The Minimum Flight Routine (MFR) for UK MoD Puma Helicopter Rotor Track and Balance

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Abstract

Helicopter rotor track and balance (RTB) is the process of reducing to a minimum the rotor induced vibration present during helicopter flight. We propose here the use of an optimisation algorithm to reduce the number of dedicated flights required to perform RTB and return an aircraft to a serviceable state. The algorithm has recently been flight trialled by UK MoD on their Puma aircraft as part of a project to embody the algorithm on their existing RTB equipment. Both main and tail rotor applications were tested. Some of the results from that flight trial are shown here along with their effects on the development of the algorithm itself. The outcome indicates that there is significant potential cost saving and increased availability benefits to be made by using the algorithm across the fleet.

Background

The Minimum Flight Routine (MFR) algorithm was first conceived in early 2006, development then commenced in the summer of 2006 through a Knowledge Transfer Program (KTP) between Helitune and the University of Bristol. During this 10 man-year development project the MFR algorithm has been successfully implemented on a number of helicopter platforms. This paper specifically covers the embodiment of the MFR algorithm for the UK MoD Puma Helicopter.

Rotor Track and Balance

Rotor track and balance is concerned with reducing to a minimum those vibrations present in helicopter flight that can be reduced. That is vibration due to non-uniformity of the rotor blades rather than the inherent vibration associated with a helicopter in flight [1]. RTB is typically performed in any one of three circumstances:

1. after maintenance procedures have been carried out;
2. after a specified period of flight hours or elapsed time, e.g. every ‘n’ hours or ‘m’ months whichever is sooner; or
3. if the pilot reports excessive vibration.

The exact intervals between RTB will vary from operator to operator and between aircraft types.

Blade tracking measures the relative differences in blade tip paths. Early mechanical methods of determining the track of rotor blades, such as ‘flag tracking’ are described

in [2]. Today this is typically carried out using an optical camera on board the aircraft. The introduction of optical methods extended the range of conditions under which the blades could be tracked, allowing in flight track to be measured. The earlier methods were of course, restricted to use on the ground.

Vibration monitoring is achieved by placing accelerometers in key positions around the aircraft to measure the vibration levels. These responses are recorded at pre-defined airspeeds along with the track data.

Helicopter rotor blades have various methods of adjustment to correct for the non-uniformities that cause increased vibration and out-of-track. Typical adjustments would include modifications to the pitch link length, trim tab angles and redistribution of blade balance masses. These adjustments can be made individually or in a combinatorial sense to reduce overall vibration. A more detailed explanation is given in [1].

This collected data set is used to calculate a set of adjustments to correct for the non-uniformities evidenced in the collected flight data. After engineers have made the adjustments, a further flight is made and a further data set collected to verify that an improvement in the vibration and track has been made. This process can be repeated until the vibration and track are within approved limits for that particular aircraft type.

This paper focuses on the MFR algorithm. Before moving on to discuss this, we look at the currently in-service rotor tuning algorithm used on the Puma. Both this description and Figure 1 can be found in [4].

Figure 1 shows the individual corrections without any consideration of their possible secondary effects, this we call a ‘single axis adjustment’. These corrections, when applied individually have the effect of reducing either axis to zero. In the example given, the axial correction point is at 0.3 ips at 7 o’clock which requires a correction of ‘Blade 2 + 2.5 Flats’. Recording data on a subsequent flight will show a secondary effect of this adjustment in that the radial will have been modified, moving it from 0.25 ips at 3 o’clock to some other predictable position. Ignoring these secondary effects then, will never result in an accurate radial correction. To remedy this situation we have to apply a "dual-axis (multi-plane) adjustment" and predict where the radial will move as a result of the axial adjustment, then obtain a correction from the predicted position. This logic should then be applied to the 2^{nd} axis to obtain a correction. Further, this iterative procedure will continue until an exact adjustment to get both axial and radial to zero has been calculated, or the adjustments become too small to be accurately or reliably applied. There may be occasions where a complete solution is not possible because corrections to one axis are detrimental to the other.

