Rapidly Building a Parametric Model to Estimate the Structural Fatigue of a Fast Jet

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RAPIDLY BUILDING A PARAMETRIC MODEL TO ESTIMATE THE STRUCTURAL FATIGUE OF A FAST JET

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ABSTRACT

To effectively plan maintenance actions for a fleet of fast jets requires accurately monitoring the fatigue of the structure. In this application, a parametric model is used to estimate the stress experienced at different locations on the aircraft given flight parameters (acceleration forces, speed etc.) collected from on-board sub-systems. The estimated stress is then combined with previous stress cycles to calculate the overall fatigue of the structure at different locations. The problem addressed in this paper, is the rapid generation of new parametric models that accurately estimate the stress experienced when new aircraft configurations are introduced. Firstly, an initial parametric model is constructed using a physics-based model of the new aircraft configuration. Secondly, and the main focus of this paper, a tool based on numerical optimisation methods is used to refine the parametric model using data collected from test flights, where flight parameters and strain measures at different locations are recorded on a test aircraft in the new configuration. This paper presents how an optimisation tool can be utilised by a structural engineer to refine an existing parametric model to estimate the structural fatigue of the new aircraft configuration and presents a brief analysis of different parameters within the tool. The paper concludes that the tool enables a parametric model to be rapidly generated that accurately estimates fatigue, and hence enables the maintenance procedures to be scheduled for new aircraft configurations.

KEYWORDS : *Structual Health Monitoring, Fast Jet, Optimisation.*

INTRODUCTION

Condition-Based Maintenance (CBM), where maintenance actions are only performed when necessary, requires a process to accurately monitor the condition of the platform [2]. In this paper, the authors are interested in monitoring the structural health of a fast jet in a new configuration such that maintenance actions related to the structure, such as Ultrasonic testing, can be performed only when required. To be able to monitor the structural health of the aircraft requires an estimation of the fatigue of the structure, which is based on the stress cycles experienced at different locations on the aircraft (Figure 1 shows the different locations typically monitored on a Fast Jet [1]).

The approach taken to estimate fatigue is shown in Figure 2 where the stress experienced by the aircraft can either be calculated from strain gauges installed on the aircraft or by using a parametric model that estimates stress given the aircraft flight parameters (acceleration. forces, Mach no. etc.) for a given aircraft configuration (model revision, payload etc.). In general, the estimated or measured stress is used to construct a histogram of the mean and alternating stress cycles experienced by the structure over the aircraft's lifetime. Miner's rule [3] is then used to estimate the number of remaining cycles before an inspection is required by combining the histogram of stress cycles with material failure properties (SN curves) derived from material bench tests.

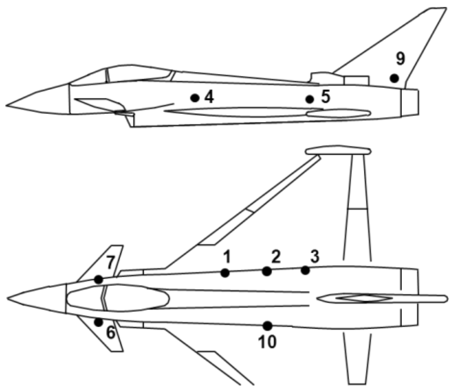


Figure 1 - Locations where the health of the structure is monitored

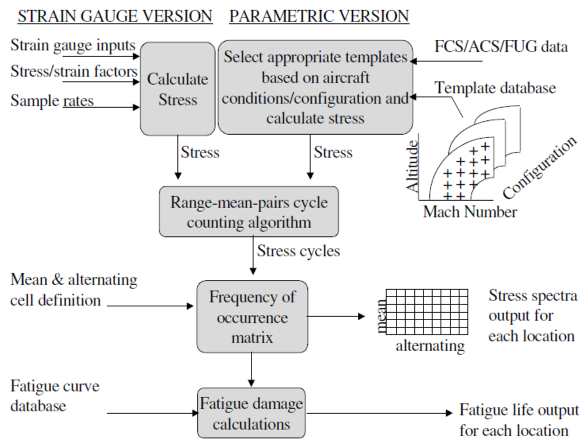


Figure 2 – Overview of the fatigue monitoring system (reproduced [1])

