of its physical environment (through processes described in the next Section). The acoustic signature is propagated around various lossy transmission paths to a location where the signature may be measured with a sensor with an appropriate frequency response.

Figure 4: Principles for the measurement of fluidic flow by passive means.

For the fuel system of interest, pipe restrictions and valve orifices offer geometric features of interest that may cause the generation of acoustic signature indicating flow through specific pathways of the fuel system.

It is well known that one of the principle sources of vibration and pressure irregularities are structures in the flow that shed vortices [15], the nature of which are similar regardless of geometry shape but highly dependent on Reynolds number. At high Reynolds numbers, where flow is dominated by fluid inertial forces, but below the supercritical range, periodic shedding frequencies become less regular broadening the frequency content of the shedding phenomena. The vortex shedding behaviour is described by the Strouhal number (S) as a ratio of frequency of vortex shedding (normalised by the characteristic length (L) of the structure in the flow) and fluid velocity (U), Equation 1. The acoustic power (W) generated by these effects is proportional to a power (n>5) of the flow velocity for a given characteristic length (Equation 2), but which has been shown to fluctuate at in the higher Reynolds numbers.

$$f_s = \frac{SU}{L} \qquad \text{(Equation 1)}$$

$$W \sim U^n L \qquad \text{(Equation 2)}$$

Valve induced vortex shedding experiments [16] have been shown to correlate flow rate to measured acoustic energy (in the range 100–300 kHz) when the flow velocity is raised to n=8 as suggested by the theory of Lighthill (1952) [17] for a freely expanding jet. The phenomena has been shown to occur in control valves [18], and can also induce resonant whistling for certain geometries [19]. Cavitation is not expected to be present in our system since vapour pressure of kerosene at 180°C is lower than ambient water and the fuel has a bulk downstream pressure of greater than 10 bar. As such, vortex shedding is considered to be the dominant source of higher frequency noise.

The sensing system has been tested on an aerospace fuel thermal stability (AFTS) test rig [20]. The AFTS rig was originally developed by Rolls-Royce to evaluate fuel thermal decomposition and deposition rates. This rig has been further developed at the University of Sheffield, in conjunction with industry, to include a variety of an aero-engine valves, filters and other fuel system components. Typical operation involves fuel circulation at 20 litres per hour over 300 hours at 180 °C, during which time the various system valves are periodically actuated.

A recording of the acoustic signature for a check valve opening event is shown in the time and frequency domain plots in Figure 5. The valve starts in the closed state, where some low amplitude signatures above 150 kHz can be seen along with some lower frequency artefacts of signal processing. The valve rapidly opens at 1.5 seconds, with an estimated transient time of 0.2 seconds. In the established open condition, a novel frequency at approximately 180 kHz can be seen to emerge along with an increase in the energy at multiple frequencies in the 200kHz-400kHz range. There is only evidence of amplitude, and not frequency, change during valve transients. The measured frequencies are both in line with those found in other literature and consistent with theoretical expectations related to the flow shedding effects from fuel system geometry [21]. There is also a low frequency (c. 1Hz) amplitude oscillation in the open state as described for systems with these Reynolds numbers in Blevins (1990).

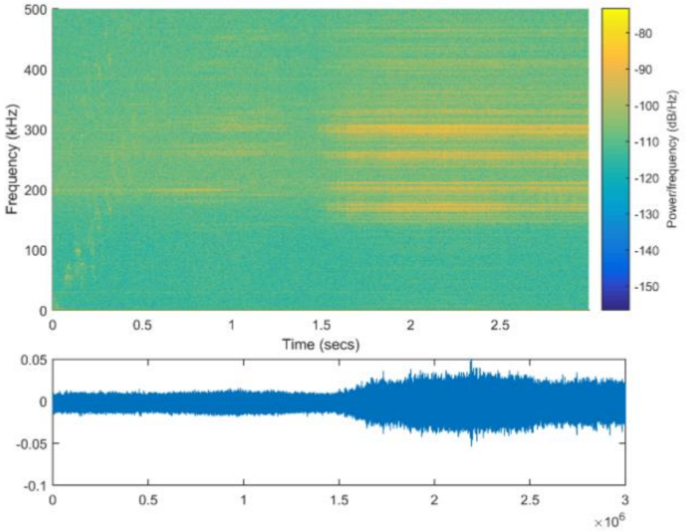

Figure 5: Opening flow scheduling valve response [21]

4.1.2 Acquire

The acquire stage defines how data is sampled, both at the appropriate time or operational state and rate. Some degree of data pre-processing normally takes place during this phase and may include data reduction or compression.

