Application of Active Noise Control in Corporate Aircraft

Philip JB Jackson and Colin F Ross

Ultra Electronics Ltd , Noise & Vibration Systems
1 The Business Park, Cowley Road, Cambridge CB4 4WZ, United Kingdom
Tel: +44 1223 426 699, Fax: +44 1223 426 696, Email: philipj@ultranvs co uk

ABSTRACT

Following the successful introduction of Active Noise Control (ANC) systems as standard production fits on commuter aircraft (Saab2000, Saab340B and Dash8Q series 100, 200 & 300), recent efforts have focused on developing low-cost, low-weight systems for smaller corporate aircraft

This paper describes the approach taken by Ultra to the new technical challenges and the resulting improvements to the design methodology A review of system performance on corporate (King Air & Twin Commander) turboprop aircraft shows repeatable global Tonal Noise Reductions (TNR s) of >8 dBA throughout the whole cabin, achieving reductions >20 dB in some locations at the blade-pass frequency (BPF), and major comfort benefits throughout the flight envelope with a weight penalty of less than 20 kg

1 REVIEW

1 1 Overview

Ultra Electronics has been working since 1991 to develop and supply Active Noise and Vibration Control (ANVC) equipment for aircraft cabin quieting *UltraQuiet* ANC systems have been in service since 1994 Recently, falling costs, of both development and production items, has enabled us to target smaller aircraft

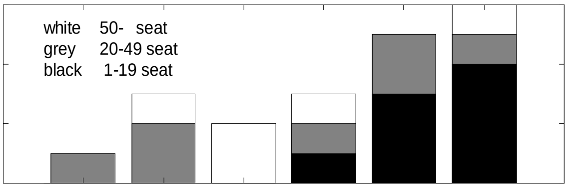

Figure 1 1, Regional (50+ seats), commuter (20-49 seats) and corporate (1-19 seats) aircraft demonstrated ANC system

The *UltraQuiet* system is now available for retrofit on the King Air series of corporate aircraft and installations are being developed for other turboprop and jet aircraft in both the commuter and corporate sectors

Table 1 1, Corporate aircraft with available ANC system designs

Manufacturer	Model	Number of Propeller Blades
King Air	C90	3
King Air	B200	3
King Air	B200	4
King Air	350	4
Twin Commander	1000	3
Twin Commander	690	3

1 2 Implementation

The principle components of the ANC system are, for the corporate aircraft, typically 24 microphones, 12 loudspeakers with power amplifiers and enclosures, and an electronic control unit In theory these components could be installed almost anywhere on the aircraft, but the number of practical locations for microphones, and particularly loudspeaker enclosures is greatly restricted by the aircraft structure and other aircraft systems (see Fig 12)

On smaller, corporate aircraft there are no over-head luggage bins and, with a lighter airframe, the available space between the exterior skin and the trim is reduced Consequently, new solutions have been sought with microphones in the seat head-rests, and loudspeakers behind or underneath