In fleet operations, the accuracy of the estimated fatigue life depends primarily on two factors, the fatigue monitoring tools that are used (estimated stress) [5] and the accuracy of the model being used for the prediction of damage (fatigue curve database) [4]. In this paper, the authors are concerned with the former where the stress is estimated from flight parameters [6][7][8] using a parametric model. The parametric model can be used alongside strain gauges to overcome missing data or in isolation. The parametric model used to estimate the stress is dependent on the aircraft configuration and hence must be refined when changes are made to the shape, materials or payload of the aircraft. The aim of this paper is to develop a tool to rapidly generate parametric models for new aircraft configurations that accurately estimate the stress experienced and hence allow the maintenance to be scheduled effectively.

This paper outlines an approach to the construction of a parametric model using an initial physics-based model and then introduces an optimisation method that iteratively refines the parametric model using data collected from a set of test flights. In Section 2 the problem of building a parametric model is outlined. The iterative optimisation process followed by a structural engineer is defined in Section 3. The experimental results of using the process are presented Section 4 with analysis of the optimisation tool shown in Section 5. Section 6 provides concluding remarks and brief discussion on future work.

1 PARAMETRIC BASED STRUCTURAL HEALTH MONITORING

In this paper, a parametric model is constructed using a set of 2600 templates where each template represents a point in the flight envelope indexed using the location (See Figure 3 for an example of the template locations), Mach number, and altitude. Each template contains a set of 9 parameters (angle of attack against side-slide (ALPHA), angle of attack against Foreplane angle (FPLN) etc.) which in turn consists of a matrix that is defined across subsonic Mach bands and side-slip values. The estimated stress at each location on the aircraft for any point in the flight envelope is interpolated using the variables in the closest templates. The goal of this work is to estimate the value of the 585,000 variables contained in these templates such that the estimated stress accurately reflects the stress experienced for a new aircraft configuration.

The construction of the templates is achieved using a two stage process. Firstly, a finite element analysis and the results of ground-based airframe fatigue tests are combined to generate an initial set of templates for the new aircraft configuration. The templates generated from this initial process are then used as a starting point for the numerical optimisation outlined in the next section. Templates are specified along the Mach number and dynamic pressure bands (Q Bands) through the flight envelope of the aircraft. Each of the templates generated represents a point in the flight envelope as shown in Figure 3 where individual templates are used at different times in a flight. For example, Figure 3 shows the progression of a fictitious flight through the template space and the templates used for interpolation are shown by a solid square. The goal of the second stage is to refine the estimated stress using knowledge from a structural engineer and real-world data collected from a representative aircraft fitted with strain gauges. In this paper, the authors show how a set of templates can be quickly built for a new aircraft configuration using an optimisation process overseen by a structural engineer.

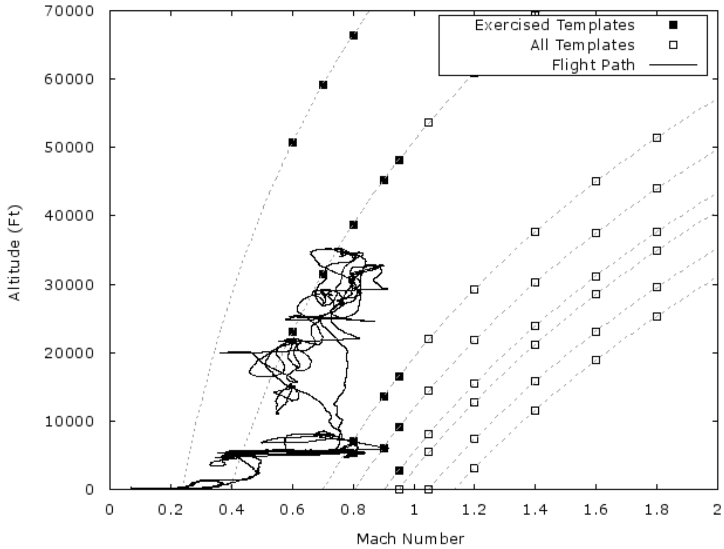


Figure 3 – Locations of the templates on the dynamic pressure bands with an example trajectory shown in black through the flight. envelope. The used templates are shown in solid black squares and unused templates are shown as outline squares.

