EXPERIENCE IN ROTOR BALANCING OF LARGE COMMERCIAL JET ENGINES

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ABSTRACT Experience over the past ten years in vibration and cabin noise control of new airplane /engine systems is summarized. Why the newer systems required more stringent control is discussed. The transition from single plane balance methods, in common use on older systems, to conventional 2-plane influence coefficient (I.C.) methods, and then to optimized 2-plane I.C. methods is described. Examples of residual unbalance predictions from an extensive test data base are shown. Application of finite element analysis to understand data anomalies is described. Issues of I.C. variance and use of generic I.C.'s are discussed. Improvements using optimized balance methods are shown. Advanced control systems are discussed including use of transient engine runs and airplane on-board data acquisition systems. Projections for future design methods are offered.

NOMENCLATURE

\[ w = N_1 \] low pressure rotor speed
\[ \bar{\mathbf{u}} \] = average residual unbalance vector over speed range
\[ \mathbf{W} \] = diagonal weighting matrix

Note: all following quantities are complex and functions of tracked rotor speed, \( w \).

\[ [ \mathbf{A} ] \] = engine vibration influence coefficient matrix
\[ [ \mathbf{u} ] \] = engine vibration vector
\[ [ \mathbf{f} ] \] = rotor unbalance vector
\[ A_{ij} \] = element of influence coefficient matrix
\[ i = 1, m \] = no. of pickups
\[ j = 1,2 \] balance planes, \( 1 = \text{fan}, \ 2 = \text{low pressure turbine (LPT)} \)

1. INTRODUCTION

The purpose of this paper is to share experience in rotor balancing of jet engines for controlling engine and airplane system vibration and cabin noise. The work covers a period of time commencing in early 1984 to the present. It involved 4 airplane models (747-400, 737-300, 767, 757) and 8 different engine models from at least 3 engine consortiums, who were collaborators in this effort.

Boeing at one time was directly involved in design and manufacture of rotating equipment through the Gas Turbine Division (divested in the late 1960's) and had some remaining expertise in rotor balance, but little direct interest. This changed unexpectedly during early testing of a new generation of commercial airliners starting with the 767 in 1984. Lower operating speeds of the higher bypass engines and a new engine/airframe integrated design philosophy were key factors.

Older engine's operating speeds, used on 707, 727, 737, 200 airplanes, were in excess of 100 Hz. The newer large fan engines were typically in the 40 to 60 Hz regime -as it turns out, in a particularly sensitive region of the cabin acoustics. The new design philosophy achieved large aero-performance gains and improved maintainability by mounting the engines closer to the fuselage and to the wing on short, stiff struts, with thrust reverser and cowlings hinged off the strut and clamped to the engine. More efficient transmission of engine rotor tones into the airframe resulted. After some initial testing, to confirm rotor out-of-balance as the forcing function, the obvious first and immediate action was to try to improve the engine rotor balance.

In addition to rotor balance, considerable other Boeing work has taken place to control transmission of engine vibration. Active vibration cancellation has been studied [1]. Some Installations have been retrofitted with engine mount isolation involving fairly extensive design and test work [2]. Some engines have been retrofitted by the engine manufacturers with oil-damped rotor bearings.

2. TECHNICAL BACKGROUND

Some of the early noise and vibration data are shown in Figures 1 and 2. Figure 1 shows a typical noise spectrum from the forward cabin where background noise levels are very low. The peak \( N_1 \) (low rotor speed) tone level exceeded limits by about 10 DB. Peak vibration levels of engine forward and aft vibration pickups (Figure 2) (from factory pass-off tests) were used as control parameters. Solid symbols denote engines squawked by Boeing test pilots during airplane pre-delivery flights. In this sample,
approximately 34% of the engines required some degree of him balance to bring them below new target vibration limits needed for pilot acceptance.

Older installations — by today’s standards had very liberal vibration limits. These limits were specified as not-to-exceed vibration levels, requiring demonstration by the engine manufacturer on each engine during a factory pass-off test. These limits were on the order of 2 to 6 mils single amplitude (SA) for the low rotor induced vibration.

These limits had evolved from older systems which had relatively flexible coupling of the engine and airframe and could be achieved without very sophisticated balance methods. Consequently, rotor balance in the large commercial aircraft industry in the early 1980’s was a somewhat neglected technology. In general, only the fan was balanced on-wing, using a single pickup. A commonly used method was the Somervaille, 3-shot method [3], which required no phase measurement.

There was considerable skepticism regarding rotor balance as an effective means of controlling cabin noise. Vibration levels below 2 mils were considered very difficult to achieve. Observations of engine vibration revealed poor repeatability and other inconsistencies suggesting lack of stable system characteristics needed for trim balance success. Additional resistance to improving rotor balance derived from a view that high vibration limits were necessary to avoid too frequent in-service trim balancing. There was no definitive data to support this view nor much data on low pressure turbine residual unbalance in assembled engines.

