C-130J In-Flight Propeller Balancing

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Abstract

This paper describes a program by the RAAF/DSTO to develop and deploy propeller balance procedures for the C-130J aircraft, utilising vibration data from the on-board engine monitoring system. Previous practice for C-130J aircraft was to periodically install temporary wiring and sensors, and carry out a number of ground runs, to arrive at a propeller balance solution. However, the C-130J engine vibration monitoring system, which records propeller-speed vibration amplitude and phase, has the potential capability to be used to compute a balance solution. This will reduce maintenance effort and increase aircraft availability, and in addition, provide an improved balance solution, through the use of in-flight data, rather than ground-run data. Software to certification level DO178B Level D was developed to implement the system in a form suitable for flight-line use. This paper provides an overview of the test program and software developments, and data from in-service experience.

Keywords: C-130J, propeller balance, engine vibration, AE2100D3, C-130, Hercules C-130, propeller dynamic balance, propeller vibration.

Introduction

The practice of propeller trim balancing, and fan trim balance (the latter for turbofan aircraft), is in wide use by the aviation community. The benefits of trim balancing are in the reduced vibration levels of the powerplant and associated accessories, which will also translate through to reduced airframe vibration and possibly noise, if the rotational frequency is in the audible range. Any vibration reduction is necessarily restricted to the fundamental rotational frequency of the component in question, where for medium-large turbo-prop aircraft this is of the order of 1000 rpm, and for the modern large turbo fans, of the order of 3000 rpm. The term 'balancing' in this application, however, although in almost universal use, is something of a misnomer. The function of trim balancing is essentially to reduce the vibration levels, at the rotational speed of the propeller/fan, as measured at the vibration sensor location. It is not primarily intended to produce a highly balanced propeller or fan assembly; the intention is to reduce engine and airframe structural vibration. Trim balancing will compensate for the small but inevitable installation issues of eccentricity and misalignment that will occur even with a statically well-balanced assembly. In addition, trim balancing will compensate for in-service degradation due to blade erosion and the effect of repairs, and also aerodynamic unbalance effects[1]. The latter may also be dependent on the flight regime, and can lead to an on-going debate as to the relative benefits of using in-flight data versus data from ground running, and the merits of active propeller balancing [1].

[1] A typical cause of aerodynamic unbalance is where one blade is at a different pitch setting from the other blades – this will result in a once/revolution vibratory force/moment at the propeller hub.

Modern aircraft are increasingly being equipped at time of manufacture with integrated on-board engine monitoring systems, and the C130J-30[2] aircraft introduced into the RAAF in 1999, is no exception. This aircraft, whilst externally appearing to differ little from the earlier Lockheed C-130 series aircraft (other than the added fuselage length dimension of the -30 variant), is a software intensive system, in comparison with the earlier largely mechanical C-130 aircraft. Other significant differences between the aircraft types are the power plants, which for the C-130J are Rolls-Royce AE2100D3 engines, in place of the Rolls-Royce T56 engines of the C-130E/H. Each AE2100D3 powerplant is equipped with a Nacelle Interface Unit (NIU), which is a key component of the integrated on-board engine monitoring system. The NIU's are linked with the main aircraft mission computer, to provide monitoring of, and exceedance alerts, for a wide variety of engine parameters. Engine and gearbox vibration levels are included amongst these parameters. Much of the aircraft powerplant maintenance actions are based on alerts from these engine sensors (including vibration). A significant exception is provision for propeller trim balancing, which prior to the deployment of the propeller balance software described in this paper, required the temporary fitment of an additional sensor on each powerplant; temporary wiring to each nacelle for the vibration sensor and 1/rev tach pulse signal, and extensive ground running[3]. This is a procedure similar to that used for the C-130E/H. In view of the existence of the integrated vibration sensors and signal-conditioning on C-130J aircraft, DSTO and the RAAF carried out an exploratory program [2] to investigate the potential for, and the effectiveness of, the existing on-board system to provide a propeller balance solution from in-flight data, downloaded post-flight from the Removable Memory Module (RMM) into the Ground Maintenance System (GMS). The benefits of this procedure would be considerable - a total elimination of ground running and temporary fitment of balancing equipment, and a potentially better solution, as the balance solution is obtained from the flight regime where it is of most benefit. This is not a novel concept – for large turbofans the balance data is now acquired in-flight, as it is for some turbo-prop aircraft such as the Dash-8's. However, the procedure has not been previously been implemented for the C-130J.

This paper describes the flight test program undertaken by the RAAF to validate its use for propeller trim balance; the development of certified software, and field results from the first year's deployment with the RAAF fleet. The flight test program was divided into two phases – an initial comprehensive trial over seven flights to validate the system, and a follow-up trial to test the procedures for normal operational use. The results of both flight test programs are summarised, including details of the effect of the various flight regimes on propeller-speed vibration. The development of the certified propeller balance software to provide a balance solution took place several years after the flight trials, and has now been distributed to most of the C-130J Joint User Group (JUG) members[4]. The software has been in use with the RAAF since January 2010; initial the results from this deployment is summarised.

[2] The RAAF variant of the C-130J aircraft is designated C130J-30. This is a stretched version of the C-130J aircraft. However, because of the commonality of engine avionics for both types, and the colloquial usage of the C-130J designation for all variants, there is no distinction made in the variants in this paper, and the C-130J designation is used from this point onwards.

[3] A proposal was put forward by a US equipment manufacturer to retrospectively hardwire the C-130J with an independent propeller balance system, based on the use of their ground support equipment – effectively a permanent installation of the temporary fitment. This would have still required ground-runs. It is not known if any of these systems have been installed in C-130J aircraft.

[4] The distribution of the software is subject to licensing agreements with the RAAF.

Ground Balance Procedures Using Temporary Fitment of Balancing Equipment

As initially supplied to the RAAF, the C-130J did not have a propeller trim balance procedure as a part of the maintenance process. It is believed that the introduction of field balance procedures was brought about by operator requests; one of the initial ones being as a result of vibration issues experienced by WC-130J 'Weatherbird' aircraft operators [3]. In the trim balance procedure subsequently used by the RAAF and other operators, the procedure is to temporarily install wiring which taped to the upper wing surface (Fig. 1); connection of a vibration sensor on the front face of the Propeller Gearbox (PGB) (Fig. 2); and connections are made to the once/rev sensor by connecting a T-piece into the wiring at the engine nacelle (Fig. 3). The cabling is then brought through the flight deck overhead hatch (Fig. 1 inset) into the flight deck, to interface with the balance analyser. The drawbacks with this procedure are several:

(a) The maintenance time (and materials) involved in the temporary fitment and removal.
(b) The requirement to disconnect aircraft wiring (the tach sensor connection - Fig. 3).
(c) The need for personnel to work at height on the upper wing and fuselage and powerplant nacelle – an increasingly difficult OH&S issue.
(d) The need for ground running – the aircraft is typically towed to a dedicated run-up area, suitable weather conditions are necessary, fuel costs can be considerable and engine hours are expended.
(e) The loss of aircraft availability - typically a day (two shifts) is required to install wiring, test, and return to fight worthy status, if no problems are encountered.