2 TEMPLATE OPTIMISATION

In this section, the authors formally define the optimisation problem and outline the design choices that have been used to reduce the problem into a tractable form. Optimising the templates requires a blend of automated optimisation with the subject matter knowledge from a structural engineer. The optimisation tool developed within this paper is not meant to be a single automated process but one that allows the structural engineer to iteratively refine the accuracy of the templates while visualising and verifying the model produced. This iterative process enables a structural engineer to focus the finite computation on key areas of the templates. It also allows the template variables to be visually inspected and validated, which is extremely important for any certification case.

The refinement of the templates is performed in an iterative manner where initially the templates are optimised against a subset of the flight data available, which is known to exercise the majority of the templates. Then, after inspection and possibly manual alterations by the structural engineer, the optimisation process is targeted at particular parameters (ALPHA) or portions of the flight envelope (templates). The goal of the optimisation problem is defined in Equation (1).

$$\theta^* = argmin_\theta \left(\sqrt{\sum_{i=0}^{N} (f_\theta(x_i) - Y_i)^2} \right) \tag{1}$$

where x_i is the flight parameters from a test flight of length N, Y_i is the measured stress calculated from the strain gauges mounted on the aircraft, f_θ is the algorithm to calculate stress from the flight parameters using the templates θ. The aim of the optimisation is to find the templates θ^* that minimise the Root Mean Squared Error (RMSE) between the estimated stress from f_θ and the measured stress Y. The challenge in performing this optimisation arises from the number of variables within the templates and the complexity of the function used to estimate the stress (f_θ) which contains hysteresis and is highly non-linear. The approach taken in this paper is reduce the overall optimisation problem into a sequence of smaller (tractable) problems. Firstly, the number of templates considered is reduced to only those exercised in the test flights. Figure 3 shows a test flight through the template space and this can be used to reduce the set of templates to the minimum set used. For example in Figure 3, 19 templates are exercised during the example flight (those marked with solid black squares). The optimisation can therefore be substantially reduced by only considering a subset of the templates which influence the function f_θ. The templates exercised are extracted by instrumenting the code that implements the stress function although importantly this code is not functionally altered.

The optimisation problem has now been reduced to 19 templates (for this example test flight) all together these templates still contain approximately 3,825 variables to optimise. A second insight that can be utilised to reduce the complexity of the optimisation is that specific flight parameters have a greater influence on the estimated stress for particular locations on the structure. For example at location 1, the parameters ALPHA, FLAP and SLAT have the greatest influence (as determined by a subject matter expert in structural modelling). Therefore the optimisation process can be focused on improving those parameters within only the utilised templates. The optimisation process is separately performed in a sequential manner for every location. For every location, an optimisation is performed independently, but sequentially, on each of the utilised templates for all the significant parameters, identified by a structural engineer. The optimisation performed is a bound constrained Nelder-Mead Simplex algorithm [9] where the decision variables are adjustment factors that are applied to the relevant parameter section of the template file under optimisation.

3 EXPERIMENTAL RESULTS

In these experiments, an initial set of unrefined templates were used as a starting point to build a parametric model for a new aircraft configuration and the accuracy of the estimated stress was evaluated during the optimisation process. The improvement in the accuracy was investigated by performing the optimisation for three different locations across the aircraft. Locations 1, 6 and 9 were selected because they explore different relationships between flight parameters and the stress experienced. To validate the approach, the optimisation was performed over seven flights, referred to as the training set, and then the accuracy was validated on seven different flights, which are referred to as the test set.