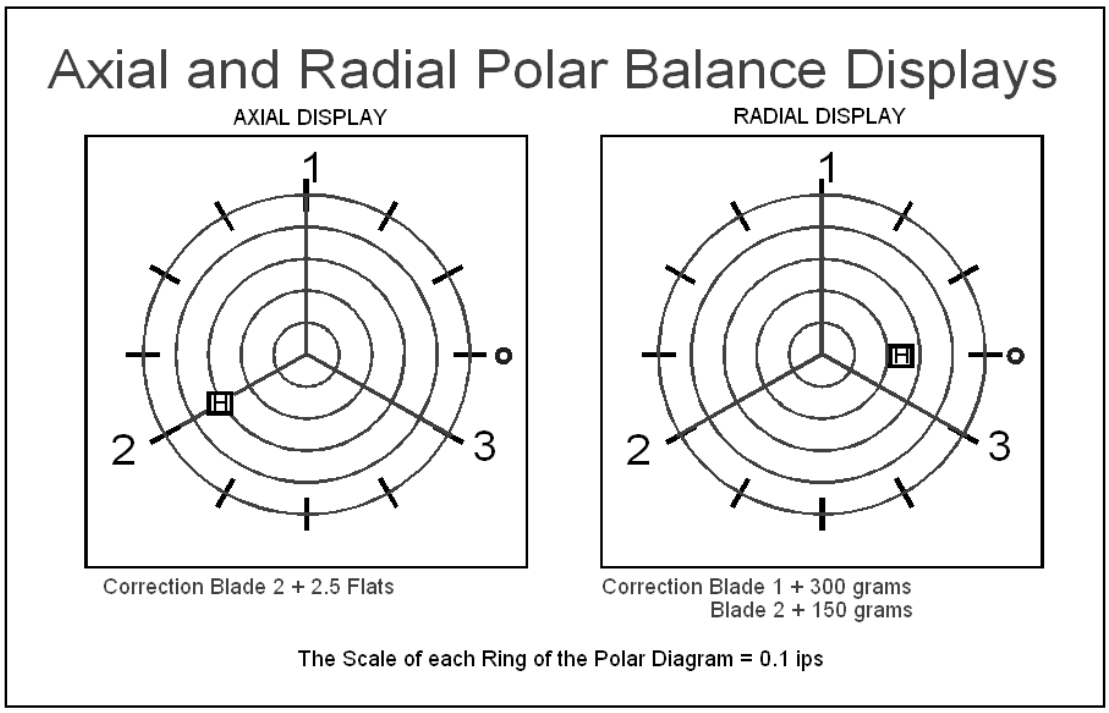


Figure 1: Axial and radial polar balance displays

Minimum Flight Routine Algorithm

The Minimum Flight Routine (MFR) algorithm was developed to reduce the number of flights needed to perform RTB, therefore reducing operating costs and increasing aircraft availability. It uses independent adjustment sensitivities at each flight condition to calculate a combined RTB solution using available adjustment types. The solution is predicted to minimise the track split and vibration (at the first harmonic) across the required flight conditions while ensuring any prescribed parameters on adjustment ranges are observed.

The sensitivities of the rotor state adjustments are calculated as a partial derivative of the flight condition. Clearly the inputs need to be related to aircraft type and tail number and so are applied in conjunction with:

- A description of the aircraft, number of rotor blades etc
- A description of the adjustments available
- A matrix representing the collected track and vibration data
- A matrix describing the sensitivity of vibration and track to rotor adjustment.

These input parameters fit within an overall set of constraint equations which include:

- The target track and balance limits to achieve
- A weighting factor allowing the operator to tailor the solution

Having aligned the sensitivities, the optimisation process is applied to minimise the solution matrix. The algorithm provides as outputs a matrix of adjustments and a predicted set of track and vibration measurements to be expected once the adjustments are applied.

Independent sensitivities are used to allow calculation of the cross coupling effects between axes of interest. For example, a Tab adjustment can have sensitivities for both lateral and vertical balance when running the MFR.

The sensitivities were calculated by analysing the historic RTB flight data from the whole aircraft fleet which gives a fleet average sensitivity at each required flight condition. A summary of the findings of this analysis follows.

To avoid the user having to configure the input parameters manually after each flight, pre-defined 'profiles' are used. Depending on the profile used, the algorithm can solve for lateral balance, vertical balance and track at all required flight conditions and using all adjustment types simultaneously. This approach allows the method to account for and if necessary correct for any defined cross coupling effects.

The algorithm can be set up with vibration limits for each flight condition being solved. This "tolerance banding" allows the limits to be different at each stage of the RTB process.

An RTB solution with fewer adjustments to make is seen as preferable to one with more adjustments. Before returning a solution, the MFR can optionally perform a 'cleanup' to minimise the number of adjustments made. In the case of weight adjustments for example, the geometry of the blade positions is used to minimise the number of blades on which weight is applied. For a four bladed main rotor - as is found on the Puma - this means weight will be applied to a maximum of two blades.

During the Puma flight trial discussed below, a number of other tools where used. A ground station software application was used as a storage facility as well a providing visualisation tools. A tool to analyse the fleet-wide sensitivities was also developed and utilised within the ground station.

Sensitivity Analysis

The Mod Puma fleet historic RTB data has been used to calculate fleet average sensitivities for each Rotor/Axis/Adjustment type/Test condition. The following plots (Figure 2 Vertical Pitch Sensitivities, Figure 3 Vertical Tab Sensitivities and Figure 4 Lateral Tab Sensitivities) show mean and standard deviation for sensitivity phase and magnitude. The items shown on the plots are:

- Green dot - those that fall within 2 standard deviations of the average (in amplitude and phase)
- Pink dot - those that fall outside 2 standard deviations of the average (in amplitude and phase)
- Purple dot – those that fall between 170° and 190° out of phase with the average
- Grey dot – the move vector was too small to be used
- Red Square – the sensitivity from the personality file
- Blue square – the "average" sensitivity calculated from the fleet data (the phase is the average, the amplitude is the minimum of the average and the median value)

The plots use scientific degrees rather than clock notation

A number of findings from this analysis were incorporated into the flight trial. It can be seen that the sensitivity values for the same rotor, axis and adjustment vary across flight conditions. These results show a clear need to use distinct sensitivity values at

each condition rather than a single sensitivity for an 'average' flight condition. The MFR uses this expanded set of values.

The results confirm and illustrate what is generally accepted, that certain adjustments give more reliable results than others. For example, the variability in the vertical pitch sensitivity (Figure 2 Vertical Pitch Sensitivities) is low, particularly in forward flight. This observation is to be expected given that vertical pitch (along with tab) is the principal method of controlling vertical vibration. In contrast, the lateral tab sensitivities (Figure 4 Lateral Tab Sensitivities) show an extremely high degree of variability both in magnitude and phase. Consequently, this sensitivity is not normally used for RTB, and was not initially used by the MFR.