As will be described later in this paper, the software balance procedure requires no temporary fitment of equipment, no disturbance to aircraft systems (other than removal of an engine nacelle side panel to install balance weights), 'no working at height' on upper aircraft structure, or ground running.



Fig. 1: Temporary wiring for vibration sensor and tacho, upper wing surface and flight deck.

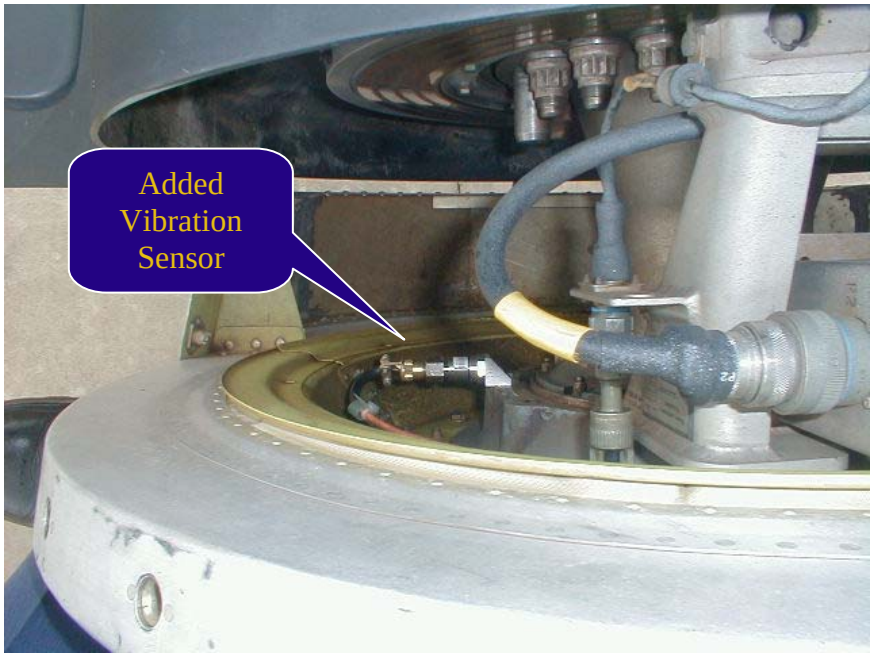


Fig. 2: Temporary installation of vibration sensor front face PGB.

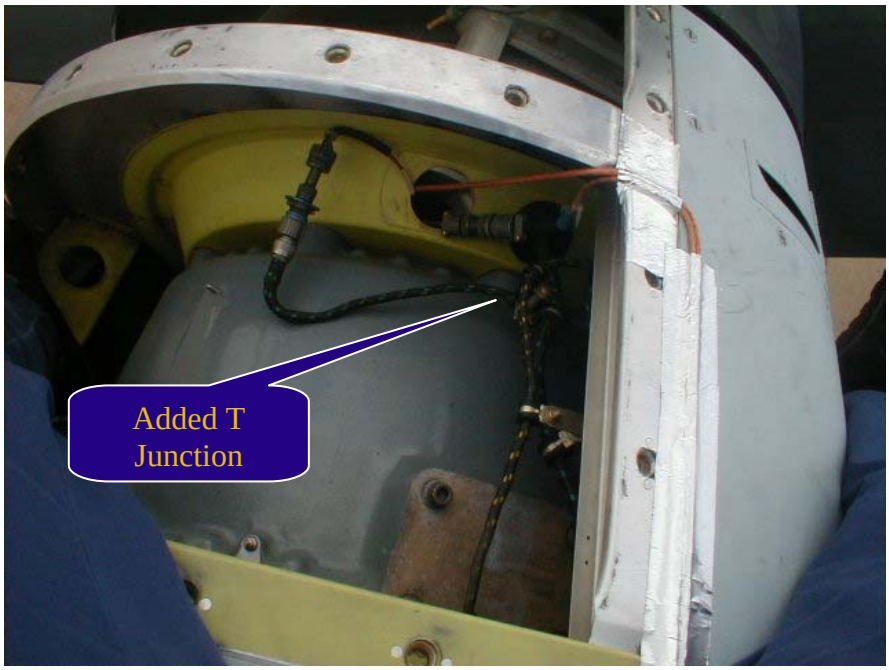


Fig 3: Temporary fitment of tacho connection.

Rolls-Royce AE2100D3 Powerplant Vibration Monitoring System

The AE2100D3 engine has three permanently-installed high-temperature accelerometers, type Endevco 6222M92, mounted on the propeller gearbox (PGB), compressor and turbine. These sensors are connected to the NIU, where signal conditioning, and filtering in a variety of bands is carried out. The filtering includes overall vibration in a low and in a high frequency band, and three tracking filters linked to the speed of the propeller, power turbine and gas generator. The output from the tracking filters are the vibration levels at the fundamental (once/revolution) rotational frequency of these three components. In addition to these vibration amplitude readings, the system provides for a critical feature required for a propeller

balance solution, and that is the phase of the propeller 1/rev amplitude, relative to the once/revolution propeller tacho pulse, which is derived from an inductive sensor triggered by a tab on the propeller hub. The filtering in the five bands described above is applied to all three sensors, so that there are a total of fifteen vibration amplitudes, and propeller phase also, from each of the three accelerometer locations.

Background to Propeller Trim Balancing

The basic theory of trim balancing of single and multiplane rigid rotors was documented by E.L. Thearle in 1934 [4], and remains essentially unchanged since that time [5]. The key requirement is a measurement system capable of narrow band-pass filtering the vibration amplitude at a frequency of once/shaft revolution, and the phase of this (sinusoidal) vibration relative to a once/revolution timing pulse from a stationary sensor detecting the passage of a reference marker fixed to the shaft. The influence coefficient (ICF) is then evaluated by placing a trial weight on the rotating assembly, and by measurement of vibration amplitude and phase on two successive runs – one without, and one with the trial weight, the influence of the trial weight alone can be established by vectorially subtracting the initial vibration from the vibration with a trial weight. The trial weight ICF vector is then used to compute a balance solution for any unbalance of that assembly. Once having established the system influence coefficient, subsequent balancing on that assembly (or nominally similar ones) can take place without the preliminary trial weight runs. There are various conventions for definition of the influence coefficient vector, the definition used here is:

Correction weight phase = ICF(deg) + (Vibration phase +180 deg) (1)
Weight magnitude = ICF(magnitude) * vibration magnitude (2)

The relative simplicity of the trim balance procedure is in its use of trial weights to determine the influence coefficients, which eliminates the requirement to evaluate the machine dynamic properties, or the phase or amplitude scaling factors of the sensing system.. There are several provisos to this procedure, however:

a) All trim balancing has to be carried out at the same machine speed (due to the usual change in a system dynamic response (dynamic stiffness) with speed.
b) While the *actual* phase lag in measurements is unimportant (so long as it is consistent), knowledge of the phase convention – whether phase is defined as the vibration signal relative to the tach pulse[5], or vice versa, is critical.
c) For propeller balancing, if aerodynamic effects are thought to be significant, then it would be prudent to carry out evaluation of the ICF at a similar flight regime for the runs with and without a trial weight, so that the changes in vibration amplitude and phase are limited to the effects of the trial weight.