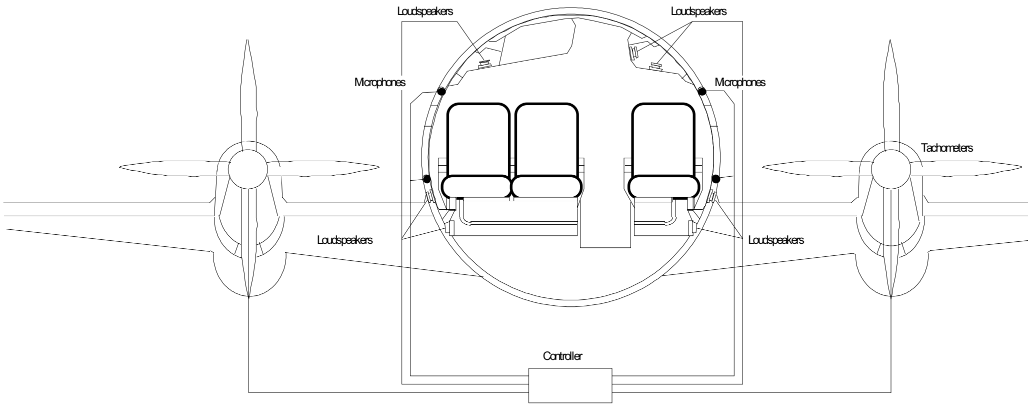

Figure 1 2, Schematic of typical commuter aircraft ANC installation seats, or mounted onto bulkheads Whereas, these solutions would pose additional problems on commuter aircraft, with large numbers of otherwise identical seats, which may be moved and reconfigured, and allow limited leg-room

1 3 Typical Sound Power Spectra

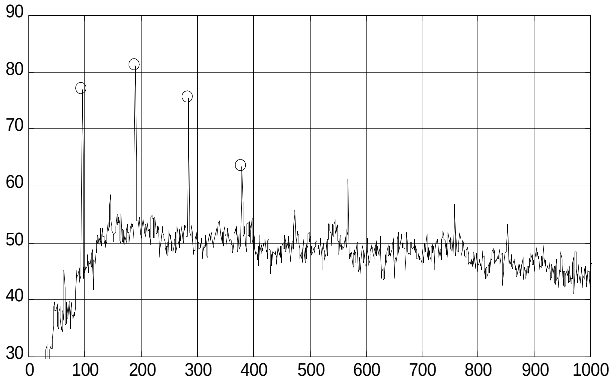

Figure 1 3a, Original (ANC off) power spectrum from King Air C90

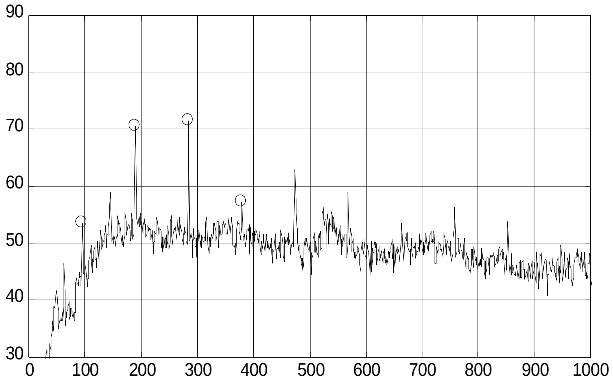

Figure 1 3b, Residual (ANC on) power spectrum from King Air C90

The above data come from measurements on King Air C90se N3196K, at standard cruise at 22,000 ft

Table 1 2, Typical summary of sound power on King Air C90

SPL	Original		Residual		Reduction	
	dBL	dBA	dBL	dBA	dBL	dBA
Controlled	1004	85 9	86 7	76 6	137	9 3
Uncontrolled	900	80 0	90 0	80 0	0 0	0 0
Total	1007	86 8	91 6	81 6	9 1	5 2

It is clear from the spectra that the main noise source is at the blade-pass frequency and its harmonics, but in order to minimise the residual A-weighted sound power, it is necessary to set targets for both narrow-band and broad-band treatments Currently, the most cost-effective solutions are active and passive, respectively

1 4 Design Objectives

The main objectives of a narrow-band ANC system are to;

reduce the tonal noise so as to maximise comfort throughout the cabin

achieve these reductions over the whole flight envelope, including changes in engine speed, but with performance optimised for cruise conditions

be robust against changes in aircraft loading

provide a good installation, in terms of weight, size, power consumption, maintenance and cost

1 5 Definition of Cabin Comfort

Traditionally, comfort has been directly related to the loudness of the tones, and performance measures are defined in terms of the Sound Pressure Level (SPL) at the BPF harmonics at which control is to be performed By summing these SPL s with the background (or uncontrolled) noise (see Table 1 2), the overall SPL measured on a Sound Level Meter can be compared directly

