An investigation into active synchrophasing for cabin noise and vibration reduction in propeller aircraft.

David M. Blunt\textsuperscript{a} and Brian Rebbechib

Department of Defence
Defence Science and Technology Organisation
506 Lorimer Street
Fisherman’s Bend VIC 3207
Australia

ABSTRACT

Low frequency cabin noise and vibration in propeller aircraft is dominated by the propeller blade-pass frequency and its low-order harmonics (< 500 Hz). The passive control of these frequencies in an aircraft cabin is difficult due to the weight penalties involved. Previous studies have shown that properly optimised propeller synchrophase angles can result in the significant global reduction of cabin noise and vibration (up to about 10 dB), not just the redistribution of this noise and vibration. However, most aircraft synchrophasers have fixed synchrophase angles, precluding the adaptation of the synchrophase angles to changes in the cabin noise environment brought about by different flight conditions, which can vary significantly in military aircraft during normal operations. This paper presents the activities that are being undertaken to investigate the effects of different altitudes and airspeeds on the optimum synchrophase angles in the four-engine military propeller aircraft operated by the Royal Australian Air Force (RAAF AP-3C, C-130H and C-130J-30), and the potential for active synchrophasing to compensate for these effects.

1 INTRODUCTION

Aircraft interior noise and vibration can be a serious problem, particularly in military propeller aircraft, where noise levels often exceed 100 dB and cargo vibration levels can limit the transport of munitions or sensitive equipment.

Low frequency cabin noise and vibration in propeller aircraft is dominated by the propeller blade-pass frequency and its low-order harmonics [1-4]. Typical blade-pass frequencies range from 60 Hz to 120 Hz. The passive control of this noise and vibration is difficult, as it usually requires unacceptable weight penalties [5]. However, many aircraft with two or more propellers have synchrophasers, including the P-3 Orion and C-130 Hercules (Figure 1).

Figure 1: RAAF P-3C Orion [6] & C-130H Hercules [7].

\textsuperscript{a} Also Ph.D. candidate at the School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia. Email address: david.blunt@dsto.defence.gov.au
\textsuperscript{b} Email address: brian.rebbechi@dsto.defence.gov.au
Synchrophasers are electronic devices that send signals to the engine speed control and/or propeller pitch control mechanisms in order to keep the rotational phase angles of the propellers at certain predetermined settings relative to a master propeller, which is usually one of the inboard propellers. They are designed to eliminate the annoying beating phenomenon that occurs when two or more propellers are rotating at slightly different speeds, and to promote the reduction of blade-pass noise in the cabin by changing the phase of the noise and vibration sources.

Previous analytical and experimental studies have shown that synchrophasing can reduce interior noise levels [8-15]. Those on actual aircraft [16-18] have shown that synchrophasing can provide a significant global reduction of the blade-pass noise (~10 dB) and/or cargo floor vibration (up to 50%) in an aircraft cabin, not just the redistribution of this noise and vibration. This global noise reduction is due to the rearrangement of the relative amplitudes of the fuselage vibration modes in such a way that they couple less efficiently with the cabin acoustic modes. However, synchrophasing has only achieved limited success as a method of noise and vibration control in practice. The reasons for this are twofold:

a) Firstly, the synchrophase angles in some aircraft may not be properly optimised due to inadequate measurements, the wrong optimisation strategy, or the consideration of too few synchrophase angle combinations. For instance, four four-bladed propellers with a synchrophaser angle resolution of five degrees will have 5,832 possible synchrophase angle combinations. This is obviously two many to optimise by trial and error, and requires a systematic optimisation strategy based on good experimental data.

b) Secondly, and perhaps more importantly, the fixed synchrophase angles found in most existing synchrophasers, including the P-3 and C-130, may be insufficient to cope with the changes in propeller noise levels and characteristics brought about by changes in flight conditions during normal operations. For instance, it is generally known that propeller noise levels are influenced by factors such as thrust and inflow distortion [19], and that cabin propeller noise levels are influenced by altitude and airspeed [2, 3]. Military aircraft also have a much broader range of flight conditions as part of normal operations than civilian passenger aircraft, which are operated in cruise flight in a limited range of altitudes for most of the time.

The active control of synchrophase angles using feedback from cabin mounted microphones and/or accelerometers together with appropriate adaptive optimisation strategies should improve the potential of synchrophasing to reduce cabin noise and vibration over a wider range of flight conditions. Although active control using secondary sources such as loudspeakers, shakers, or piezo-films may ultimately provide greater reductions in cabin noise and vibration, this type of control comes at the cost of added complexity and weight. Active synchrophasing should offer worthwhile noise and vibration reductions with fewer penalties, and be a lot easier to implement and retrofit to existing aircraft. Active synchrophasing may also enhance the performance of other active noise control methods by minimising the noise entering the cabin.