Flight Trial Test Procedure

[5] There is no industry standard for the phase convention. Experimental trials for the C-130J NIU established the phase convention in use there in which a positive phase angle occurred when the tach signal led the vibration signal.

Phase 1 Flight Trial

Objectives for Phase 1 Trial

The objectives of the Phase 1 Trial were to:

(a) Confirm that the Nacelle Interface Unit (NIU computes reliable and accurate vibration phase and amplitude parameters at propeller shaft frequency (phase being relative to the 1/rev pulse sensor at the propeller hub), from the three engine-mounted accelerometers;

(b) Establish if the vibration amplitude and phase from these accelerometer locations, particularly the propeller gearbox (PGB), could be used to compute a valid propeller balance solution.

In addition, although not used for the balance solution, airframe vibration data at a number of locations in the cargo area and flight deck were recorded.

Instrumentation for Phase 1 Trial

In addition to the on-board NIU which provides data via the mission computer, and is downloaded post-flight, for this trial the Rolls Royce Data Bus Analyser was used to continuously record engine and flight parameters at 1 sec intervals for the entire flight. Also, four tri-axial accelerometers (12 data channels) were installed in the aircraft to record airframe vibration at aircrew and propeller-plane regions, via a Sony SIR-1000 digital tape recorder. This recording system is shown in Fig. 4, and accelerometer locations in Fig. 5. The tri-axial accelerometers were mounted at the base of the pilot and co-pilot seats, and in the cargo compartment area propeller plane, on the port and starboard sides of the aircraft. The bandwidth of the recording system was 5-5000 Hz. Accelerometers were Endevco 2258A-100 tri-axial Isotron-type.



Fig. 4: Additional tape-recording system for airframe vibration

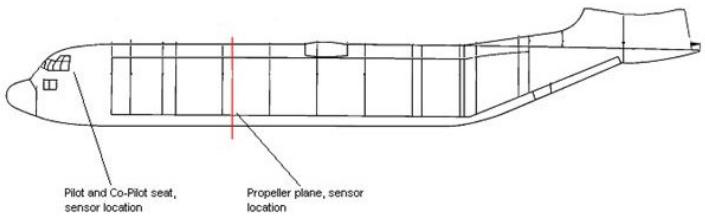


Fig. 5: Accelerometer locations for airframe vibration measurement

Trial Outline Phase 1

A total of 7 flights were carried out. Firstly, an initial flight to baseline the results, after carrying out Ground Support Equipment (GSE) propeller balance at 1500 HP on the ground. Flight 2 had unbalance on only one engine (no. 3). The following four flights 3-6 had unbalance on all 4 engines, with weights moved successively to 4 locations on the propeller hub. Flight no.7 was a test to validate the balance ICF solution derived from the previous flights, using flight no. 6 as the 'unbalanced' case. The trial 'unbalance' weights were a total of four 60-gram weights, which results in an effective unbalance weight vector of 230 grams[6]. The weight locations were incremented per flight by 75, 90, 60 and 75 deg for Engines 1,2,3 and 4 respectively, the variations in incremental angle were to avoid existing weights on the hub. A significant trial weight vector of 230 grams was considered necessary to generate a distinct change in vibration levels.
Each of the seven flights followed the same profile, with stabilised segments of greater than 6 minutes at three altitudes – 20,000 ft, 25,000 ft and 30,000 ft, and a range of power lever angles (PLA) from 65 to 78 deg (Table 1). This matrix of flight conditions was developed to ascertain if there is a regime dependency for propeller-speed vibration, and to gain data over as wide a flight parameter set as possible. For the purposes of the ICF calculation, only data from the same altitude/power setting were compared between successive flights, as this should remove any possible effect of aerodynamic unbalance.

Table 1: Altitude and PLA for stabilised test points

Altitude ft	20,000	20,000	25,000	25,000	25,000	30,000	30,000	30,000
PLA deg	70	78	65	70	78	65[7]	70	78

Phase 2 Flight Trial

Trial Outline Phase 2

The Phase 2 flight trial was undertaken several months after Phase 1, and was designed to trial the use of balance procedures for normal squadron use, and also further confirms the validity of the ICF's derived from the Phase 1 trial. The trial utilised specific engineering authorisation from the RAAF Airlift Systems Program Office (ALSPO), as the balance procedures differed from those currently approved, which use the GSE propeller balance

[6] The propeller hub has 24 evenly-spaced balance weight locations, with a maximum allowable weight of 60 grams/location. The four trial unbalance weights were located in adjacent holes.
[7] At 30,000 ft, 65 deg is below that considered appropriate for normal operations.

equipment. The procedure used for this trial was to initiate an EMS event record[8] to provide propeller-frequency vibration amplitude and phase data, from the pinion gearbox (PGB) sensor. This record is then viewed subsequent to ground run or flight by analysis of the engine records, which are obtained following Removable Memory Module (RMM) download to GMS. The steps followed for this trial were then to:

1. Measure existing propeller balance weight magnitudes and locations.
2. Undertake a routine flight, with an in-flight EMS event marker selection in stable cruise, if possible at a typical routine cruise altitude and power setting.
3. Analyse EMS event marker data post-flight and compute a balance solution.
4. Install balance correction weights.
5. Carry out a ground run to verify no adverse effects, utilising EMS event marker selection and data analysis. This step was a precautionary one, due to the novelty of this procedure[9].
6. Carry out a routine flight with an in-flight EMS marker selection preferably at same flight condition as step (2).
7. Post-flight analysis of EMS data and verification of effectiveness of balance solution.

Step 1 above could also be carried out concurrently with Step 4, if the balance solution could be computed at that time[10].
The EMS data from step 3 above was used to select which engines to use for a balance solution for this trial. If the level was already low then a solution was not attempted.

Balance Procedure Phase 2

The previous Phase 1 trial had enabled the derivation of influence vectors over a wide range of flight conditions. For this trial an average of those influence coefficients was used, the value chosen being:

ICF magnitude = 290 grams/inch per second (IPS) rms[11] (3)
ICF phase = – 95 deg. (4)

The correction weight solution is then:

Weight magnitude = 290 * (vibration amplitude IPS). (grams) (5)
Weight phase = -95 + (vibration phase +180). (degrees) (6)

The ICF magnitude chosen for the Phase 2 trial tends towards the lower of the 4 values found from the Phase 1 trial (see later section of results and discussion for Phase 1), to attempt to ensure that there would be at least some reduction in vibration, and avoid the possibility of an 'overshoot', as could result if the correction vector magnitude was too large.