It was found in the early stages of the trial that the suggested adjustments quickly 'saturated' the available tab adjustment. Including these values, uncertain as they are, was found to reduce the amount of pitch adjustment suggested by the algorithm.

The reason for this maxing out of tab can be seen by looking at the magnitude of the vertical tab sensitivities (Figure 3 Vertical Tab Sensitivities). Tab is known to have a greater effect at higher forward flight speeds due to its effects on the aerodynamics of the blade. This observation can be seen in the way the magnitude of the tab sensitivity drops at each successive forward flight condition. Unsurprisingly, fewer degrees of tab adjustment are required at higher speeds to generate a given movement of the balance point.

It will be observed that there is still variability present in the more effective sensitivities. This characteristic highlights the importance of using multiple aircraft trials to determine sensitivity coefficients. Namely that any particular aircraft may deviate from the fleet average in its response.

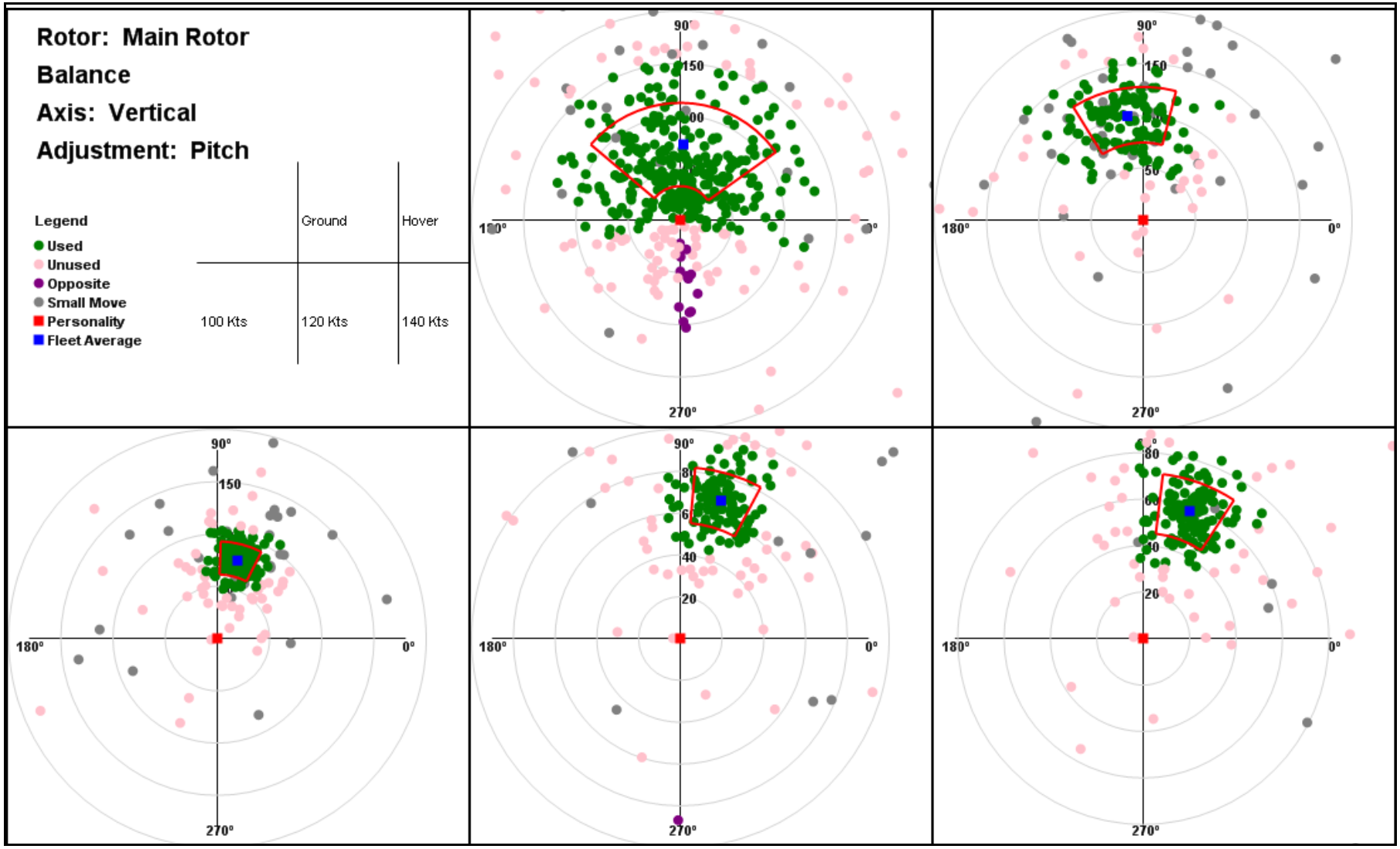


Figure 2 Vertical Pitch Sensitivities

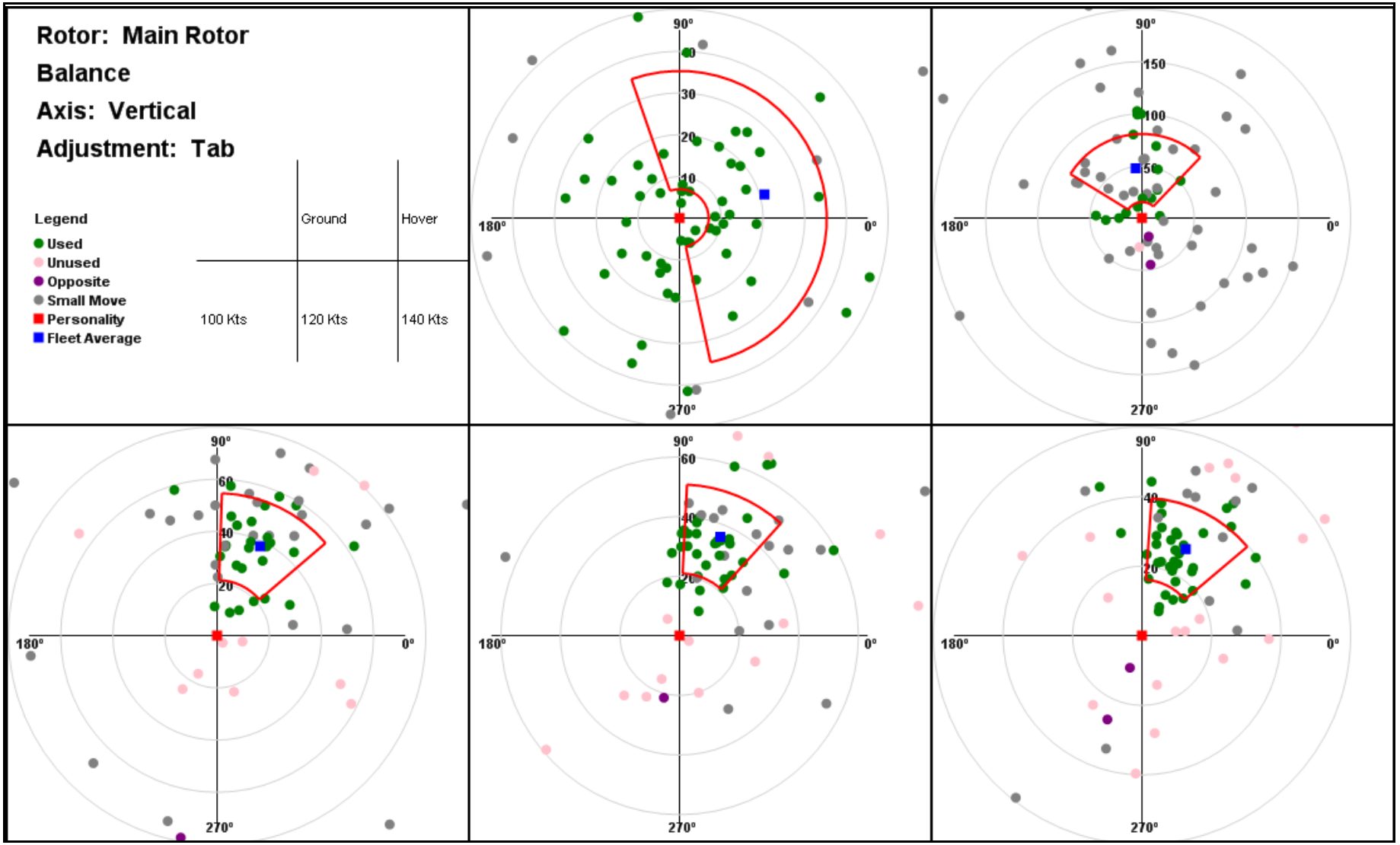


Figure 3 Vertical Tab Sensitivities

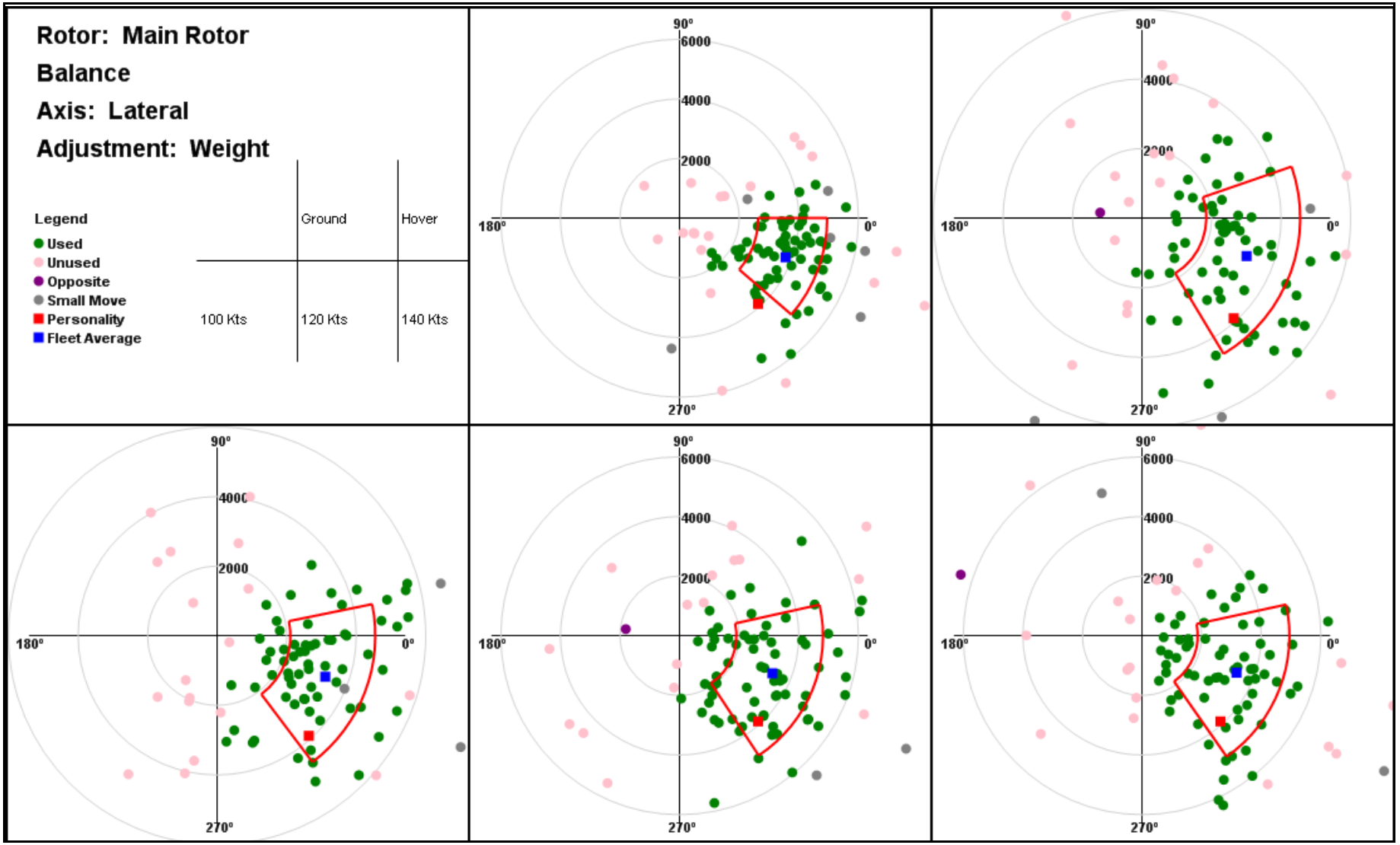


Figure 4 Lateral Tab Sensitivities

Flight Trial Setup and Procedure

The data collection and application of adjustments was carried out by UK MoD engineers. Running of the MFR algorithm to provide RTB solutions was carried out remotely by the authors. Flight data collected from the aircraft was sent electronically