A contrary viewpoint that rotor balance should be very effective in reducing cabin noise — which was subsequently validated — was based on the belief that control at the source would be superior to downstream control where the vibration was highly dispersed. This viewpoint also supported the addition of oil damped rotor bearings in the engines.

**3. SYSTEM CONFIGURATION AND INFLUENCE COEFFICIENT (I.C.) METHOD**

A typical engine schematic is shown in Figure 3. Two balance planes are standard, the fan and the last stage of the low pressure turbine. Vibration pickups were on the engine stationery structure, a forward pickup and an aft pickup, the minimum required. Fan balance weights were placed on a standard balance ring. For the LPT, wire was wrapped under the Up shroud as trial weights but was unsatisfactory for permanent corrective balance. This problem was solved by the engine manufacturers by developing a balance clip [4], as illustrated in Figure 3. The N1 pickup provided rotational speed including a once-per-rev phase reference.

The theory of I.C. balancing is straightforward. The real challenge is in meeting all the requirements for carrying
out the process, not the least of which is an accurate measurement system. Therle [5] published one of the earlier treatises on multi-plane I.C. balancing. Goodman [6] proposed a significant advance based on using a least squares formulation.

For a two source system, calculation of I.C.'s requires at least three engine runs with: 1) an initial unbalance state (variously termed the as-built, as-received, residual unbalance state, etc.) in which the resultant unbalance is unknown. 2) a known fan unbalance inserted, and 3) a run with a known LIT unbalance inserted. Runs 2 and 3 may each include both fan and LPT unbalance increments as long as they are linearly independent increments. The two accelerometers must be located so their responses are linearly independent over the selected speed points. Generally, a fourth run is conducted with corrective balances inserted to verify the balance improvement, which then enables 3 independent calculations of I.C.'s, taking the four runs three at a time.

By subtracting the vibration of the initial run from that of subsequent trial unbalance runs at a given speed, a general expression for the I.C. matrix [A] may be written:

$$[\Delta u] = [A][\Delta f]$$

where $m$ = no. of trial runs and $p$ = no. of pickups. Two pickups is a standard configuration. The number of trial runs varies from a minimum of two.

one can now select two or more runs from (1) to calculate $[A]$. In general

$$[A] = [\Delta u][\Delta f]^{-1}$$

where $[\Delta f]^{-1}$ is the generalized inverse of $[\Delta f]$ (i.e. $[\Delta f]^T([\Delta f][\Delta f]^{-1})^{-1}$). Often data from more than one engine is added to (1), providing so called generic I.C.'s.

Residual unbalance, $[\ell]_{res}$, is predicted by using the inverse I.C. matrix and the initial vibration data at each speed point. $w_i$:

$$[\ell]_{res} = [A]^{-1}[u]_{init}$$

Following Goodman [6], data at all speeds may be combined to predict a mean or effective unbalance over the entire frequency range. Using a weighting matrix $[W]$ to emphasize important frequencies.

$$[\ell]_{res} = [A]^{-1}[W][u]_{init}$$

where $n$ = number of speed points and where $[W]$ is a diagonal matrix of O's and I's for selecting desired speed points or pickups.

4. VALIDATION OF THE I.C. BALANCE APPROACH

This section briefly describes initial studies used to help validate the feasibility of controlling cabin noise via rotor balance. Of particular interest was residual unbalance data to see if two plane unbalance assumptions were satisfied as evidenced by reasonably constant magnitude and location as a function of rotor speed. Single plane methods, effect of mounting and flight conditions, and determining best location of pickups, were studied in this context.

Included are comparisons of residual unbalance prediction using the following.

1) Somervaille 3-shot method versus 2 plane I.C. method. (Figure 4). Results show the deficiency of the Somervaille method in predicting LPT unbalance in the case when the pickup location responds also to fan unbalance and violates the assumptions of the method.

2) Different combinations of trial unbalance runs. (Figure 5). Results were mixed but encouraging. The large fluctuations were believed attributable to a variety of causes including unbalances at other than balance planes, non-linearities, test error, and variation of unbalance during trial runs. In a factory test significant fan blade relative movements were in fact observed verifying this latter cause.
3) Different mount configurations and flight altitudes. (Figure 6) The pronounced linear variation was of some concern as it could pose a serious limitation on balance control required over a wide frequency range. Also for engine build diagnostic purposes it was important to understand the sources of unbalance. Moment unbalance was suspected but hard to verify due to difficulty of adding weights to interior stages of the turbine. A finite element model (Figure 7) provided an easy analytical "test". LPT moment unbalance was added to the model along with fan and lpt radial unbalance at the normal balance planes. then the 2-plane I.C. method applied to

**Figure 5. Residual Unbalance Predictions Using Multiple Trial Runs (ibid)**

**Figure 6. LPT Residual Unbalance for a* Engine Having Various Mount Configurations and Flown at Various Altitudes**

**Figure 7. Finite Element Analysis Showing Effect of LPT Moment Unbalance Using a 2-Plane I.C. Prediction of Residual Unbalance**
predict the equivalent fan and lpt unbalance. As shown in Figure 7, the expected behavior was produced and the theory supported.