Trial Summary Phase 2

[8] The EMS event is selected by aircrew. A single button push will record 20 successive engine data records at 1 second intervals, 14 of which are prior to the event, one at the time of event selection, and 5 subsequent records.
[9] When the procedure using in-flight data is finalised it is anticipated that the ground run will not be required.
[10] Computation of a balance solution requires knowledge of existing weights (magnitude and locations) due to the maximum weight limitation at each location (in this instance 60 grams).
[11] Unless otherwise stated, all vibration velocities referred to in this paper have units of inches/sec rms.

Two RAAF C-130J aircraft were selected for the Phase 2 trial, chosen on the basis of availability, and local deployment. The trial took place 5 months after the Phase 1 trial. The test flight summary for the two aircraft (designated here as aircraft A and B) is given in Tables 2 and 3. It can be seen that there is some variation in altitude and power settings when the event marker was selected on the before and after balance flights. This is a consequence of the operational requirements (these were regular operational flights).

Table 2. Aircraft A

Test No.	Date[12]	Test sequence	Event marker			
			Altitude feet	PLA Deg	CAS kts	RMM ID
1	20 May 2004	Acquire data	20,000	65	230	431
2	20 May 2004	Ground run Verify post-bal OK to fly	-	48	-	432
3	20 May 2004	Post-balance flight verification	10,000	40[13]	250	433

Table 3. Aircraft B

Test No.	Date[14]	Test Sequence	Event marker			
			Altitude feet	PLA deg	CAS kts	Download ID
1	20 May 2004	Acquire data	21,000	65	225	378
2	20 May 2004	Ground run Verify post-bal OK to fly	-		-	380
3	22 May 2004	Post-balance flight verification	25,000	68	215	382

Results and Discussion – Phase 1 Trial

Analysis of Results

Analysis of the results showed the following:

1. The unbalance added to engine 3 (only) for the second flight did not have a significant effect on the other three engines, as shown by comparison of results between flights 1 and 2 (see Fig. 6 and Table B1, Appendix B, for 20,000 ft and 70 deg PLA). This indicates that the effect of cross-coupling of propeller frequency vibration between powerplants is small, and confirms that this possible effect will not act to preclude the validity of in-flight balancing, although all engines operate at nearly identical rpm.

2. The influence coefficient obtained from an analysis of all flights and flight regimes shows consistent results for a specific powerplant (see Figures 6a and 6b). However, there is a noticeable variation between the ICF's for the four engines, especially engines 1 and 2 in comparison with engines 3 and 4, that is greater than the spread between flights and flight regimes. This variation is not so great that it precludes the use of one ICF value for balancing of all engines, and at this stage there is not sufficient data to show if this variation is either

[12] Date/Time in this table is Australian Summer EST (GMT+10). NIU time/date is Z (GMT)
[13] There was variation during the 20 sec event period - PLA variation was 39-41deg, altitude varied 500 ft. – apparently on a descent profile.
[14] Local time Australia EST

engine location specific, or a variation due to engine mounts or other localised factors. The ICF was computed by either referencing all of the balance weight iterations back to the first (unbalanced) flight, or by subtracted the weight changes for the successive flights, i.e. flight 4-3, 5-4, 6-5 and 6-3. All of these techniques produced very similar results.

3. Airframe vibration data is presented in Figures 7 and 8. Fig. 7 shows a comparison of the 1P (17 Hz once/revolution of propeller) and 102 Hz Blade pass frequency for the 6-bladed propellers. In these figures, the vibration levels are averaged across flights 1-6. Fig. 7 highlights the relative insignificance of the 1/revolution vibration in comparison with the blade-pass vibration levels, where peak levels are concerned. Figure 8 normalises results at each location, by dividing both the 1P and 6P by the overall vibration at that location. In this figure it can be seen that at the crew stations, the propeller-speed vibration is relatively more significant than in the cargo area.

Summary of Results Phase 1 Trial

1. From the ICF data for the PGB sensor (Fig 6a and 6b), the averaged ICF values show a spread in magnitude of 271 to 475 grams/IPS, and phase angle from –83 to –115 deg. This is a significant spread, and as mentioned above, this may be a specific powerplant dependency, or possibly a feature of the specific location (engine position). The engine mounts of nos. 1 and 2 were subsequently inspected, however no problems were evident.

2. Notwithstanding the data spread, a good balance solution should be possible, that would result in a vibration reduction on all engines, provided that the ICF used is conservative in amplitude, and an averaged-phase value of all powerplants. Using a non-conservative ICF (i.e. one attuned to the less-sensitive locations), may overshoot the solution on some engines, and result in little or no vibration reduction.

3. A balance solution was trialed on flight 7, using flight 6 as the ‘unbalanced’ case. The ICF chosen for the weight calculation was 460 grams/IPS at –85 deg. The results are listed in table 2, where it can be seen that a large reduction was obtained for engines 3 and 4, but little or no reduction on engines 1 and 2. Whilst initially disappointing, this result was, with hindsight, quite predictable. It can be seen by reference to Figs 6a and 6b that this ICF value was quite inappropriate for engines 1 and 2. Had a more conservative and average-phase ICF been chosen, such as 290 grams at –95 deg, then the resulting vibration on flight 7 would likely to have been that shown in the last column in Table 4.

4. Effect of Flight Regime – Fig. 9 shows the effect of different flight regimes over four flights for engine #2. The data are summarised in Appendix A. These are the four flights (3-6) for which trial ‘unbalance’ weights of 240 grams were successively incremented by 90 degrees. Included on this plot are values at 1500 Shaft Horsepower (SHP), obtained on engine run-up prior to take-off (the power setting used for the GSE ground run balance procedure). The features of interest here are the absence of a systematic flight regime effect, and the relative minor effect of the different flight regimes. The 1500 SHP (ground run-up) amplitudes are significantly less than those measured in-flight. Note that in this instance, the initial unbalance is effectively the centre of a circle drawn through the four clusters, thus it is apparent that there was a small but significant unbalance existing prior to flight #3.