to University of Bristol/Helitune, where the MFR was applied to the data. The suggested adjustments were returned to the engineers who reviewed them before applying them to the aircraft. Good communication channels meant that delays in processing were kept to a minimum and the maintenance schedule was not unduly affected by the turnaround of the data.

For the flight trial, the MFR was set up to comply with the advice and limits described in [3]. The RTB equipment used on the trial was also installed as per [3]. The following MFR profiles were used in the Puma trial:

- **Main Rotor Ground Profile** – sets out to establish a good Ground Track and Balance (both lateral and vertical) using Pitch adjustments.
- **Main Rotor Flight Profile** – seeks to simultaneously minimize both the Lateral Balance and the Vertical Balance, and Track Split at all test conditions(Ground, Hover, 100 Kts, 120 Kts and 140 Kts) using a combination of the three adjustment types.
- **Tail Rotor Ground Profile** – sets out to establish a good Radial Balance using Weight only.
- **Tail Rotor Flight Profile** – seeks to reduce the Radial Balance to a minimum at Ground, Hover, 100kts, 120kts and 140kts test conditions. The Axial Balance is given a lower importance than the Radial Balance.

Aircraft A – Main Rotor RTB

Main rotor RTB was carried out on this aircraft before it returned to service following maintenance.

Flight 1

This flight was a ground run, used to collect initial data for use by the algorithm. The MFR used the ground profile to produce the solution in Table 1 below