The acoustic emission technology requires sampling rates in the order to 1MHz, perhaps feasible on test bed but not in-service. Analogue band-pass and averaging front-end could ultimately be designed to allow sampling at the bandwidth of the valve dynamics, rather than the vortex shedding frequency. During test the richer information of full rate data could be obtained and digitally processed, though the cost in transfer and storage may be high. For our prototyping in a rig environment, a USB based National Instruments device was used. Connectivity issues in using USB connectivity were found, and a more reliable alternative, e.g. high-speed Ethernet, would be recommended for future similar rate data acquisition.

This resulting valve flow/position sensing data, regardless of whether passive or more conventional sensing is used, would be in the order of 5 Hz to capture full dynamics of the valve. This is too great a volume of data to justify in-flight transfer (though almost certainly not an issue in test). Therefore, feature extraction is often used to reduce data volumes. Features are required to be informative to making the end analysis and decisions, whilst also minimising the data volume. Our immediate goal is to detect a valve in the incorrect state, thus a simple threshold is used to quantise the analogue processed signal into an open or closed state.

4.1.3 Transfer

Transfer involves the movement of data between system interfaces. In-service, typically this will entail transfer between the acquisition system local to the asset and a central data centre, whereas on a testbed a range of digital buses and data formats may be allow real-time observation in a control room or longer term storage.

The open / closed state of the valve can be efficiently described as either time / state-transition pairs or a run-length encoded time series, which will be of low volume since the number of pilot / mains transitions are usually infrequent in a flight.

4.1.4 Analyse

Our work to date has deployed the passive sensing technology as a valve state detector, this the dynamics are not assessed. This is open area for development. For effective health management the detection of incipient faults, which provide sufficient warning of failure, and the trending of such indicators, are needed to enable preventative maintenance policies. In Eleffendi et al. (2012) [22] we discussed health management strategies for valve diagnosis. The work assumed that a measure of flow / valve position and actuation force were available to observe the static friction growth increasing the required force, F_M, to initiate movement in the valve, which is shown in the valve response as nominal and degraded conditions in Figure 6 generated from the AFTS rig. In the architecture presented in Figure 1, the actuation force is a function of engine pump speed and splitter valve position. Given an indication of when the valve opens (from a detected flow change), a correlation to estimated actuation valve initiation force (F_M) may be calculated and thus trending of frictional force growth. The need for a position or flow sensors, to provide the indication of valve opening, can be eliminated using the method provided in this paper.

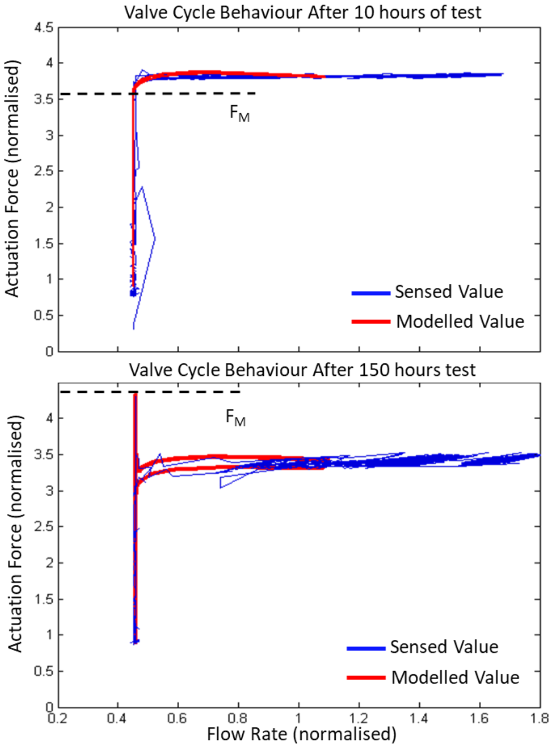

Figure 6: Valve actuation response to before and after fuel endurance testing on the AFTS rig [21].