Figure 6 Raw Vibration
Flight 1 and Flight 2

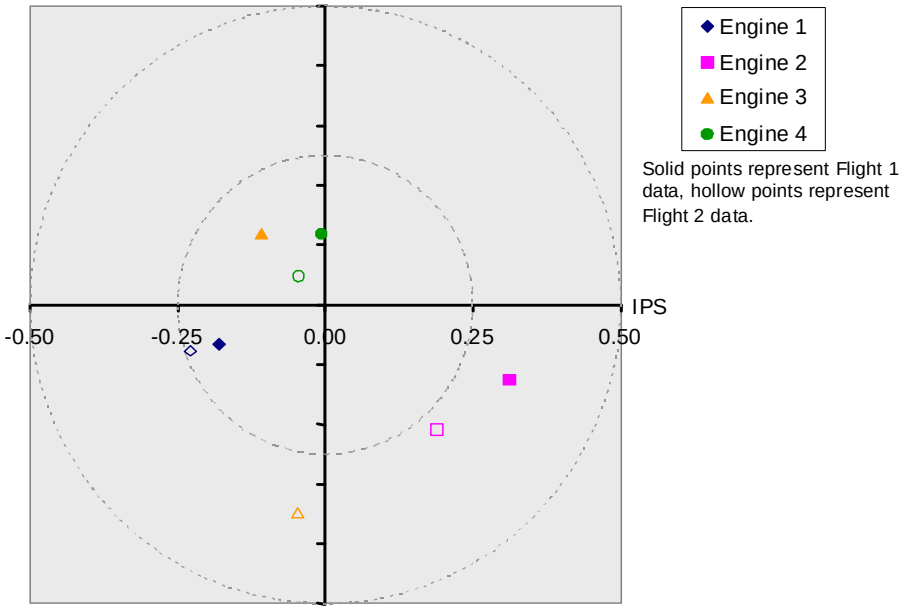


Figure 6a

Influence Coefficients
Calculated From Real Time (DBA) Data
Gearbox Sensor

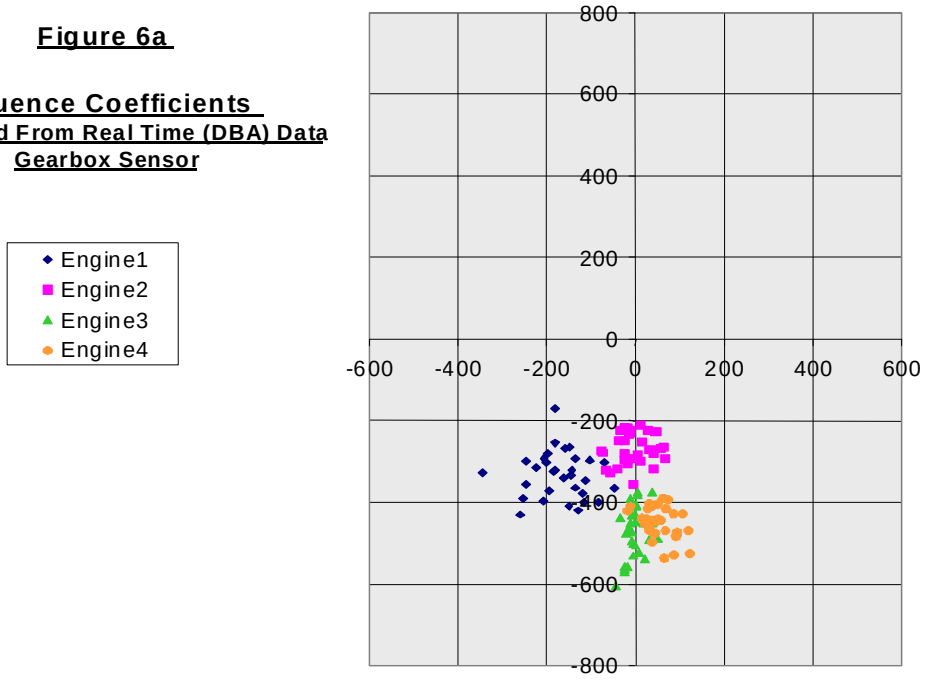
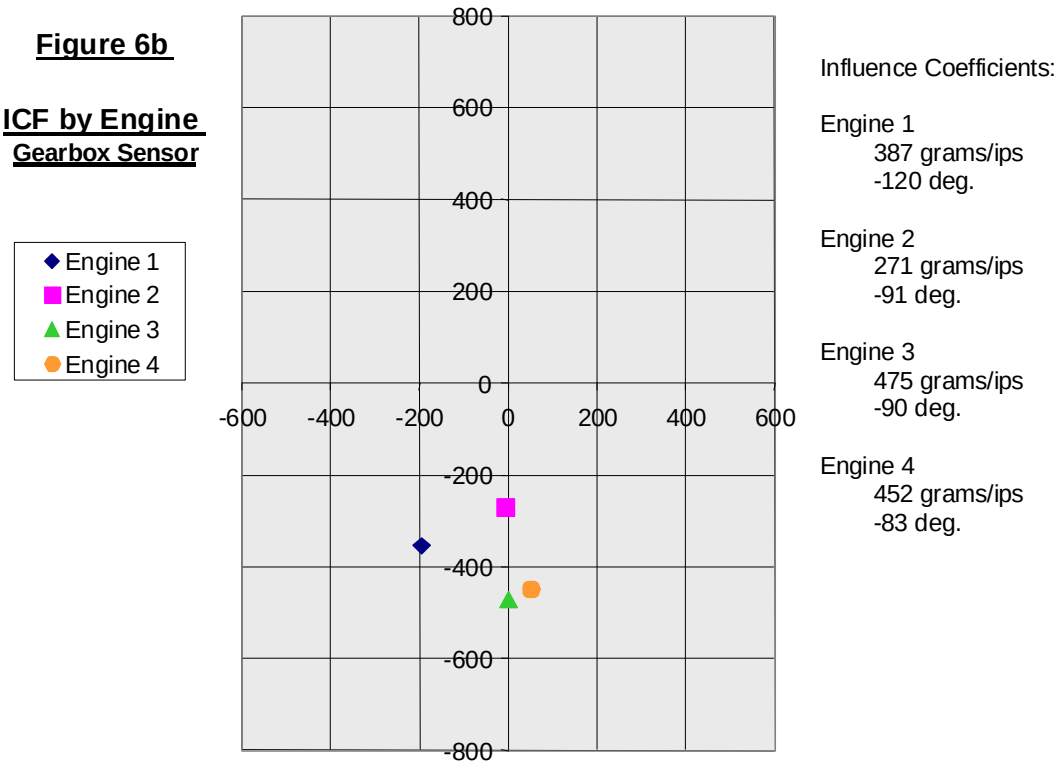


Figure 6b

ICF by Engine
Gearbox Sensor



Influence Coefficients:

Engine 1
387 grams/ips
-120 deg.

Engine 2
271 grams/ips
-91 deg.

Engine 3
475 grams/ips
-90 deg.

Engine 4
452 grams/ips
-83 deg.