The objectives of this investigation are to examine the effects of flight conditions on optimum synchrophase angles, and the potential for active synchrophase angle control to compensate for these effects. This will be done by conducting flight trials in RAAF AP-3C, C-130J-30 and C-130H aircraft types, and by developing active control methodologies specifically tailored to the observed effects. An experimental
synchrophasing rig will also be built to examine the effects of synchrophasing and to test active synchrophasing strategies in an anechoic chamber. Propeller signature theory will be used throughout to simplify the task.

2 PROPELLER SIGNATURE THEORY

Propeller signature theory was first described in a landmark paper by Johnston, Donham and Guinn [16]. Embodiments of propeller signature theory have since appeared in a number of other papers and patents [18, 20, 21]. In this theory, the total propeller-related noise or vibration at a particular cabin location is calculated by taking the vector sum of the contributions from each propeller. This assumes local linearity, which appears to be valid based on the reported results, but which will be further checked using data from the flight-tests to be conducted in this investigation.

With the propeller speeds synchronised, the noise or vibration for any combination of shaft angles is predicted by changing the phase of each signature in proportion to the change in shaft angle, and calculating the new sum of the resulting contributions. An example illustrating this is shown in Figure 2, where the Blade-Pass Frequency (BPF) signature components ($S_p \angle \phi_p$) at a point inside the cabin are shown in the top half of the figure, and the predicted noise at this same point for a different set of synchrophase angles is shown in the bottom half of the figure. Note that Propeller 2 is the master propeller, and the changes in the slave propeller shaft angles ($a_p$) are multiplied by the number of propeller blades to arrive at the appropriate changes in phase at the blade-pass frequency.

![Figure 2: Propeller signature example [After 16].](image-url)
Propeller signature theory uses an influence-coefficient approach to identifying the contributions from individual propellers to the total propeller-related noise or vibration at a particular location within the aircraft cabin. This is similar to measuring the influence coefficients in a balancing problem. Instead of a trial weight, a trial synchrophase angle is applied, and the change in acoustic or vibration response is measured.

Mathematically, the predicted effect of synchrophasing on the blade-pass frequency noise at each location can be expressed as

$$\hat{A}_k = \sum_{p=1}^{P} \hat{S}_{p,k} e^{iB\alpha_p}$$  \hspace{1cm} (1)

where $\hat{A}_k$ is the noise at location $k$, $\hat{S}_{p,k}$ is the signature of propeller $p$ at location $k$, $\alpha_p$ is the shaft angle (synchrophase angle) of propeller $p$ in radians, $B$ is the number of blades on each propeller, and $P$ is the number of propellers. A multiple of $B$ is used for the higher harmonics of the blade-pass noise. In matrix notion this becomes

$$A = S \times \beta$$  \hspace{1cm} (2)

where $A$ is a column of complex numbers representing the noise at $K$ locations, $S$ is an $K \times P$ matrix of complex numbers representing the propeller signatures, and $\beta$ is a column of $P$ unit vectors with phase angles equal to the synchrophase angles multiplied by $B$.

To solve this equation for $S$ requires noise measurements for at least $P$ independent sets of synchrophase angles. When there are measurements for more than $P$ sets of synchrophase angles, the system is over-determined. In this case, the least-squares solution for the propeller signatures can be obtained from

$$S = A \beta^T \left[ \beta \beta^T \right]^{-1}$$  \hspace{1cm} (3)

where $A$ is an $K \times Q$ matrix of measurements, $\beta$ is a $P \times Q$ matrix of phase angle vectors, and $Q$ is the number of synchrophase angle sets.

3 PROPELLER SIGNATURE EXAMPLES
Two hypothetical examples using four propellers are presented. The signatures for both examples are listed in Table 1.