The experimental results are shown in Table 1 and present the RMSE error (as shown in Equation 1), squared correlation and the slope for the training and test set both before and after the optimisation for the three different locations. For the training set, as expected, the accuracy of all of the performance metrics are increased after the optimisation was performed. In particular, the slope of the correlation has improved significantly for all the locations. The test set shows a similar result with one exception where the correlation has been slightly reduced in favour of the slope. The experimental results show that the percentage improvement is dependent on the location selected but using the RMSE as the objective function has the effect of improving the correlation and slope uniformly. For example, location 9 on the rear of the aircraft is likely to be affected by environmental factors that are not captured in those flight parameters measured.

The next set of experimental results give an example of how these improvements in the estimation of the stress are likely to affect the estimated fatigue. To be able to understand this improvement the stress (as measured by the strain gauges), the estimated stress both before and after the optimisation was processed by the Rainflow counting algorithm [11] to extract the stress cycles for all of the fourteen flights in the training and test set. The number of cycles for different stress amplitudes was combined with Miner's rule for an example Titanium alloy (Ti-6Al-4V) to show the damage fraction accumulated during these flights. The S-N curve for the Titanium alloy was taken from page 110 in [10] and is a simplistic but representative tensile fatigue model for a material on a fast jet aircraft.

		Training Set (7 Flights)		Test Set (7 Flights)	
Location	**Metric**	**Before**	**After**	**Before**	**After**
1	RMSE	9,429	**2,529**	7,582	**3,722**
	Correlation	0.9680	**0.9940**	0.9686	**0.9834**
	Slope	0.8536	**0.9864**	0.8558	**0.9840**
6	RMSE	22,602	**3,719**	20,481	**5,902**
	Correlation	0.9638	**0.9776**	**0.9573**	0.9328
	Slope	0.5681	**0.9695**	0.5634	**0.9121**
9	RMSE	8,702	**5,845**	8,677	**6,836**
	Correlation	0.7354	**0.8172**	0.6010	**0.7057**
	Slope	0.7153	**0.9008**	0.6978	**0.8114**

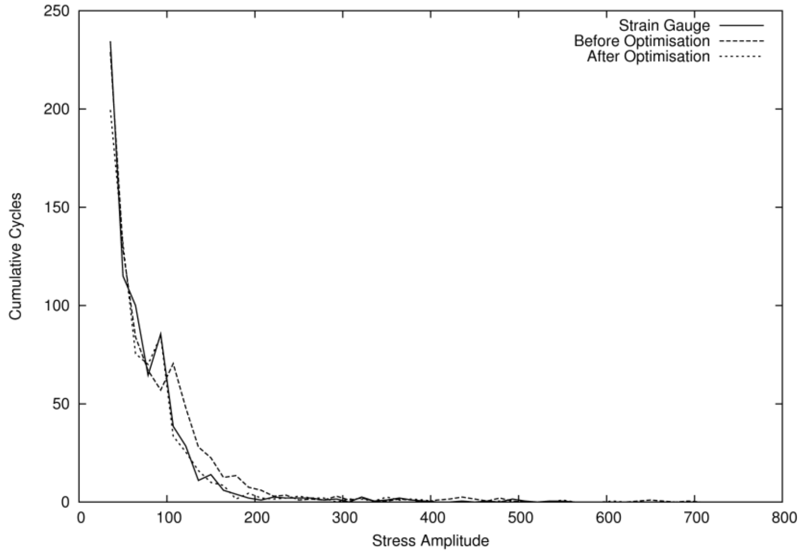
Table 1 - Comparison of optimised templates on a training and test set with three flights in each

The histograms of the stress cycles generated by the Rainflow algorithm for the stress from the strain gauges and the parametric model, before and after the optimisation, for locations 1 and 6 are shown in Figures 4 (a) and (b). The histograms show that the parametric model after the optimisation follows the strain gauge data and especially it is noticeable that the error is reduced between 100 and 400 MPA.