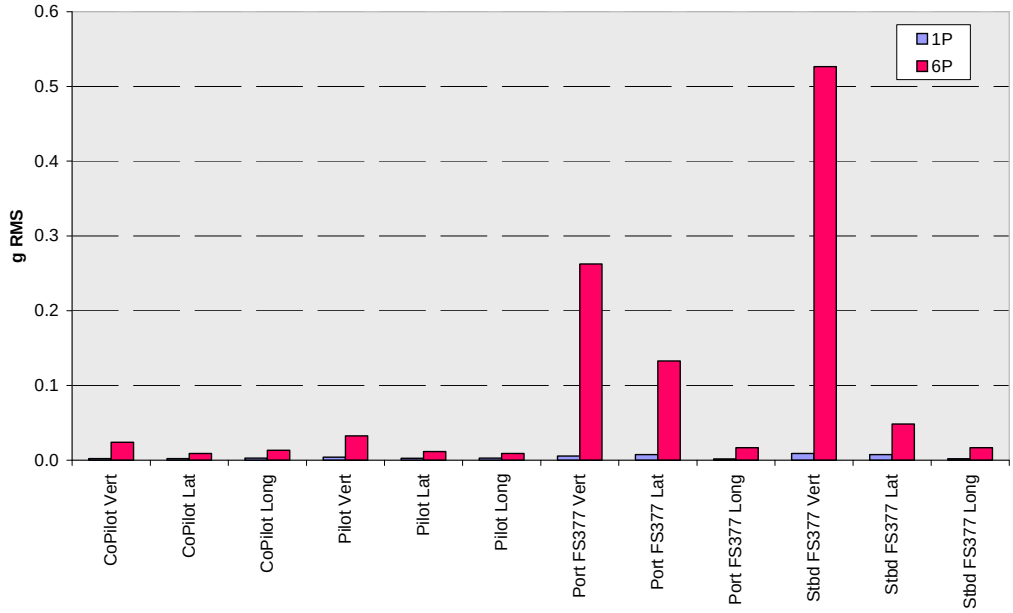


Fig. 7: Airframe vibration at twelve locations, comparison of 1P (17 Hz) and 6P (102 Hz)

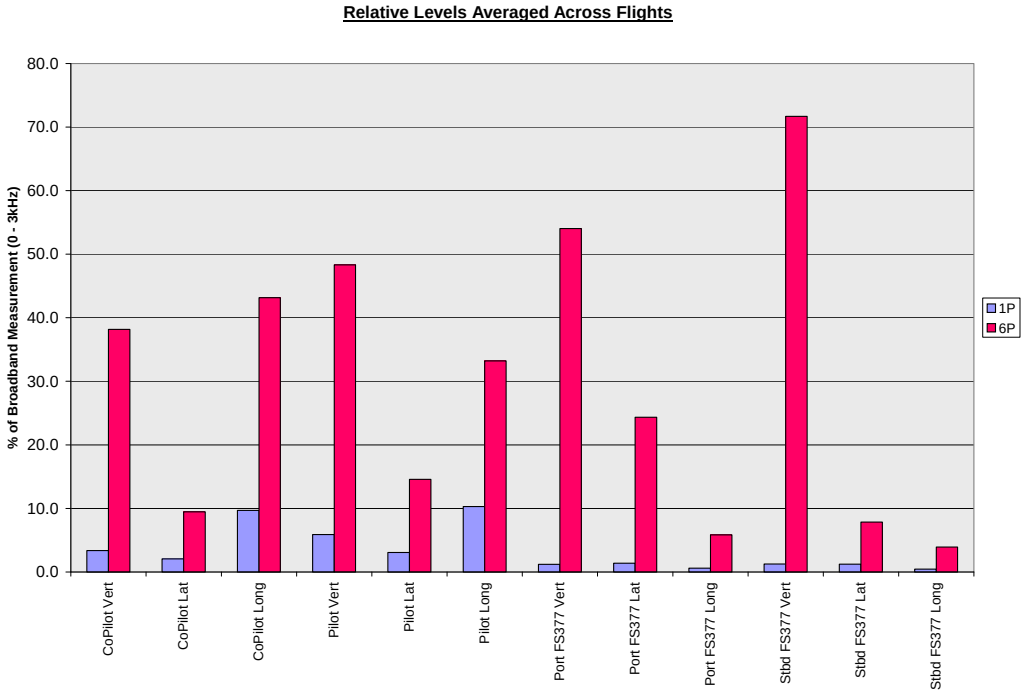


Fig. 8: Airframe vibration at twelve locations, comparison of 1P (17 Hz) and 6P (102 Hz), vibration as percentage of overall vibration at each location

Table 4: Amplitude and phase measured from Flight 7, and predictions using a more appropriate (single) ICF for the four powerplants.

Engine Position	Vibration Flight 6 25,000 ft. 70 deg PLA	Vibration Flight 7 25,000 ft . 70 deg PLA, using one ICF for all engines of 460 gram/IPS @ -85 deg	Actual specific ICF (fig 1b) mag grams/IPS for each engine	Flight 7 predicted vibration IPS with actual measured ICF's from Fig 1b, but wt soln using averaged ICF of 290 grams/IPS @ -95 deg
1	.537 @ 171 deg	.513 @88.5 deg	387 @ –120 deg	0.24
2	1.095 @ 8.5 deg	.739 @ 203 deg	271 @ -91 deg	0.11 IPS
3	0.581 @ 109 deg	0.079[15]	475 @ -90 deg	0.23
4	0.518 @ 344 deg	0.083	452 @ -82 deg	0.21

[15] Phase at very low amplitudes is not computed by NIU if variation is greater than a specific tolerance.

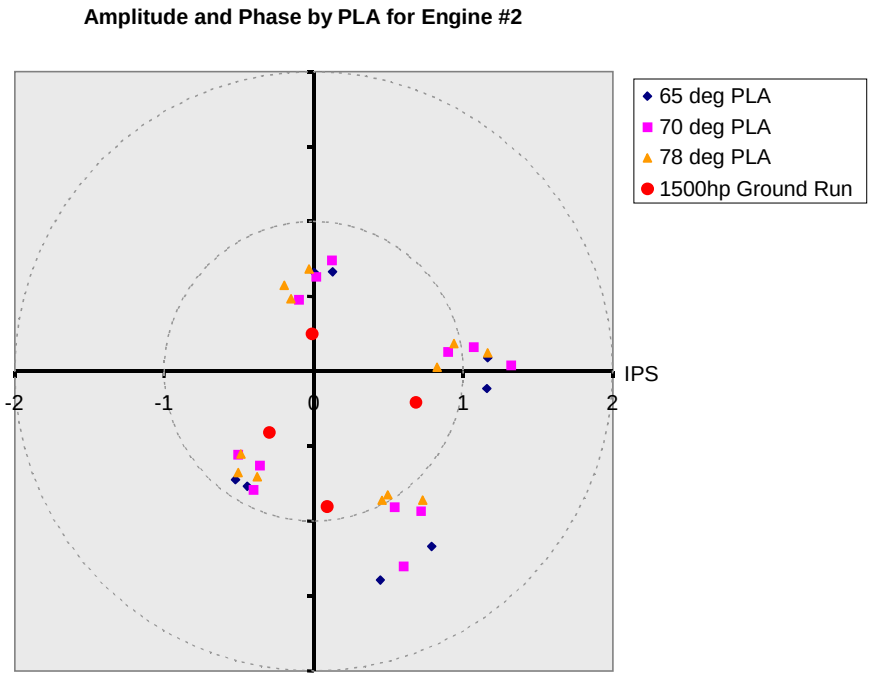


Fig. 9: Effect of flight regime on propeller speed vibration, flights 3-6

Results and Discussion – Phase 2 Trial

The initial in-flight vibration levels for aircraft A and B (prior to balance), and the predicted weight solutions computed after download of this initial data are summarised in Tables 5 and 6. The vibration levels on the flight prior to balance, the ground run after balance, and the flight after balance are summarised in Tables 7 and 8 for the two aircraft. All of the vibration levels are an average of the 20 seconds of event marker data, for each aircraft test flight, and the two engines which were balanced. Only two engines from each aircraft were balanced, a limitation which was originally imposed because of the early stage in the development of this procedure. However, it transpired that only one engine from each aircraft was significantly out of balance prior to the test, so that there would have been little value in attempting a solution on all four powerplants on each aircraft.