4) Different accelerometer pairs. (Figure.81 This would help define optimum locations if standard locations proved to be deficient. Some apparent preference is evident from this data, i.e. the pairs of accelerometers giving the most constant data.

One goal was to be able to use a generic set of I.C.’s for a given engine model and avoid excessive trial balance runs. Considerable variation in I.C.’s was observed early-on and raised doubts that this goal could be achieved. Figure 9 shows typical variance for a sample of 13 engines. It was found that only about 55% of the engines could be successfully trim balanced using 1-shot with generic I.C.’s, and the standard I.C. method. Therefore investigation of new and improved methods was initiated, discussed in the next section.

5. IMPROVED BALANCE METHODS

As might be expected, the phase angle between fan and LPT unbalance is an important parameter in cabin noise. This is illustrated in Figure 10 where, for a specified noise limit, an unbalance-to-noise I.C. model showed up to 5 to 1 difference in permissible unbalance from worst to best phase angle. Studies indicated that use of noise I.C.’s to balance engines would be superior to engine vib pickups. Practical limitations placed it in a back-up position to be used if needed.
Engine runs on the airplane on-ground were at the time the only practical balance mode. The objective was to reduce the peak vibration levels to prescribed limits over frequency bands of 30 Hz or more. These limits often varied with frequency corresponding to different flight regimes. Algorithms developed for noise minimization studies (previous paragraph) were also suited for the vibration minimization problem with varying limits. The least squares approach did not appear to offer the required versatility because of the varying vibration limits.

In our initial efforts, discussed in Section 4, using elementary I.C. balancing, plots of residual unbalance amplitude and location (e.g., Figures 5, 6, and 8) were “eyeballed” and best and most reasonable corrective balances selected. Results, for a sample of 12 engines, are shown in Figure 11. The improved algorithm was based on an iterative exhaustive search routine programmed into a portable PC. It guarantees an absolute min-max for vibration over specified frequency ranges. Reference [7] gives a complete description, including PC software (OPTBAL). Figure 11, for a sample of 13 engines, shows the considerable improvement using this improved balance method.

8. ADVANCED SYSTEMS

During the course of this work a variety of options were identified for enhancing cabin noise and vibration control, using rotor balance related parameters. Practicalities related to economics of commercial airplane operations generally ruled out most of these options. Cost, simplicity, maintainability, are paramount. The LPT balance clip [4] (Figure 3) is a classic example that fits these requirements. Accelerometers or microphones in the cabin as balance pick-ups is not — at least on current systems — but may be in the future. [8] Two improvements that do appear to be acceptable are discussed.

The first is the use of engine accel/decel runs to collect data. Although the engine vibration may be considerably different for steady state, accel, and decel, studies have shown that they produce acceptably equivalent balance solutions. Table 1 shows data from one such study.

The second improvement is the incorporation of a in-flight data collection system that monitors the need for balance and generates the appropriate balance solution. [9] It is based on a two-plane optimized balance algorithm. In-flight vibration is recorded at preset rotor speeds and stored. Using embedded balance software and pre-loaded I.C.’s, corrective balances are displayed upon query via a on-board maintenance terminal during ground maintenance checks. (See Figure 12)

There are several advantages to an on-board system. It avoids the costly ground runs that generally are under tight constraints due to community noise restrictions and flight schedules. It measures data in the actual operating environment, not on the ground where vibration may be different than in flight. It can be incorporated into the existing vibration monitoring system.

7. CONCLUDING REMARKS

Engine and airframe vibration system characteristics were studied in this work to a depth “ever before carried out in commercial airplane operation. The maxim that ‘invention follows need” has been aptly demonstrated. Low engine vibration pass-off levels, once considered impractical, are now standard. In the process, many improvement systems were proposed, some still under active consideration. In the future we believe that most in-service, engine related vibration control will use on-board systems with data collected in flight or from brief engine accel/decel runs on ground.
In the design of new systems, finite element models are expected to define system characteristics and accurately predict both the noise and vibration due to rotor unbalance in the early design phases. In the past, flight test was the only reliable alternative. The math models, after perhaps some fine tuning via updating techniques now under study, should be a valuable aid in rotor balancing, providing checks on test data, helping define optimum pickup locations, and understanding data anomalies.

8. ACKNOWLEDGEMENTS

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9. REFERENCES


### Table 1. Comparison of Predicted Balance Corrections Using Dwell and Transient Data—747-400

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<th>Engine position</th>
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<th>Fan Amp oz-in</th>
<th>Phase degrees</th>
<th>LPT Amp oz-in</th>
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