Nevertheless, the inference of valve positon using the techniques outlined in this paper provide capability for the detection of valve failure, by sensing uncommanded or non-responsive flow rate change. The sensor was placed in the AFTS rig over a period of 2 years during which time over 2000 hours of operation at temperature have been recorded, with no sensor faults being seen. To enable logging of data over these log periods only nine 3-second snapshots of data during each valve cycling were recorded. The nine snapshots were triggered at consistent time intervals during a commanded valve close-open-close profile, with snapshots 6 & 7 occurring in the valve open state. The snapshots were processed using a digital bandpass filtered RMS energy measurement and also a frequency domain difference calculation between the snapshot 1 and every other snapshot. Two months of this post processed data is shown in Figure 7, showing a reliable difference between open (snapshots 6 & 7) and closed state.

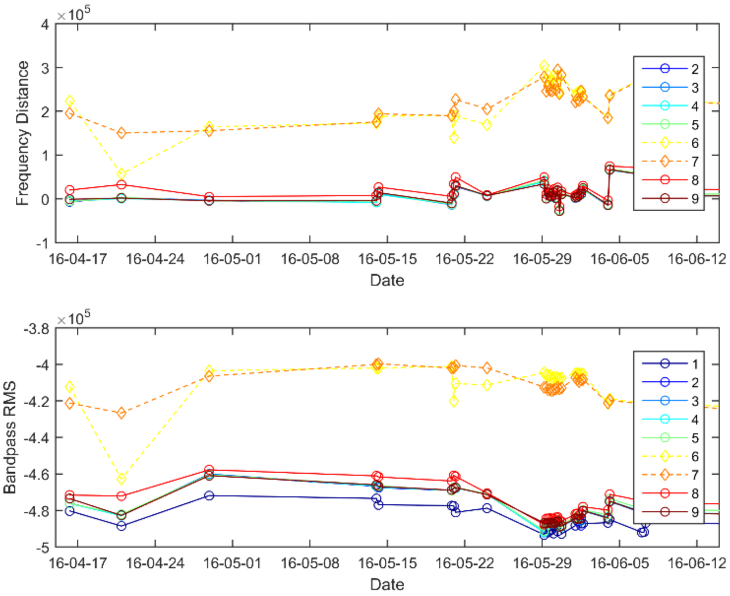

Figure 7: Acoustic spectrum features generated from data snapshots collected between April and June 2016, showing difference between open state (snapshots 6 & 7) and closed state [21]

4.1.5 Summary

The non-invasive sensing approach is believed to offer a low weight, reliable approach to flow sensing in this application. The accuracy of flow measurement is limited to only an approximate estimate and thus is only fit for characterising valve health rather than a full validation of system performance. The value to testbed may therefore be diminished. On the other hand, a relatively simple application of analogue signal processing and software can deliver low volume signal suitable for in-service monitoring.

4.2 Effect Monitoring – TGT Profile Modelling

4.2.1 Sense

Conventional TGT sensing is well known, with different configurations of harnessing are often used in test bed in comparison to in-service. The pattern of eight TGT recordings divided by their mean value at three critical operating conditions are shown in Figure 8, for a testbed test with seeded fault. It shows that gas temperature is relatively uniformly distributed in normal condition, with about ±3% section-to-section variations compared with its mean value. However, a fault (reduced flow into one combustor can) changes the uniform pattern, as the two red lines in Figure 8 portrays the faulty pattern caused by 5% and 15% partial blockage at take-off, respectively. The degree of pattern deviation depends on the severity of the fault. For an incipient fault, e.g. 5% blockage, the changed pattern lies on the margin of the normal temperature band (ring area between the dashed lines), but not exceed it, thus fault of this magnitude is not distinct. More sophisticated analysis techniques are required to enhance the sensing.