The results show a vibration reduction in all the four cases where a solution was implemented. Three cases (Engines 1 and 4 of aircraft A, and Engine 4 of aircraft B) showed reductions of the order of 50%, with Engine 3 of aircraft B showing only a small reduction. However the latter was initially at a low vibration level and it is to be expected that phase will be less reliable at low amplitudes. Also, the application a single influence coefficient across the fleet will necessarily be less precise than establishing a unique value for each engine. It is usual for the GSE ground-run balancing procedure to require more than one iteration to reach a required solution, so the lack of an 'exact' solution here is not surprising.

Table 5: Aircraft A Test 1, 20 May 04 initial flight to acquire pre-balance data

Engine	PGB Vib amplitude IPS	PGB Vib Phase deg	Predicted weight solution	
			Mag (grams)	Angle (deg)
1	0.405	161	117.4	246
2	0.142	116	-	-
3	0.20	205	-	-
4	0.255	15.2	73.9	100.2

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Table 6: Aircraft B Test 1, 20 May 04 initial flight to acquire pre-balance data.

Engine	PGB Vib amplitude IPS	PGB Vib Phase deg	Predicted weight solution	
			Mag (grams)	Angle (deg)
1	-[16]	-	-	-
2	0.260	55	-	-
3	0.247	284	71	369
4	0.69	363	200	88

Table 7: Aircraft A Test result summary

Engine no.	Balance Carried Out	PGB Vib. In-flight test 1 20,000 ft cruise	PGB Vib. test 2 ground post-balance	PGB Vib. Post-balance test 3 10,000 ft
1	Yes	0.405	0.06	0.197
2	No	0.142	0.07	0.134
3	No	0.20	0.42	0.170
4	Yes	0.255	-[17]	0.117

Table 8: Aircraft B Test result summary

Engine no.	Balance Carried Out	PGB Vib. In-flight test 1 21,000 ft cruise	PGB Vib. test 2 ground post-balance	PGB Vib. Post-balance test 3 25,000 ft cruise
1	No	-	0.10	0.17
2	No	0.26	0.28	0.18
3	Yes	0.25	0.12	0.22
4	Yes	0.69	0.10	0.36

Development of Certified Propeller Balance Software

The procedure used during the Phase 2 trial, whilst adequate for trial purposes and to demonstrate the validity of the balance procedure, did not embody software which had undergone a certification process, or was in a form appropriate for use as a regular tool by maintenance personnel. Accordingly, the RAAF embarked on the development of software to DO178B Level D standard, placing a contract with QinetiQ AeroStructures, Melbourne Australia, for that purpose. The development of this software was undertaken according to a DSTO/RAAF specification, and embodied the technical features described above. A further technical feature incorporated was a weight split algorithm developed by DSTO [6], necessary because of the discrete location and magnitude of the trim balance weights – 24 evenly spaced locations around the propeller hub, each with a maximum of 60 grams weight. An example of the output from the propeller balance is software is provided in Fig. 10.

[16] PGB accelerometer replaced subsequent to flight due to faulty sensor output.
[17] GMS Download failed.

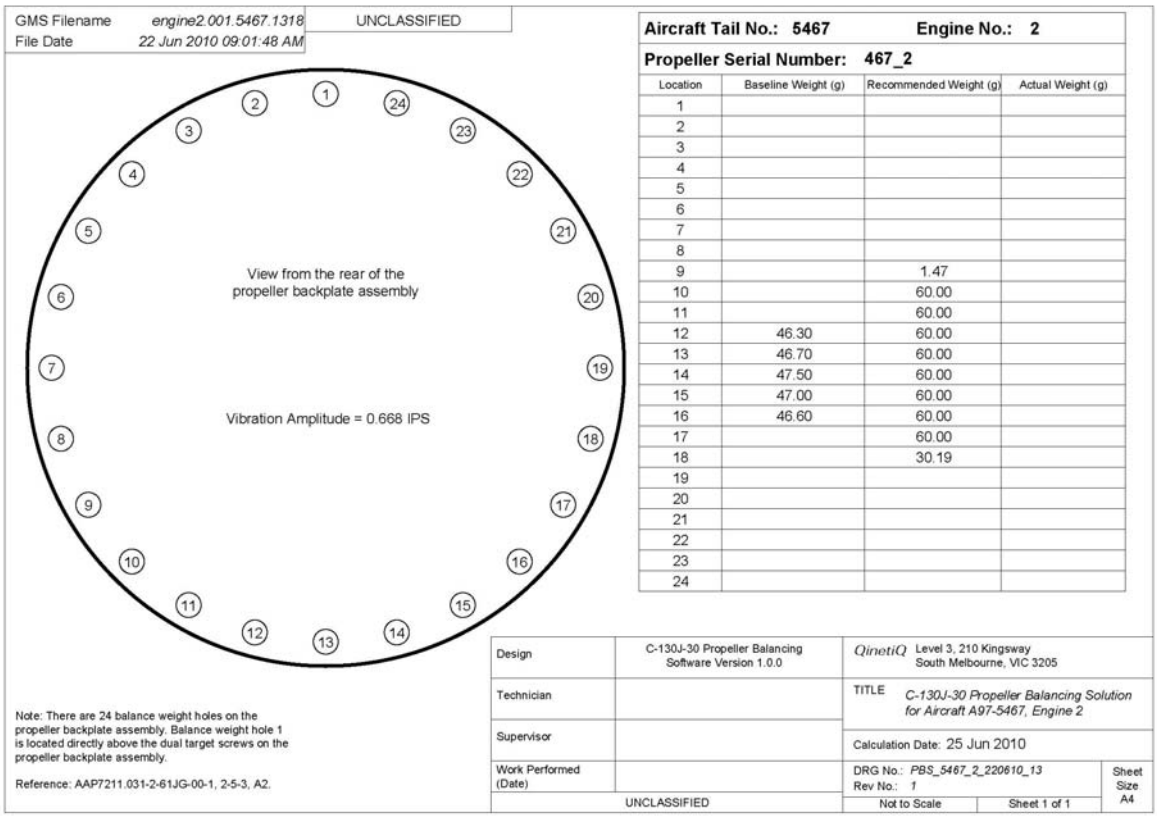


Fig. 10: Balance solution output.