<table>
<thead>
<tr>
<th>Propeller</th>
<th>1</th>
<th>2 (Ref)</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td>Sound Pressure (Pa)</td>
<td>0.35</td>
<td>2.00</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Sound Pressure Level (dB)</td>
<td>84.9</td>
<td>100</td>
<td>91.5</td>
</tr>
<tr>
<td></td>
<td>Phase</td>
<td>0°</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>Example 2</td>
<td>Sound Pressure (Pa)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Sound Pressure Level (dB)</td>
<td>94.0</td>
<td>94.0</td>
<td>94.0</td>
</tr>
<tr>
<td></td>
<td>Phase</td>
<td>0°</td>
<td>0°</td>
<td>0°</td>
</tr>
</tbody>
</table>
In the first example, the expected effect of synchrophasing on the blade-pass frequency noise at a single cabin location is shown for a typical military aircraft. The signature amplitudes are chosen so that the outboard propellers contribute less to the cabin noise than the inboard propellers, and one of the inboard propellers has more influence over the cabin noise than the other. The latter acknowledges that the axes of the propellers are usually at a slight angle of attack with respect to the airflow (about 2°), and because all the propellers usually rotate in the same direction, the more highly loaded down-going blade on Propeller 2 (in this instance) is closer to the fuselage than the corresponding blade on Propeller 3.

The predicted noise levels at the blade-pass frequency for the first example are plotted three-dimensionally in Figure 3. Here, x, y and z axes represent the phase of the contributions from the three slave propellers at the blade-pass frequency (i.e., $\beta_{\alpha_1}$, $\beta_{\alpha_3}$, $\beta_{\alpha_4}$), and the colour axis represents the sound pressure amplitude. Slices through the mid-points of the phase axes highlight the minimum of 0.55 Pa (88.8 dB) in the centre of the plot, and the maximum of 3.45 Pa (104.7 dB) in the outer corners of the plot.

A feature to note about this example is that the minimum occurs at only one phase angle combination; namely ($\pi$, $\pi$, $\pi$). This is because the sum of the amplitudes of the three slave propeller signatures (1.45 Pa) is less than the amplitude of the master propeller signature (2 Pa). If this was not the case, a minimum sound pressure of zero Pascals could in fact be achieved with a range of synchrophase angles. This is illustrated in the second example, shown in Figure 4, where the propeller signatures are all equal, and the locus of phase angles giving a sound pressure of zero Pascals zigzags its way across the phase-angle space.

The potential for this phenomenon to reduce the noise at other cabin locations needs to be further investigated. The probability that it will occur will be higher in aircraft with more symmetrical propeller noise contributions from both sides of the fuselage; i.e., where the propeller signatures, and in particular the inboard propeller signatures, are closer in amplitude. One such aircraft is likely to be the new Airbus Military A400M (Figure 5), which will have propellers that rotate in opposite directions on either side of the fuselage [22]. The A400M will also have 10,000+ shp engines with 5.33 m (17.5 ft) diameter propellers [23], so propeller noise is likely to be a significant issue in this aircraft, and one for which active synchrophasing may provide an elegant solution.
4 ACTIVE SYNCHROPHASING

Only a limited amount of work has been done on active synchrophasing to date. Actual flight-tested systems have only been developed by the United States Air Force Research Laboratory (AFRL), the National Aeronautics and Space Administration (NASA), and Fokker, which are discussed below. Other work of note includes the patents held by General Electric [21, 25], United Technologies Corporation [20], and the Institute of Sound and Vibration [26]. The algorithms for optimising the synchrophase angles disclosed in these patents include the exhaustive search of all synchrophase angle combinations, and the more conventional gradient-descent type active control techniques. However, they do not appear to have been tested with any experimental data incorporating the effects of variable flight conditions, so the real-world performance of these algorithms is unknown.

4.1 AFRL

The AFRL contracted Lockheed Martin Control Systems in 1999 (subsequently acquired by BAE Systems North America) to develop a prototype active synchrophaser system for the C-130 Hercules aircraft [27, 28]. This system was designed for the T56-
powered variants of the aircraft, which have four-bladed propellers, not the C-130J, which has a different engine and six-bladed propellers [29].

The AFRL C-130 active synchrophaser had a closed-loop mode and an open-loop mode. The closed-loop mode attempted to minimise the noise measured by an array of cabin microphones. The open-loop mode maintained specific relative phase angles between the propellers to reduce fly-over noise. Flight tests were completed in 2002. Interior noise levels were claimed to be reduced by 10 dB on average [28], and by up to 22 dB in the cockpit during one phase of the test [30]. Fly-over noise was claimed to be reduced by 3 dB to 4 dB [29]. Unfortunately, no further details of the system’s performance under different flight regimes, or the control algorithms, microphone locations, or system architecture were publicly released.