The system is designed to minimise a cost function, Eq(1), which contains a term proportional to the sum of the squares of the components of the microphone signals at the BPF s

$$J = \sum_{i=1}^{N} \left| \underline{y_i}^T k_i \underline{y_i} \right| + \ldots \qquad (1)$$

where y is the complex coefficient of the microphone signal at harmonic i, the first N harmonics are being controlled, k is a weighting factor for the design and ^{T} denotes the vector transpose

Thus, problem areas, where the tonal noise is particularly predominant, will automatically be targeted, since their original SPL will make a large contribution to the cost function

The dramatic subjective impact of attenuating the tones is not typically reflected in SPL s measured in dBA figures For most purposes targets can be set on an A-weighted scale, but recent efforts ([1] Paulus E and Zwicker E, 1984) have been directed at using improved models of the response of the human ear

On the small corporate aircraft, since the cockpit is integrated with the cabin and may contain passengers , it is incorporated into the definition of the controlled region, and hence included in the cost function, which governs the overall performance of the system design

1 6 Performance Assessment

Assessment of the perceived cabin comfort is made using measurements of the SPL at passenger head-height, whereas practical locations for ANC microphones are situated elsewhere, typically in the aircraft trim Distinction is made between these two rôles, and microphones are described as monitor microphones and control microphones, respectively

1 7 Flight Envelope

By monitoring the engine speed from a tachometer, or other correlated signal, the system is able to track the BPF as it changes for taxi, take off, initial climb, climb, cruise and descent The system is able to tune its response dynamically, unlike passive treatments Since most of the flight time is spent cruising, the system performance is optimised for cruise conditions

1 8 Robustness

For larger aircraft tests have shown that the system performance is not significantly affected by changes in the number of passengers on board, or even the cabin layout On completion of a design, flight tests are sometimes performed for verification

However, on corporate aircraft the difference between having the cabin empty and full of passengers changes the volume of air in the cabin cavity significantly As a result frequency response functions (FRF s) can change by up to 10 dB, in the case of passengers, actuators and sensors all being closely situated These FRF s are an essential part of the control loop, and changes will have an effect on the behaviour of the system as it adapts to variations in the original sound field Since the effects of these changes can have an impact on the system performance, measurements are taken of the sound field in flight at the control frequencies and FRF s, for both empty and full scenarios These measurements enable us to perform predictions of the effects of passenger loading for different configurations, and to check for changes to the magnitude and phase of FRF elements Accommodated into the configuration design process, these data enable us to design a system which is robust to variations in the cabin acoustics

1 9 Installation

Weight, power consumption and maintenance are standard criteria in the design of the system components Loudspeaker enclosures, which are tailor made for each aircraft type, are designed to give the maximum acoustic performance with the space available, using light weight materials, including moulded plastics and honeycomb laminated panels

The system size is typically determined as a pay-off against system performance and cost The corporate aircraft system is designed to cope with a range of microphones (1-32) and loudspeakers (1-16) Non-recurring costs have been reduced by improving the techniques for carrying out aircraft measurement and design trials These improvement make use of technological advances and pipe-lining of tasks, increasing parallelism

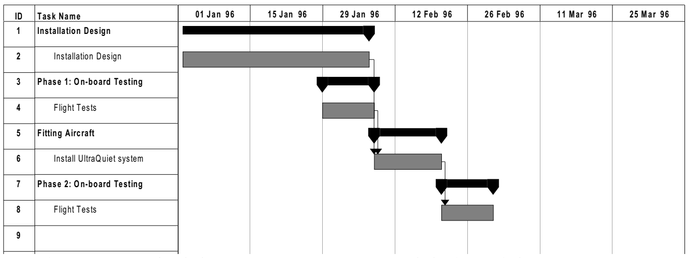

Figure 1 4, Schedule for a measurement and design trial on a corporate aircraft

The completed design is available 5 weeks after the start of aircraft tests

2 TECHNICAL ISSUES

2 1 Performance Limits

The ability of the *UltraQuiet* system to meet its design objective of maximising the cabin comfort, depends on the significance of the contribution of controlled BPF harmonics to the noise in the cabin, and the ability of the system to match the primary noise field with a secondary field, sometimes called anti-sound

