TONAL ACTIVE CONTROL IN PRODUCTION ON A LARGE TURBO-PROP AIRCRAFT

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INTRODUCTION

The noise within a turbo-prop aircraft cabin typically has a significant contribution caused by the rotation of the propellers. This rotation creates pressure waves between the tips of the propeller blades and the aircraft fuselage. These pressure waves cause vibrations in the structure of the aircraft that are transmitted into the cabin as noise by components attached to the fuselage.

The active noise control system installed on the Q400 aircraft introduces a secondary acoustic and vibration field into the aircraft that counteracts the original field. The result is a dramatic reduction both in the noise and vibration within the cabin. As the system is fully active, it continuously adapts to changes in flight condition.

Traditionally large turbo-prop aircraft have been uncompetitive with regional jet aircraft due to high noise levels within the cabin causing passenger discomfort. However the active control system on the Q400 turbo-prop has reduced the cabin noise level to the same levels as seen in regional jets.

This paper describes the design process undertaken to develop the active noise system that is fitted to all Q400 aircraft. This process involves initial acoustical measurements and data analysis to determine potential actuators and a superset installation followed by further acoustical measurements to determine the optimal actuator and sensor arrays and final test flights to confirm system effectiveness.

SYSTEM OVERVIEW

The active noise system fitted on the Q400 essentially consists of an array of sensors, an array of actuators and power amplifiers, and a controller that determines the optimal output signals to the actuators based on the input signals from the sensors. The controller also requires reference signals related to the rotation rates of the two propellers and a signal related to the differential pressure across the skin of the aircraft. Figure 1 shows a schematic of this system.

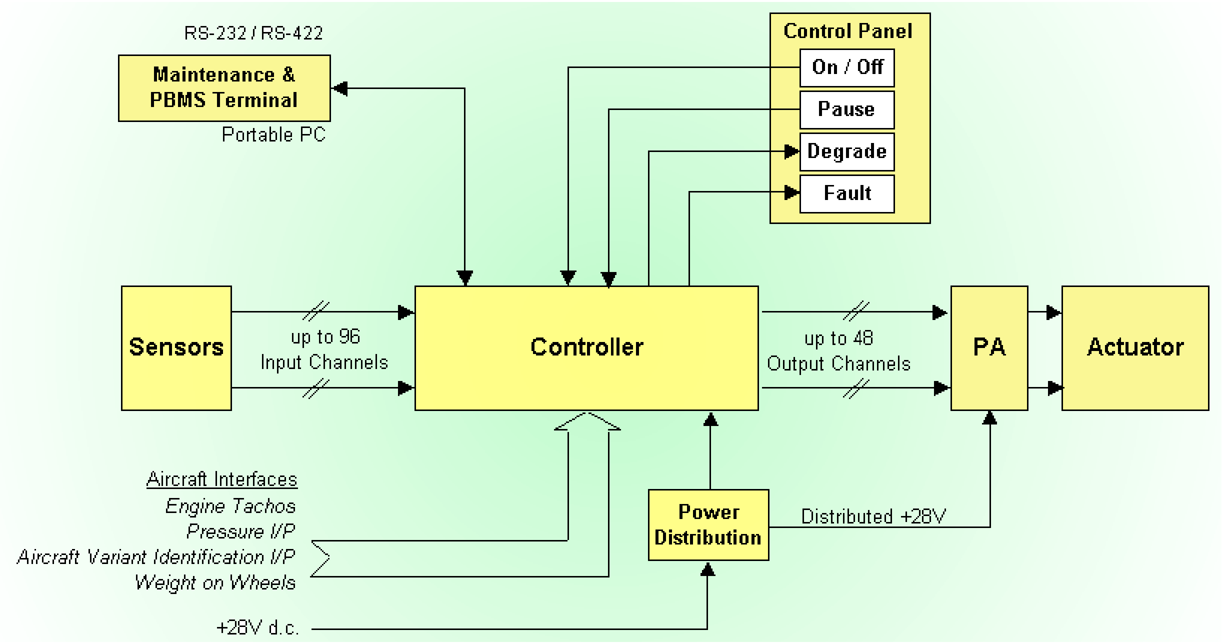

Figure 1: System Overview Schematic

The control algorithm is set to minimise a weighted sum of the signal power at the sensor locations at eight tones harmonically related to the speed of the two engines. The choice of weighting for particular sensors is determined during the design process to achieve the required spatial noise reductions throughout the aircraft.

Two types of sensors are used on the Q400; accelerometers installed on the seat rails and microphones fixed behind the aircraft trim panels and in the overhead bins. The microphones face into the cabin through small holes and are sealed behind the trim to ensure the microphones measure the sound levels on the inboard side of the trim. It should be noted that these sensors are not mounted at passenger seated head height where the noise reduction is actually required. As such part of the design process is to determine the sensor locations such that when the controller minimises the signal power at these locations the noise is reduced effectively at passenger seated head height.