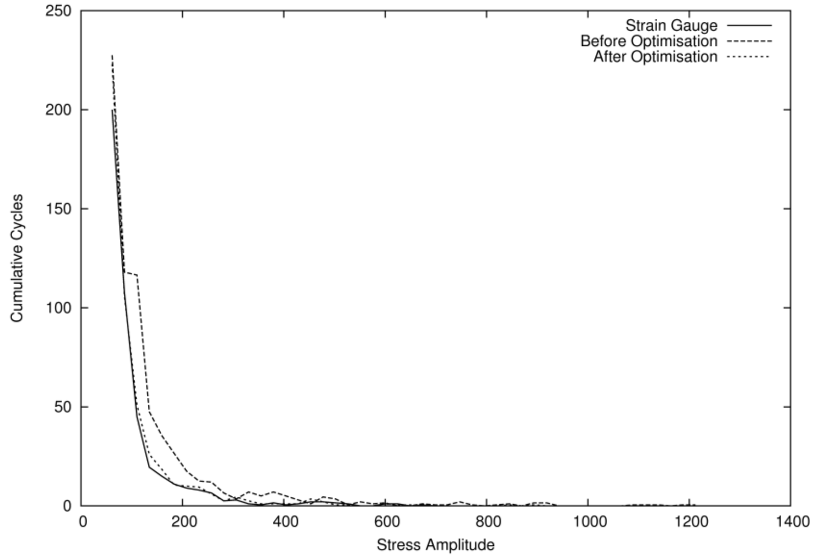
Using Miner's rule, the number of cycles per stress amplitude for location 1, as measured by the strain gauges, resulted in a damage of 0.006% after 14 flights. The damage estimated before refining the parametric model for this new configuration is 0.156% but this is reduced to 0.006% after the optimisation. Although this is only a small set of flights (17 hours) for a particular section of the flight envelope, if this was extrapolated for the life-time of the aircraft (up to 80% damage) then this would enable 24 times more flying hours to be performed before maintenance was conducted. This result is replicated on location 6 where the damage calculated by the strain gauges is 0.024% and the parametric model before is 3.645% and 0.092% after but the damage calculation is not altered for location 9 (measured 1.175%, before 1.487% and after 1.525%). The lack of improvement for location 9 is likely to be due to the reduced accuracy of the estimated stress, as shown in Table 1. As previously mentioned, this reduced accuracy is likely due to environmental factors that are not captured within the flight parameters. Although, these results clearly show that improving the estimated stress from the parametric model using test data can have a real impact on the estimated fatigue for a new aircraft configuration.

4 OPTIMISATION ANALYSIS

This section presents a preliminary analysis of the optimisation process. Firstly, the assumption of which parameters are important for particular locations on the aircraft is investigated. The parameters used for each location within the optimisation were initially derived from analysis of the structural model but to validate this hypothesis, an exhaustive search over the different parameters was conducted. An optimisation of each parameter was performed using an initial set of templates. After evaluating all the parameters, the templates generated by the parameter that produced the minimum RMSE are then used as the starting point for the next iteration. The results in Table 2 show the set of parameters found within the sequence for three different test flights compared with those derived from the structural model.



(a)



(b)

Figure 4 - Histogram of stress amplitude for (a) Location 1 and (b) Location 6

The experimental results show that the initial parameters selected were largely the same except that the optimisation algorithm found that Out-Board Flap reduced the RMSE slightly more rather than In-Board Flap. Also, the forward plane angle (Fpln) was found to reduce the RMSE where this was not predicted by the structural model for this particular location. Although, it is worth noting at this point that the optimisation routine is not aware of the physical meaning of the parameters and hence, the improvement seen from adjusting OBFlap and Fpln could be an artefact from the initial physics-based model or previous adjustments to the templates. For example, previous adjustments may have improved the templates for those parameters which have known relationships, leaving the optimisation to explore those that have only a weak relationship. For location 6, the majority of the parameters for the flights tested showed a strong correlation with those suggested by the structural analysis although some of the flap parameters (Flap, PortIBFlap and PortOBFlap) appeared to have an impact. Hence, an optimisation of the flap parameter is suggested from these results.