Clearly, matching must be achieved both in space and time to yield reductions of the combined sound field

2 2 Spatial Match

Potential Locations For a practical installation on an aircraft, suitable locations have to be identified, taking into account conflicting items, such as the airframe, wiring looms and the Environment Control System

For microphones, these constraints are governed by the available surfaces to which a harness can be fed

For loudspeakers, the potential locations are much more limited, and, for the retrofit market, are restricted further by customisation and other variants The volume of the loudspeaker enclosures is a critical factor affecting the ability of the loudspeakers to give the required performance

Primary Sound Field On smaller aircraft there is a higher density of transmission paths into the cabin, because the structural components (wings, tail, fuselage) are more strongly coupled, as is the interior trim, which is typically in two or three pieces, rather than 20-30 for a commuter aircraft Consequently, there are many routes for the source, sound or vibration, to enter the cabin, which is much smaller itself, leading to a more complex primary sound field in the cabin

System Size T he number of microphones and loudspeakers employed by the ANC system limits the number of degrees of freedom available for matching the primary sound field The system size is a critical design decision, which is based on the performance predictions using the available locations, and competing factors, such as cost and weight

Higher Harmonics Despite the system size being smaller, the density of the ANC components on the aircraft is much higher than on a commuter aircraft, whose cavity is usually an order of magnitude larger Thus, on corporate aircraft with the microphones and loudspeakers less widely spaced, the matching of noise at the higher harmonics of the BPF (2×, 3×, etc), which have wavelengths of as little as a metre, is better

2 3 Temporal Match

Transients Fluctuations in the external air pressure, which cause turbulence, have a much more significant effect on smaller aircraft, which means that the engine loading is more variable, which, in turn, creates large transient effects in the sound field The dynamic adaptation of the ANC system is designed to track variations while providing good rejection of sensor noise, with the aid of appropriate filtering of tachometer and microphone signals

Synchrophase Angle On most twin-engine commuter aircraft, the angle between the left and right propeller shafts is held near constant by a synchrophaser Synchrophasers on corporate aircraft are generally of a much lower specification than larger aircraft some even fly without one between the two propeller shafts The effect of the greater variability in the synchrophase angle on the resultant sound field is significant, so the system has to be designed inherently to cope by considering the two propeller contributions to the sound field individually Sound is controlled by combining the coefficients at the instantaneous angle, which provides consistent performance in variable conditions

2 4 New Opportunities

Collaboration Integration of the *UltraQuiet* system design with design of passive solutions has highlighted the scope of Ultra s measurement system in measuring the effect of passive treatments and trouble-shooting

Not only can targets be set for the main constituents of an integrated sound treatment program, but they can be assessed and modified using a detailed analysis of their performance On one aircraft, a leak in the cockpit was acting as a broad-band noise source, which was identified during flight tests with the *UltraQuiet* system, once the system was operating

Quick Turnaround By changing connections from a super-set of installed components, adjusting some configuration parameters and re-measuring the FRF s, a new array of microphones and loudspeakers can be essayed The capability to reconfigure the system in 4 hours, ready for continuing flight tests, has greatly increased the scope for speedy ratification of simulations and demonstrating improvements to the design, without a serious effect on the aircraft schedule For example, two alternative solutions can be assessed by direct measurement and subjective experience, whereas previously decisions would have been made using only predictions

In a limited time-span a greater number of design iterations can be achieved with such a short turnaround time

Analysis The control unit and measurement system are independent in operation Using off-the-shelf production hardware, interface equipment, and a rugged measurement system, the control microphone signals can be monitored during control, simultaneously with the monitor microphones With the two systems operating independently the measurements are unbiased by the control unit being in operation or not, which could otherwise lead to spurious performance measurements

An expanding toolbox of analysis tools offers the capability to verify control unit FRF s against measured FRF s, and to visualise the sound field measurements and predictions, which facilitates trouble-shooting of malfunctioning components