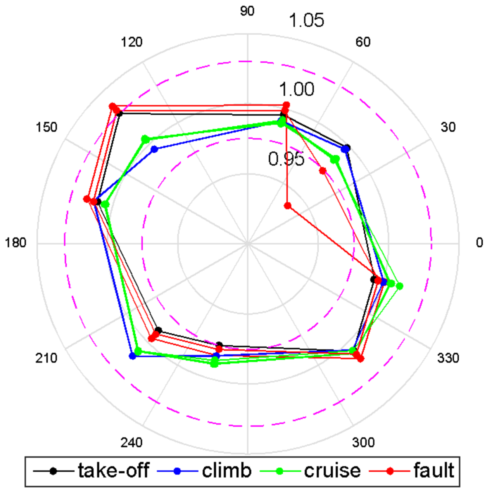

Figure 8 Radar plots of normalised T550 profiles [11]

4.2.2 Acquisition

In testbed scenarios, sudden changes mean continuous monitoring is required, which may not be the case of condition monitoring in service. Appropriately chosen snapshots may make characterising behaviour simpler. For temperature profile monitoring, non-linear behaviour is significant only if a continuous full flight capability is required. As illustrated by the P30 vs TGT relationship in Figure 9, local regions of linear behaviour at operating points of interest may be selected to allow simpler characterisation of behaviour. Data selection decisions on the number of training points, within range, need to be made based upon model performance measures. The cost of data transfer means that the acquisition of data for the monitoring function is constrained, but this can also aid in simplifying the monitoring of the process.

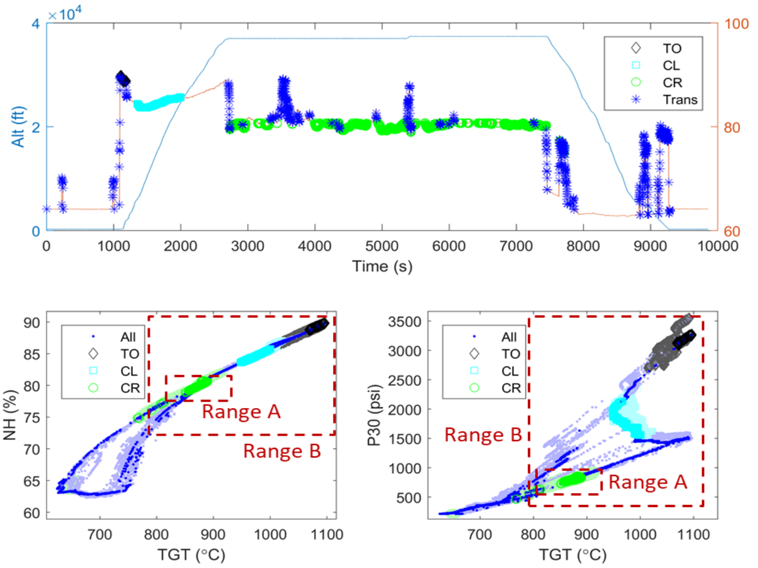

Figure 9: Non-linearity exhibited across the full operating envelope is greatly reduced by considering Take-off, Climb and Cruise conditions individually. Upper plot shows the altitude (Alt) and shaft speed (NH) of a typical flight profile, highlighting the different flight conditions with the transient conditions excluded. The relationships between parameters (left TGT and NH, and right TGT and P30) are shown in bold for the selected profile, also shown in lighter shading are the parameter relationships from other flight profiles.

4.2.3 Transfer

The data acquisition scheme for snapshot monitoring reduces the data volumes required for transfer in-flight, but in addition to volume constraints, the format of data may also be restricted. Existing data transfer schemes, using ACARS (ARINC 622), on a gas turbine quantise the data for each parameter into multiples of the 91 available ASCII symbols. The limitations imposed by these schemes can be limiting in precision per bit of information. Vector quantisation (VQ) is a data compression technique that can reduce data volume or quantisation error by increasing the information per symbol when compared to the currently used scalar quantisation [23]. Figure 10 depicts a simple example of scalar and vector quantisation for a 2D example. In scalar quantisation the 2-D space of NH and TGT is evenly gridded along both axes, illustrated by the dotted grey lines. If using 10 levels to quantise each dimension, it requires 100 sub-regions to cover the whole 2-D space. However, it is clear that NH and TGT measurements represented by blue circles do not fully spread over the space but are highly correlated. Therefore by using VQ scheme the space is divided into fewer numbers of sub-regions, while preserving the quality of compression as much as possible. Green dots demonstrate the location of 10 code vectors, and green lines represent the division of regions in the 2-D space. Each measured value (such as that illustrated with the red dot) is then described by an identifier to its nearest code vector (i.e. green dot) plus some residual. Depending on the acceptable error magnitude allowed, these residuals may be discarded or entropy encoded into the transferred data.