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Solve post-flight 1

Position	Weight	Pitch	Tab
Blade 1	0	0	0
Blade 2	0	+10(up)	0
Blade 3	0	-15(down)	0
Blade 4	0	-12(down)	0

Table 1 Aircraft A, Flight 1 Adjustments

Flight

After applying the adjustments, a second ground run was carried out. The main rotor head track split had improved but was still outside limits, so the aircraft did not proceed to hover and forward flight. A second ground solution was obtained as shown in Table 2

Solve post-flight 2

Position	Weight	Pitch	Tab
Blade 1	0	0	0
Blade 2	0	+2(up)	0
Blade 3	0	-11(down)	0
Blade 4	0	-11(down)	0

Table 2 Aircraft A, Flight 2 Adjustments

Flight 3

A third ground run was carried out after making the further adjustments shown in Table 2. This time the track split had been brought within limits. A tail fault was detected however which prevented the aircraft progressing to hover and forward flight.

Flight 4

Once the tail rotor fault had been rectified, the trial continued and the crew were able to collect a full set of flight data. It can be seen from Figure 6 that a number of conditions were outside limits. The MFR provided the solution in Table 3 using the flight profile.

Solve post-flight 4 – flight profile

Position	Weight	Pitch	Tab
Blade 1	+290	+7 (up)	-1 (down)
Blade 2	+220	+2 (up)	+1 (up)
Blade 3	0	-14 (down)	0
Blade 4	0	0	-1 (down)

Table 3 Aircraft A, Flight 4 Adjustments

Flight 5

A further flight was carried out to verify the effects of the adjustments. The data collected on this flight verified that both track split and vibration had been brought within the prescribed limits.