3 RESULTS

3 1 Performance of the *UltraQuiet* system on corporate aircraft

These results, made by the measurement system acting in isolation from the control unit, use monitor microphones placed at an array of passenger ear locations, throughout the cabin (see Fig 3 1)

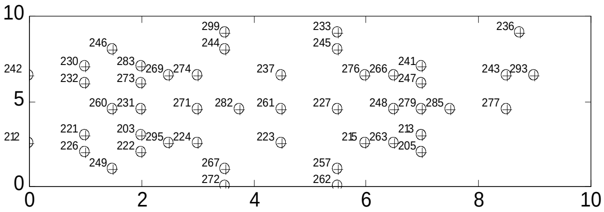

Figure 3 1, Plan view of microphones at monitor locations on King Air C90

The ANC system was fully installed on the aircraft as for a production fit, so that the control unit was mounted under the floor, the loudspeakers in the trim and under seats, and the microphones behind the trim and in the seat head-rests Results for the King Air C90se N3196K at 16,000 ft in standard cruise show, in addition to an overall difference of 81 dBA, how the residual (ANC on) sound field is more uniform throughout the cabin (see Figs 32 in Appendix)

The loudest location in the cabin (corresponding to position 223 [30, 2 5] in Fig 31) has been reduced by 14 dBA, which illustrates how it has been targeted by the system Similarly, the cockpit noise has been greatly reduced The reason for the higher residual in the cockpit is a combination of the contribution of the higher harmonics being greater nearer to the propellers, which are proud of the nose, and the tighter restrictions on choice of locations in the cockpit (limiting the spatial match)

Table 3 1, Tonal Noise Reductions on King Air C90

Area	TNR	
	dBL	dBA
Cabin Seats	137	110
Cockpit Seats	121	9 6
Whole Aircraft	111	8 9

3 2 Review of *UltraQuiet* Performance on Corporate Aircraft

Table 3 2, below details the Tonal Noise Reductions achieved with ANC on corporate aircraft, based on cabin average SPL s

Table 3 2, *UltraQuiet* system performance on corporate aircraft

Aircraft	TNR	
	dBL	dBA
King Air C90	111	8 9
King Air 200	9 3	5 5
King Air 350	9 2	7 0
Twin Commander	122	8 9

3 3 Validation of Predictions

Computer simulations are run using measured FRF s and in-flight data to predict the responses of the control unit These responses are then projected onto the monitor locations (see Table 3 3)

Table 3 3, Predictions of ANC system performance at 1×BPF

SPL	Original	Residual	Reduction
	dBA	dBA	dBA
Predicted	816	695	121
Measured	816	691	125

This two-step process enables us to gain a more realistic impression of realisable performance at the passengers ear, rather than quantifying the SPL s at the control microphone locations, which would be overly optimistic, as well as more sensitive to any errors and inconsistencies in the data set

Predictions and measurements can be used to illustrate the spatial distribution of the noise in the aircraft, and to help identify potential problems (see Figs 33 in Appendix)

4 SUMMARY

There is a good correlation between frequency domain predictions and measurements with ~05 dB error on a cabin wide basis, supported by microphone-wise comparison, using a spatial plot of the measured and predicted sound fields

Limits on performance were largely attributable to the spatial match, since ideal locations were not available for selection, and only locations practical for production were used

The Tonal Noise Reductions, at harmonics of the BPF, of 11 dBA were achieved at the cabin seats of a King Air C90 by an installed *UltraQuiet* system Reductions of 9 dBA were recorded throughout the aircraft Similar performance has been achieved by ANC systems on a range of corporate aircraft

Such reductions shift the main contribution to the A-weighted SPL from being tonal noise, to the uncontrolled background noise, comprising wind noise and other broad-band sources, which represents a major improvement in cabin comfort

ACKNOWLEDGEMENT

The corporate aircraft programme runs in collaboration between the technology group, led by Martin Paxton, of Ultra Electronics Ltd, Elliott Aviation, Raytheon Beechcraft and Twin Commander Aircraft Corporation