This implies that the high quality sensing requirements (for monitoring functions) should not exceed the limitations imposed by the data transfer process, including compression. Although, it should be noted there are nearly always multiple uses of a sensor and that as legacy data formats are retired and new connectivity options emerge the transfer of data is likely to become far less constraining in-flight.

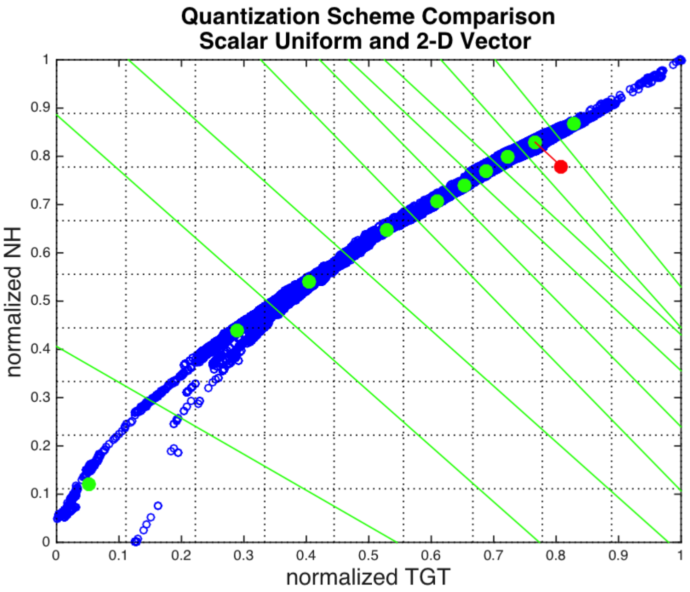

Figure 10 Comparison of scalar and vector quantisation

4.2.4 Analyse

As previously introduced, the limited sensing requires a more advanced approach to assessing the health, using the residual based methods discussed in Section 3.

Using the data transferred to ground, a model of normality is trained by learning the function f_n between each of n TGT harness readings (T_n^{TGT}) and the temperature values from the a set of k measurements radially opposite, together with high pressure (HP) shaft speed (NH), combustor inlet temperature and pressure (T^{30}, P^{30}), fuel flow (W^{fe}) and pilot/mains fuel split ratio (S),

$$T_n^{TGT} + e_n = \widehat{T_n^{TGT}} = f_n(X) = f_n\left(T_{n+i}^{TGT}, T_{n+i+1}^{TGT} \dots T_{n+i+k}^{TGT}, NH, T^{30}, P^{30}, W^{fe}, S\right) \qquad \text{(Equation 3)}$$

where $\mathrm{T}_{\mathrm{n+i}}^{\mathrm{TGT}}$ to $\mathrm{T}_{\mathrm{n+i+k}}^{\mathrm{TGT}}$ represent value from opposite temperature measures. Should three opposite readings be taken, from a 12 probe circumferential harness, the index parameters n=1, i=7, k=2. Multiple regression models (one per measurement) are constructed by training with data collected under normal conditions, providing complete prediction for the temperature profile prediction around annulus. The statistical properties of the prediction error, e_n, can then be used to detect and trend divergence from normal behaviour, such as that induced by fault conditions. The selected parameters are selected based upon knowledge of engine physical behaviour.