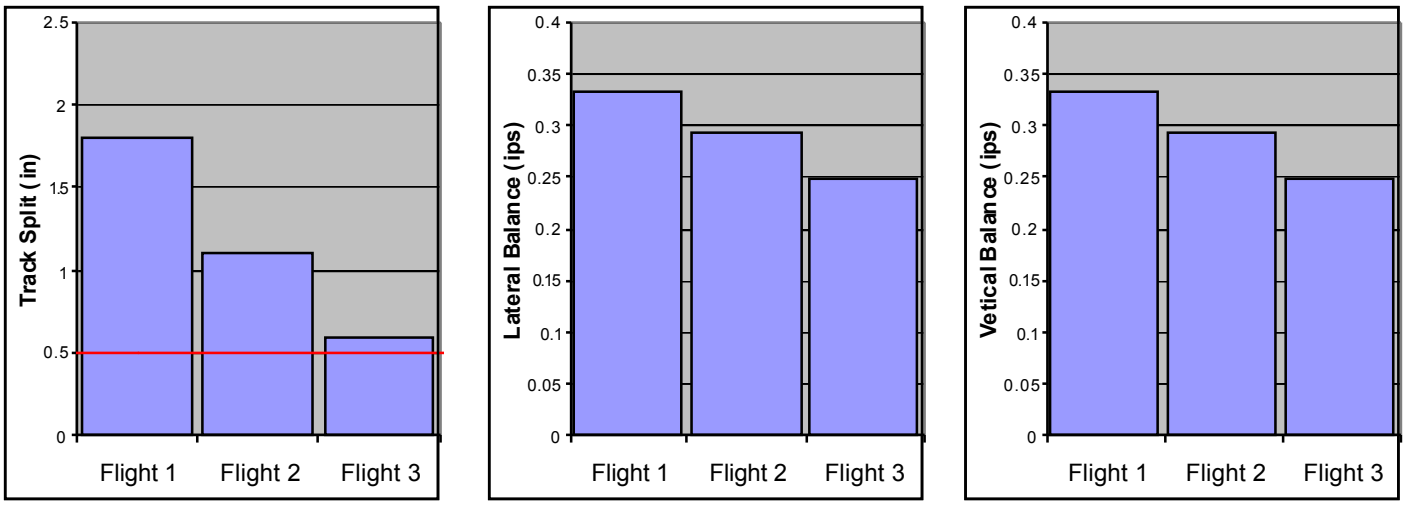


Figure 5 Ground Track and Balance over Flights 1-3

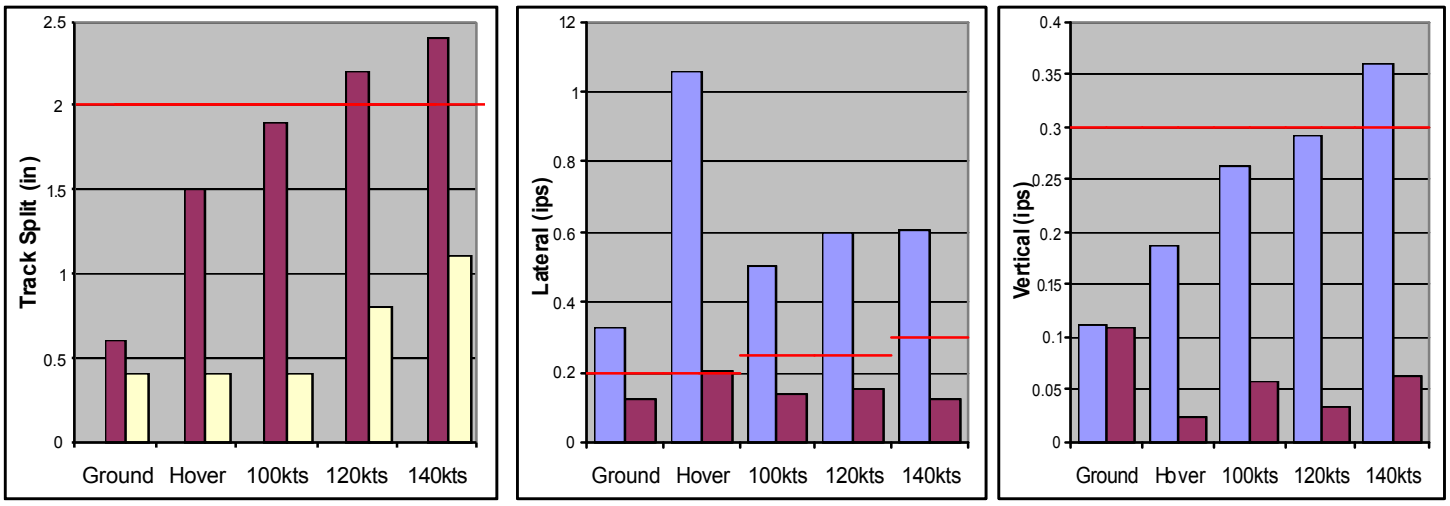


Figure 6 All Conditions Track and Balance over Flights 4 and 5

Aircraft B – Tail Rotor Balance

RTB was carried out on this aircraft prior to returning to service after maintenance.

Flight 1

A ground collection was performed for the tail rotor to provide initial data for the algorithm. The tail rotor ground solution shown in Table 4 was produced.