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APPENDIX

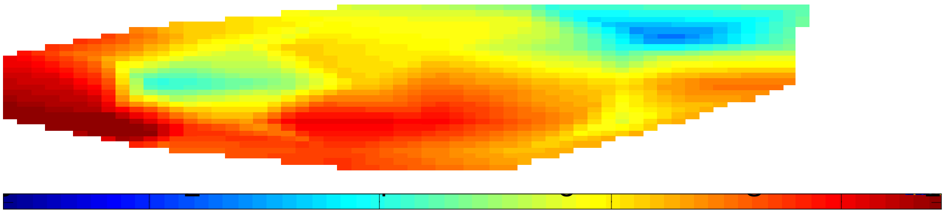

Figure 3 2a, Original (ANC off) tonal SPL spatial plot from King Air C90

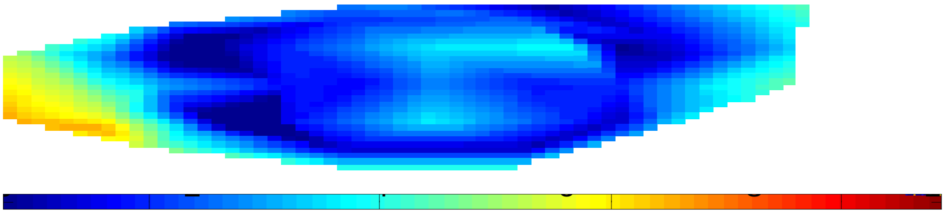

Figure 3 2b, Measured Residual (ANC on) tonal SPL spatial plot from King Air C90

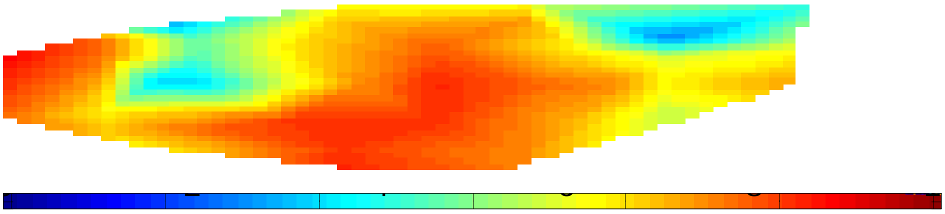

Figure 3 3a, Measured Original at 1×BPF from King Air C90

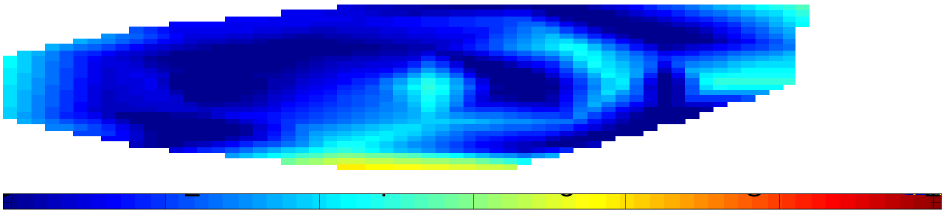

Figure 3 3b, Predicted Residual at 1×BPF from King Air C90

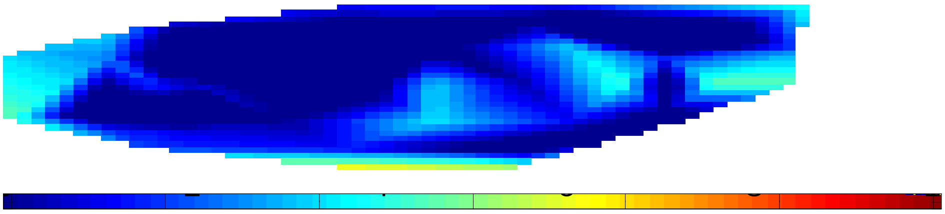

Figure 3 3b, Measured Residual at 1×BPF from King Air C90