The regression model training is essentially an optimisation problem of minimizing the following error function from a finite set of data:

$$e_n(W) = \frac{1}{2} \| f_n(X, W) - T_n^{TGT} \|^2, \qquad \text{(Equation 4)}$$

where a regression model, such as a multivariate polynomial regression model, $f(X, W) = w_0 + \sum_{k=1}^{K} \sum_{i=1}^{D} w_{i,k} x_i^k$, is employed. In such, $x_1, \cdots, x_D$ are regression variables, and $w_{1,k \dots D,k}$ are the unknown coefficients for each model order, k. Obtaining its coefficients is linear with respect to the objective function, which can be solved through a least-squares error problem.

As shown in Figure 11, both a polynomial and neural network model with the same sample size provides comparable prediction accuracy. Both models are able to predict targeting temperature accurate to less than 2 Kelvin in normal condition. The models are able to detect anomalies (deliberately induced flow restriction faults) with the magnitude of 20 Kelvin deviation of TGT, which represents 5% blockage of a fuel injector. In comparison to the raw sensor output (Figure 8), considerable robustness has been added through analysis – as shown by the margin of separation.

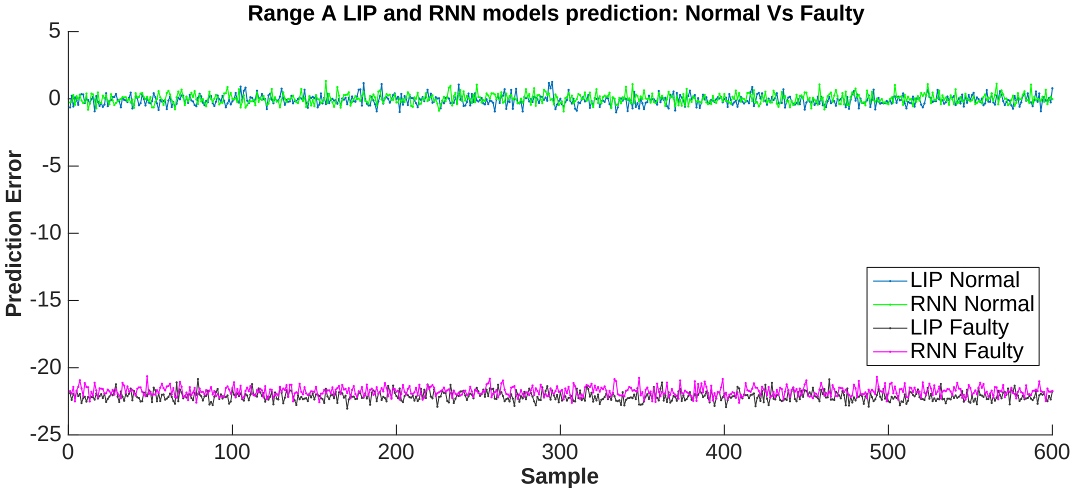

Figure 11: **Prediction errors in norma**l and faulty condition [11]

4.2.5 Summary

The TGT profile monitoring approach removes the need for additional sensing at the cost of increase modelling. The design choices between these two routes to information extraction should be carefully balanced whilst also considering the criticality required of the software functions – which can make software complexity extremely costly.

5.0 CONCLUSION

A lightweight systems engineering approach using QFD analysis can provide an effective set of assessment criteria for the application of a sensing technology. In this paper, solutions to the problem of fuel system valve sticking have been used to illustrate some of the considerations for the alternative means.

TGT profile monitoring in a test bed has the potential for high temperature combustor exit sensing with many individually harnessed transducers around combustor exit plane. In this environment, the full transfer of data throughout operation is possible using higher weight and cost apparatus. Thus the direct sensing of the state of interest is possible. In contract, a production standard engine is (today) limited to harnessed thermocouples downstream of the temperature state of interest. This drives complexity into the analysis of data that while appropriate for health monitoring application, may be unacceptable for safety critical use.

When sensing the cause of combustor fuel mis-scheduling, valve position or fuel mass input measures are key. On a testbed, individual flow metering or transducers for position sensing (installed with cooling flows) can be a proven way to assess valve issues. However there is a higher cost and weight penalty for such sensing systems in-service, thus alternative solutions are desirable. For a production engine, there is potential for the novel sensing solution presented in this paper, which, with simple on-board processing, can produce a volume of data suitable for off-board transfer and consequent alerting.

5.1 Acknowledgements

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