4.2 NASA

NASA developed a relatively simple adaptive synchrophaser for an OV-10A Bronco twin turboprop aircraft [31]. This used a phase-locked-loop engine speed controller connected to a single cabin mounted microphone. Good results were reported for a microphone position near the passenger seat. At this location, the minimised overall noise level was 12 dB (18 dB at the BPF) lower than the maximised noise level, and 9 dB (15 dB at the BPF) lower than the beat-averaged noise level. Differences of 0.8 dB, 1 dB and −5 dB to the beat-averaged noise levels at three other cabin monitoring microphones during this test also demonstrated that a small amount of global reduction was probably achieved. It was also claimed that the system would remain locked-on during transient manoeuvres. Further work extended this concept to the minimisation of exterior noise through the use of a fixed synchrophaser angle but no results were reported [32].

4.3 Fokker

Fokker developed a Propeller Blade Matching System (PBMS) [33-36] for the twin-engine Fokker 50 in order to solve a seat-table vibration problem. The PBMS actively seeks out the synchrophase angle combination (one of six) that minimises the vibration at the propeller rotational frequency measured in the aircraft cabin. However, it does not seek to minimise noise or vibration at the blade-pass frequency.

5 PROPOSED EXPERIMENTS

Flight trials have been proposed for the RAAF AP-3C, C-130H and C-130J-30 aircraft. The first trial to proceed will be for the AP-3C, which is discussed below.

5.1 AP-3C Flight Trial

The AP-3C flight trial will record the noise and vibration from 21 Brüel Kjær Type 4935 microphones and 7 PCB Type 353B33 accelerometers, along with the propeller once-per-rev (1P) tachometer signals, for 7 sets of synchrophase angles (Table 2) under 28 combinations of altitudes and airspeeds chosen to represent typical AP-3C flight regimes (Table 3). The synchrophase angles have been chosen to ensure that the recorded data will be sufficient to compute the propeller signatures at 1×, 2× and 3× the blade-pass frequency. There will also be sufficient data to compare predicted noise levels (using propeller signature theory) with actual measurements. Microphones will be clamped to the headrests of all the pilot and crew seats in order to maximise the noise reduction benefit for the pilots and aircrew in their seated positions, and to the overhead grab rail to cover the rest of the cabin near standing head height. The accelerometers will be mounted on brackets clamped to the cabin floor seat rails. All signals will be
recorded continuously with a bandwidth of 20 kHz on a 32-channel Heim D120f digital recorder. Using more than four test angle sets will allow a least-squares approach to be taken when computing the propeller signatures, as well as the opportunity to compare predicted noise levels with measured noise levels and to further validate propeller signature theory.

Table 2: Test synchrophaser angles (No. 3 master).

<table>
<thead>
<tr>
<th>Test Set</th>
<th>Propeller 1</th>
<th>Propeller 2</th>
<th>Propeller 3</th>
<th>Propeller 4</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−43°</td>
<td>+18°</td>
<td>0°</td>
<td>+12°</td>
<td>Default angles</td>
</tr>
<tr>
<td>2</td>
<td>−18°</td>
<td>+18°</td>
<td>0°</td>
<td>+12°</td>
<td>Default angles + (25°, 0°, 0°, 0°)</td>
</tr>
<tr>
<td>3</td>
<td>+22°</td>
<td>+18°</td>
<td>0°</td>
<td>+12°</td>
<td>Default angles − (25°, 0°, 0°, 0°)</td>
</tr>
<tr>
<td>4</td>
<td>−43°</td>
<td>+43°</td>
<td>0°</td>
<td>+12°</td>
<td>Default angles + (0°, 25°, 0°, 0°)</td>
</tr>
<tr>
<td>5</td>
<td>−43°</td>
<td>−7°</td>
<td>0°</td>
<td>+12°</td>
<td>Default angles − (0°, 25°, 0°, 0°)</td>
</tr>
<tr>
<td>6</td>
<td>−43°</td>
<td>+18°</td>
<td>0°</td>
<td>+37°</td>
<td>Default angles + (0°, 0°, 0°, 25°)</td>
</tr>
<tr>
<td>7</td>
<td>−43°</td>
<td>+18°</td>
<td>0°</td>
<td>−13°</td>
<td>Default angles − (0°, 0°, 0°, 25°)</td>
</tr>
</tbody>
</table>