Location	Scenario	Parameters
1	Initial	Alpha, Flap, Slat, RPYA
	Flight A	Alpha, OBFlap, Slat, RPYA, Fpln, PortOBFlap, Rudder
	Flight B	Alpha, OBFlap, Fpln, PortOBFlap, RPYA, Slat
	Flight C	Alpha, Slat, RPYA, Fpln
	Proposed	Alpha, Flap, OBFlap, Slat, RPYA, Flpn
6	Initial	Alpha, Fpln, Slat, RPYA
	Flight A	Alpha, Flap, Fpln, PortIBFlap, PortOBFlap, Slat
	Flight B	Alpha, Fpln, PortIBFlap, RPYA, Slat
	Flight C	Alpha, Fpln, RPYA, Slat
	Proposed	Alpha, Fpln, Slat, RYPA, PortIBFlap

Table 2 - Significant Parameters for Location 1

Secondly, the order in which the templates were optimised was analysed. The optimisation in the previous section was performed by sequentially optimising each template along the Q-band starting at the highest Mach No on the highest Q-band. Although, it was observed that some of the flights had a higher RMSE because they used particular templates. Hence, our hypothesis was that a lower overall RMSE could be achieved if the optimisation process was focused on these templates. To explore this further, the RMSE for a particular template was defined as the sum of the RMSE for each test flight were it was used. To be able to explore this in a finer granularity (because a large number of templates are used on each flight and hence would not result in a well-ordered list), each flight was divided into fifteen flight segments and the RMSE for each flight segment where the template was used was combined.

Figure 5 shows the RMSE for a single test flight during the optimisation process. Firstly, comparing the templates ordered by the Q-band and the RMSE shows that the final RMSE is approximately the same. Although, performing the optimisation using the RMSE ordered list of templates results in a lower RMSE with fewer evaluations. Therefore, an analysis of how varying the number of templates optimised on each parameter iteration was performed. In Figure 5, the graph also compares the RMSE when subsets of the templates are optimised for each parameter. Figure 5 shows the overall RMSE when only the top ten highest RMSE templates are optimised. The strategy shows a clear improvement on the final RMSE as the computation is focused on those templates with the highest error allowing repeated cycles over each parameter.

CONCLUSION

This paper has introduced a process that blends a physics-based modelling and data-driven optimisation to help a structural engineer to quickly refine a parametric model that estimates the stress experienced at different locations on the structure of a new aircraft configuration. The results have shown that the optimisation of the parametric model using an iterative approach allows the structural engineer to focus the limited computation and produce a refined model. The capability to quickly generate parametric models for new aircraft configurations enables the rapid certification of aircraft upgrades. The paper has shown that an improvement to the estimated stress experienced by the aircraft can have significant effect on the estimated damage and therefore on how maintenance is performed.

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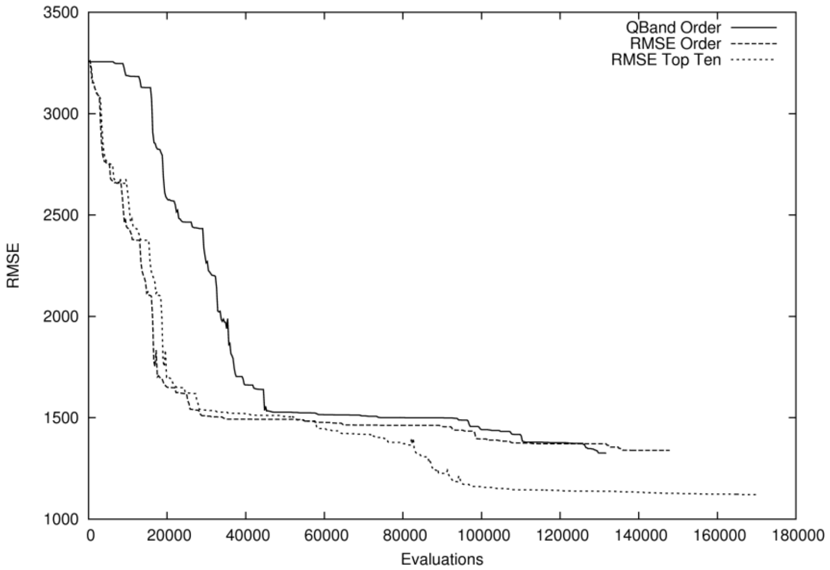

Figure 5 - The effect on the RMSE of changing the order of the templates

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