Balance Procedure with Software Solution

The balance procedure using the certified software described in the previous section is as follows:

(a) An event marker selection is made by aircrew on a flight prior to balance being carried out. This event marker selection will provide the trigger for the recording of vibration data required for a balance solution. This data is automatically downloaded into the GMS along with the maintenance data. Preferably this selection is made during cruise and stable conditions.

(b) The propeller balance software program is run at some point after RMM download, and the software identifies if the data is valid, and if a balance solution is required on any of the power plants on that aircraft (i.e. if vibration levels are above levels considered acceptable).

(c) If a balance solution is sought, the existing weight magnitude and location is entered into the software (either from a database holding prior weight data, or from weight measurement at that time).

(d) The software will then provide a balance solution. An additional feature available is that specific weight locations can be 'quarantined' if required, i.e. not available, if it is desired to retain the original static balance weights[18], or if locations are not available for other reasons.

[18] Unlike the C-130H, the C-130J propeller hub does not readily permit differentiation between 'static' or 'dynamic' weights. There is a single ring of 24 weight locations on C-130J hub. It is believed that Dowty (the C-130J propeller manufacturer), in view of the relatively lightweight composite propeller, did not envisage that installed trim balance of the propeller would be required, unlike the much heavier aluminium C-130H propeller.

(e) At a time convenient to operations, the weight change can then be made, which requires only the use of the aircraft engine work stand, removal of the port-side panel on the engine nacelle, and weight changes as listed in Fig. 10.

The procedure as described in (e) above can be accomplished in a relatively short period of time (less than 2 hours for two power plants) and requires no ground engine running. For example, during the phase 2 trial, one of the aircraft which had a balance solution implemented on two engines, had that procedure carried out during a midday pause in operations, on a day when the aircraft carried out two normal missions.

In-Service results

Background

Following on from the completion of the DO178B Level D propeller balance software, the RAAF completed their service-release procedures, and the software commenced operational use in January 2010. Table 7 lists the vibration levels from five aircraft before and after balance. All of the balance procedures were carried out with in-flight data.

Table 7: In-Service Results of propeller balance software application to RAAF C130J-30 aircraft .

Aircraft no.	Engine location	PGB vibration IPS (rms) Prop speed prior to balance	PGB vibration IPS (rms) Prop speed after balance	Data source for balance solution	Percent Reduction In vibration
1	2	0.74	0.21	in-flight	72
1	2	0.82	0.63	in-flight	23
2	3	0.57	0.24	in-flight	58
2	1	0.45	0.08	in-flight	82
2	2	0.65	0.26	in-flight	60
3	2	0.67	0.41	in-flight	39
3	1	0.85	0.35	in-flight	59
4	3	0.77	0.25	in-flight	68
5	1	0.58	0.25	in-flight	57

The results in Table 7 are the only results available at time of writing where clear records are available both before and after balancing were carried out. All of these shows a reduction in vibration levels after balancing was carried out, with an average vibration reduction of 57%.

Conclusions

1. The Phase 1 trial demonstrated that the C-130J NIU provides valid propeller-speed amplitude and phase data, over a test program of seven flights and flight regimes ranging in altitudes of 20,000ft to 30,000 ft, and power lever angles from 65 to 78 degrees.

2. A consistent difference was evident in the influence coefficients derived for each of the four power plants in the Phase 1 trial. The reason is thought to be most likely

either an engine-airframe location dependency, or individual differences in engine mount characteristics.

3. The Phase 2 trial confirmed the operational effectiveness of using in-flight vibration data to obtain a balance solution. This trial demonstrated that in three instances there were reductions of the order of 50%, with one engine showing only a small reduction. However the latter was already at a low vibration level prior to the balance procedure.

4. The Phase 2 trial demonstrated the large saving in maintenance effort and aircraft down-time possible, using in-flight data for the balance solution, in comparison with the time required for balancing using the ground-run GSE equipment. One of the aircraft being used for the Phase 2 trial carried out two operational sorties on the same day as the balance solution was obtained and installed on the aircraft. There was no disruption to its routine operational deployments on that day.

5. The effect on airframe vibration of propeller unbalance is relatively minor in the cargo areas of the aircraft, in comparison with the 6P blade-pass vibration levels.

6. The development of the certified software has led to in-service deployment in the RAAF fleet. The ground support equipment balance procedure is no longer in use by the RAAF.

7. The in-service results from the initial deployment by the RAAF of the propeller balance software has shown a vibration reduction in every instance it has been implemented, with reductions ranging from 23% to 72%, with an average across all results of 57%.

8. The adoption of the software solution for propeller balance has led to a significant reduction in maintenance effort, increased aircraft availability, savings in fuel costs and engine hours.

9. Further benefits are the improved health and safety aspects for maintenance personnel, as there is no longer the requirement to tape wires onto the upper wing surface, and perform a difficult sensor installation and tacho wire connection, at the top of the forward engine nacelle, beyond the reach of the flight-line engine work stands.

Future Developments

1. Improved results in the longer term may be possible by optimising the balance solution to minimise vibration at both the front (PGB), and rear (turbine) sensor locations, which will then effectively aim to minimise vibration at both the front and rear engine mounts. This will become clear after further analysis of field data.

2. In the longer term, there will be logistic advantages if the balance procedure is incorporated into the maintenance ground station.

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Appendix A

Phase 1 Trial PGB propeller-speed vibration amplitude and phase

65 deg	20000ft		25000ft		30000ft	
PLA	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Flight 3			0.677	79.1	0.660	89.7
Flight 4			0.893	-125.9	0.886	-120.0
Flight 5			1.410	-56.0	1.463	-72.3
Flight 6			1.167	4.4	1.164	-5.6

70 deg	20000ft		25000ft		30000ft	
PLA	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Flight 3	0.489	101.7	0.630	88.4	0.751	80.7
Flight 4	0.753	-132.2	0.888	-116.9	0.725	-119.8
Flight 5	1.057	-59.2	1.177	-52.4	1.436	-65.2
Flight 6	0.907	8.1	1.083	8.6	1.322	1.7

78 deg	20000ft		25000ft		30000ft	
PLA	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Flight 3	0.507	107.6	0.606	108.9	0.684	92.6
Flight 4	0.736	-131.4	0.844	-126.7	0.799	-118.2
Flight 5	0.962	-58.9	0.975	-62.0	1.127	-49.7
Flight 6	0.827	1.9	0.957	11.1	1.170	6.0

Appendix B

Table B1: Phase 1 Trial PGB propeller-speed vibration amplitude and phase

	Flight 1		Flight 2	
	Real	Imag	Real	Imag
Engine 1	-0.180	-0.066	-0.228	-0.077
Engine 2	0.311	-0.126	0.189	-0.209
Engine 3	-0.108	0.118	-0.046	-0.348
Engine 4	-0.007	0.119	-0.046	0.048

Gearbox vibration at 20000ft and 70 degrees PLA