Solve post-flight 1

Position	Weight (g)
Blade 1	0
Blade 2	0
Blade 3	+6.7
Blade 4	+35.4
Blade 5	0

Table 4 Aircraft B, Flight 1 Adjustments

Flight 2

On the second ground run the radial balance had improved but was still out of limits. Hence a second ground solution was provided (see Table 5).

Solve post-flight 2

Position	Weight (g)
Blade 1	0
Blade 2	0
Blade 3	+8.7
Blade 4	+4.9
Blade 5	0

Table 5 Aircraft B, Flight 2 Adjustments

Flight 3

The radial balance was now brought within limits. However, the aircraft had developed main rotor mechanical faults. The trial was halted until these had been rectified.

Flight 4
Once the trial resumed a full set of tail rotor flight data was collected. These data were used to provide the tail rotor flight profile solution shown in Table 6.

Solve post-flight 4

Position	Weight (g)
Blade 1	0
Blade 2	0
Blade 3	+5.5
Blade 4	-2.2
Blade 5	0

Table 6 Aircraft B, Flight 4 Adjustments

Flight 5
The post adjustment flight verified that the radial and axial vibration had been brought within limits.

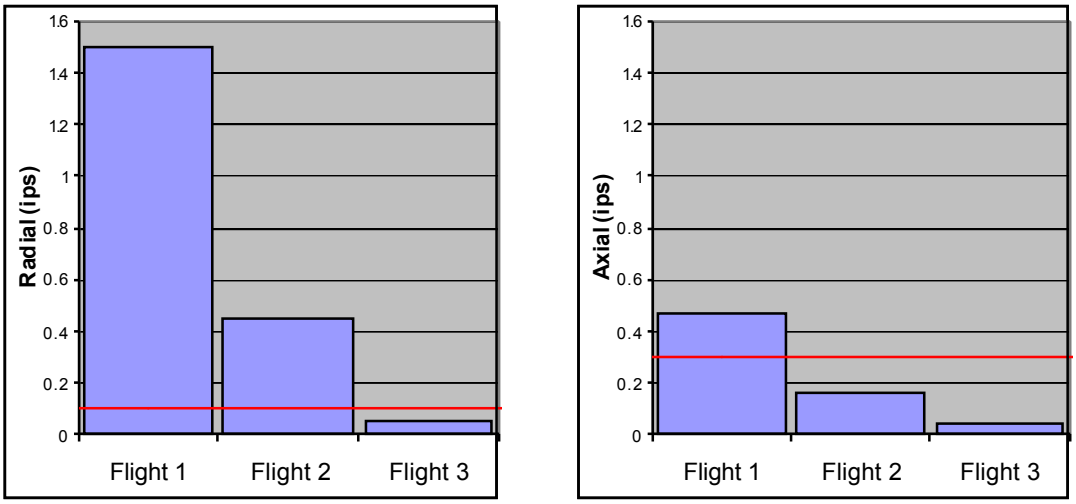


Figure 7 Ground Balance over Flights 1-3

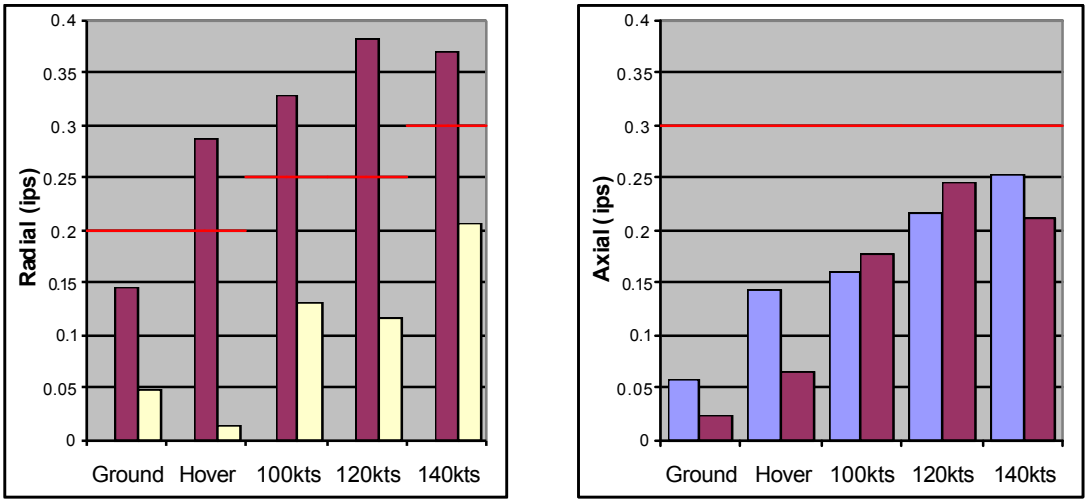


Figure 8 All Conditions Balance over Flights 4 and 5

Aircraft B Main Rotor Solution

Aircraft B Main Rotor had a number of mechanical issues during the trial and therefore could not be used in its entirety for this report. However the final solution is of interest because it demonstrates the ability of the MFR to adapt when adjustments are disabled.

Following the All-Up-Mass (AUM) check, Aircraft B required a blade sleeve change. The operators requested a solution with no Pitch adjustment if possible to avoid the need to repeat the autorevs checks.

Flight 1
This was the AUM flight. A custom profile using Weight and Tab was used to provide the adjustments in Table 7.