Table 3: Test flight conditions.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Airspeeds (KIAS)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 ft ASL</td>
<td>200 220</td>
<td>Typical of ASW</td>
</tr>
<tr>
<td>1,000 ft ASL</td>
<td>200 220 240</td>
<td>Typical of ASW</td>
</tr>
<tr>
<td>3,000 ft ASL</td>
<td>220 240 260</td>
<td>Typical of Low-Level Surveillance</td>
</tr>
<tr>
<td>FL100</td>
<td>220 240 260</td>
<td>Typical of Transit</td>
</tr>
<tr>
<td>FL180</td>
<td>220 240 260 280</td>
<td>Typical of Transit</td>
</tr>
<tr>
<td>FL200</td>
<td>220 240 260</td>
<td>Typical of Transit</td>
</tr>
<tr>
<td>FL240</td>
<td>200 220 240</td>
<td>Typical of High-Level Surveillance</td>
</tr>
<tr>
<td>FL280</td>
<td>180 200 220</td>
<td>Typical of High-Level Surveillance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Airspeeds (KIAS)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000 ft ASL</td>
<td>190 210</td>
<td>Typical of three-engine operation</td>
</tr>
<tr>
<td>3,000 ft ASL</td>
<td>190 210</td>
<td>Typical of three-engine operation</td>
</tr>
</tbody>
</table>

A modified synchrophaser and a handheld synchrophase angle adjustment and display unit (Figure 6) will be installed in the test aircraft so that the synchrophase angle settings can be changed in flight. The trim potentiometers that set the synchrophase angles of Propellers 1, 2 and 4 when Propeller 3 is the master propeller will be removed from the synchrophaser and wired through a new connector on the side of the synchrophaser to the handheld unit. Access to the synchrophaser pulse-width-modulated signals representing the synchrophase angles of the three slave propellers will be through another cable connecting the handheld unit to an existing connector on the rear of the synchrophaser. The circuitry setting the synchrophase angles when Propeller 2 is the master propeller will not be changed so that the synchrophaser will revert to the default angle set whenever Propeller 2 is selected as the master propeller.

5.2 Experimental Rig

An experimental rig (Figure 7) is being constructed in order to investigate the effects of synchrophasing in the controlled environment of an anechoic chamber. It will also be used to test active synchrophasing control strategies. The rig has been designed to incorporate a reasonable number of typical aircraft fuselage features, but not to be a perfect scale model of any particular aircraft; although the length (2.49 m) and diameter (0.87 m) of the rig have been scaled from the C-130H based on the ratio of the blade-
pass frequency of the C-130H to the blade-pass frequency of the rig (68 Hz:333 Hz). It will use 11 inch model aircraft propellers instead of loudspeakers in order to maintain as much of the characteristics of real propeller noise sources as possible. A traversing mechanism with a central circular tube that passes through the centre of the end caps will allow an array of microphones to be positioned at different axial and radial locations inside the shell. A removable floor will be incorporated in order to change the modes of vibration of the cylinder and the internal acoustic volume. A similar smaller rig was used by Jones [37]. However, it used loudspeakers instead of propellers, and had no “wing” or fuselage stiffeners.

Figure 6: AP-3C synchrophaser and the synchrophaser adjustment & display unit.

Figure 7. Synchrophasing rig.

6 CONCLUDING REMARKS

Low frequency cabin noise and vibration in military propeller aircraft is dominated by the blade-pass frequency and its low-order harmonics. This noise and vibration can be reduced using synchrophasing, but this method of control has only achieved limited success in practice. It is believed that active synchrophasing using feedback from cabin mounted microphones and accelerometers with adaptive optimisation strategies should provide a better solution. Active synchrophasing will have significantly less weight penalty than other noise-reduction techniques, and be easier to retrofit to existing aircraft.
Only a limited amount of work has been done on active synchrophasing. The current research is expanding on this work by examining the effects of flight conditions on optimum synchrophase angles, and the potential for active synchrophase angle control to compensate for these effects. This is being done through flight trials in RAAF AP-3C, C-130J-30 and C-130H aircraft, and the development of active control methodologies specifically tailored to the observed effects. An experimental rig is also being constructed to investigate synchrophasing and to test various active synchrophasing strategies under controlled anechoic conditions.

Propeller signature theory is being used throughout to simplify the task. A preliminary investigation of this theory has shown that while the blade-pass noise or vibration at many cabin locations will have a single minimum as a function of the slave propeller synchrophase angles, it is theoretically possible for it to sum to zero over a range of synchrophase angles at some locations. The potential for this phenomenon to reduce the noise at other cabin locations needs to be further investigated.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Air Lift Systems Program Office and the Maritime Patrol Systems Program Office (RAAF), Mr Scott Dutton (DSTO), Prof. Colin Hansen and Dr Anthony Zander (University of Adelaide), and the assistance provided by Boeing Australia, and Raytheon Australia.

8 REFERENCES