Solve post-flight 1

Position	Weight	Pitch	Tab
Blade 1	0	0	-1 (down)
Blade 2	0	0	+2 (up)
Blade 3	+300	0	-1 (down)
Blade 4	+300	0	-2 (down)

Table 7 Aircraft B, Main Rotor Adjustments

Flight 2
The second AUM flight showed that the solution has reduced the track and balance within limits using weight and tab adjustments only.

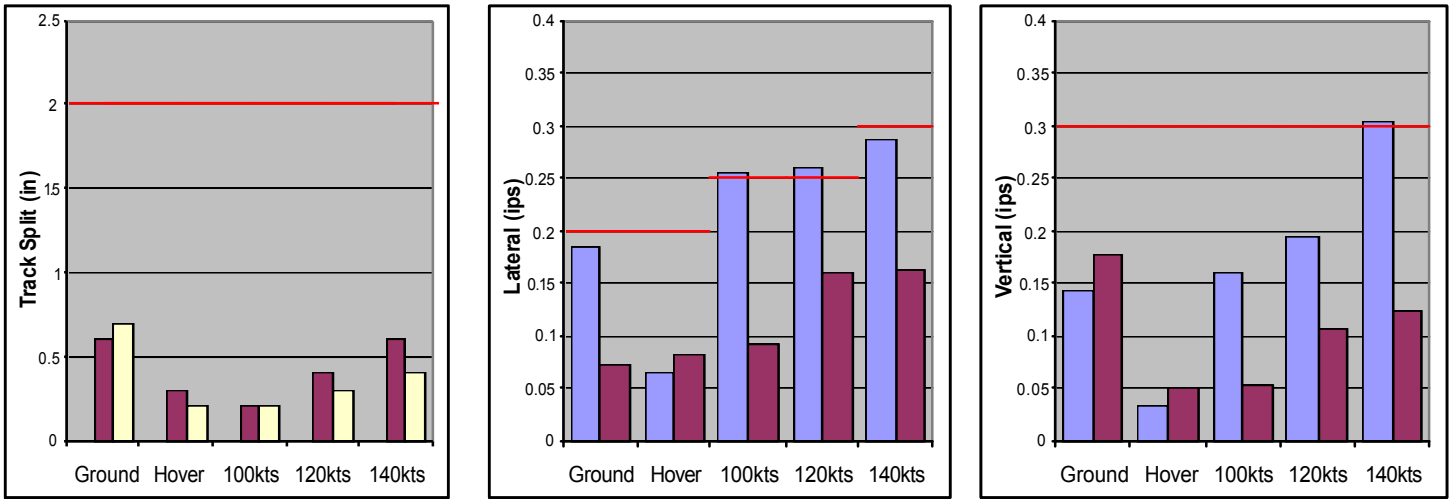


Figure 9 All Conditions Track and Balance over Flights 1 and 2

Flight Trial Observations

The algorithm underwent significant development during the flight trial period as more real world scenarios were encountered. We can draw a number of lessons from these developments.

1. The MFR went through a 'proving process' with the operators. The operators would evaluate against their own expertise, the algorithm's performance in simpler one-dimensional cases such as ground track or tail rotor ground radial balance. Success in these cases was important in establishing confidence for more complex scenarios such as a typical flight profile solve. This outcome was more evident in cases where the suggested solution was 'unconventional' or different to the operator's anticipated solution
2. The algorithm performs better when it has more flight data available. This achievement can be seen in the multiple ground runs described above compared to the single flight were data at all conditions were collected. Due to the increased confidence in the MFR, the engineers are considering increasing the current ground limits. These increased limits would make it easier for the aircraft to pass the checks required to move into forward flight where a complete data set can be collected and allows the algorithm to perform more effectively.
3. In cases where the aircraft did not react as expected to a set of adjustments, the tendency to question the mechanical integrity of the helicopter increased as the engineers' confidence in the algorithm had improved. This reaction had the benefit of preventing the operator carrying out further RTB flights when a mechanical issue meant it would not be possible to bring the aircraft within limits. .
4. It was necessary to use an expanded set of sensitivity coefficients. Individual coefficients for each flight condition were used. Additionally, several coefficients that were deemed unreliable were eventually included (lateral tab coefficients are a case in point). The additional terms were necessary to constrain the amount of distinct adjustments being provided by the algorithm.
5. A new input parameter was introduced to further constrain the tab adjustment. These 'solve limits' cap the algorithm's authority to make an adjustment. The effect of this in the case of tab was an increase in the use of pitch adjustments, and especially combined pitch and tab adjustments on the same blade. The rationale for introducing this in the case of tab was an operator request to allow the aircraft to be returned to the front line with some tab adjustment still available.

Concluding Remarks

The two parts of the study, the sensitivity analysis and the flight trial provided insights into the functioning of the MFR algorithm. The findings from both parts have been incorporated into the MFR and have given the algorithm the capability to solve RTB problems for the Puma aircraft. Some of the findings have brought about changes to the maintenance procedures for instance; the revised balance limits to be included in the next issue of [3]. Further work on this implementation will be in the form of a review of fleet-wide results once the algorithm has been in-service for a period of time. A comparison of historical flight data with that generated during the trial indicates that the average number of flights to balance an aircraft (including ground runs) was reduced by between 28% and 50%. There is the possibility of a further reduction in ground runs if the higher limits were to be adopted. A reduction such as seen in the flight trial would provide significant cost savings and availability benefits if repeated across the entire fleet.

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