The actuators used on the Q400 are inertial shakers (Active Tuned Vibration Attenuators - ATVAs) mounted to brackets fitted to the aircraft fuselage. The use of ATVAs instead of loudspeakers has significant advantages for aircraft installations. Firstly there are significantly more potential locations to install ATVAs than loudspeakers. This results in a ‘finer resolution’ of potential actuator locations which allows better spatial matching of the actuators relative to the sound field within the aircraft, typically resulting in improved noise reduction from the final system. Secondly for a production system installing the ATVAs onto the fuselage is much simpler than installing loudspeakers through the trim. Thirdly ATVAs allow both noise and vibration control.

The ATVA consists of a magnetised mass mounted between two springs with an electrical coil driven by a signal from the controller. When current flows through the coil, the induced field causes the magnetised mass to move thereby exerting a force on the aircraft structure. The natural frequency of the mass-spring combination is selected to be at the primary frequency at which noise control is required in order to minimise power consumption. A diagramatic cross-section of an ATVA is shown as Figure 2.

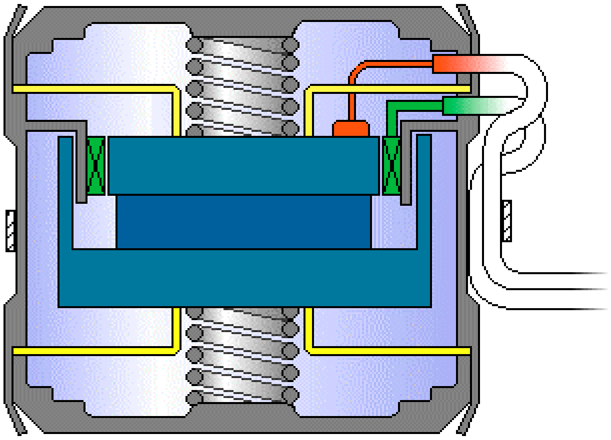

Figure 2 – Diagrammatic Cross-section of an ATVA.

The mass-spring combination has a sharp resonance (high Q) and some damping, in the form of feedback proportional to the relative velocity of the moving mass and the ATVA case, is introduced in order to spread out the resonance. This is required to ensure that the phase response of the ATVA varies slowly enough with frequency that the phase of the output force relative to the input voltage is predictable by the control element of the active noise system with sufficient accuracy to prevent system instability.

INITIAL AIRCRAFT ACOUSTIC MEASUREMENTS

The first phase of the design process is to determine the primary sound field within the aircraft and determine the secondary sound fields produced by ATVAs mounted at each of the potential actuator locations previously determined by a structural survey.

The process of measuring the primary sound field is relatively straightforward. The aircraft is instrumented with an array of microphones with two microphones mounted on foam headrests positioned at each seated head height location. A test flight is then performed at a series of standard flight conditions and measurements are taken at all microphone locations simultaneously. In order to identify the contribution of each engine to the overall sound field measurements are taken with the synchrophase system deactivated and the engines split in speed by approximately 5rpm. Two further test flights are required with identical flight conditions to identify variability between flight conditions and any anomalies with the data.

The secondary sound field data is obtained using an ATVA that is temporarily mounted at each of the potential actuator locations in turn. The transfer function between the ATVA drive signal and the response at the microphones within the aircraft (positioned at the exact same locations used during the test flights) is determined across the required frequency range. The measurements are performed on the ground with the aircraft pressurised to a level that provides the same pressure differential across the aircraft skin as experienced during typical cruise conditions. Transfer function data was measured at 1500 potential actuator locations.

ANALYSIS OF INITIAL ACOUSTIC DATA

The primary sound field data was analysed to determine the sound amplitude and phase at each microphone location for each of the eight frequencies at which control was to be performed. Similar analysis was also performed on the secondary sound field transfer function data.

Computational analysis was then used to identify the optimum set of actuators and optimum propeller synchrophase angle required to minimise the average sound pressure level at each seat throughout the aircraft across a broad range of flight conditions. This analysis was performed with constraints relating to the maximum allowed drive level from each actuator, the maximum allowed residual tonal level at each seat location, which flight conditions were most important, how easy it would be to install a particular actuator and how many actuators are allowed.

The results from this computational process determined that a set of 48 ATVAs would be sufficient to provide good tonal control on the aircraft. However, a superset of 96 ATVA locations was identified for installation on the aircraft for the next phase of testing. The reason for selecting 96 ATVAs was to allow sufficient redundancy to account for any changes in secondary sound field transfer function upon installation of the system and also to allow for the effect of the control sensor array being as yet undetermined.

SUPERSET INSTALLATION

The next phase required the installation of an active control system on the aircraft. A detailed structural survey was performed at the 96 ATVA superset locations to determine precise mounting details for the bracket onto which the ATVA is fitted. These locations are all at frame-stringer interfaces to ensure a rigid structure at the mounting point. A typical mounting method is shown in figure 3, in which the ATVA bracket is riveted both to one of the aircraft frames and to a gusset plate which is riveted to one of the stringers. The power amplifier that amplifies the signal from the controller to the ATVA is also mounted to the gusset plate at this location.

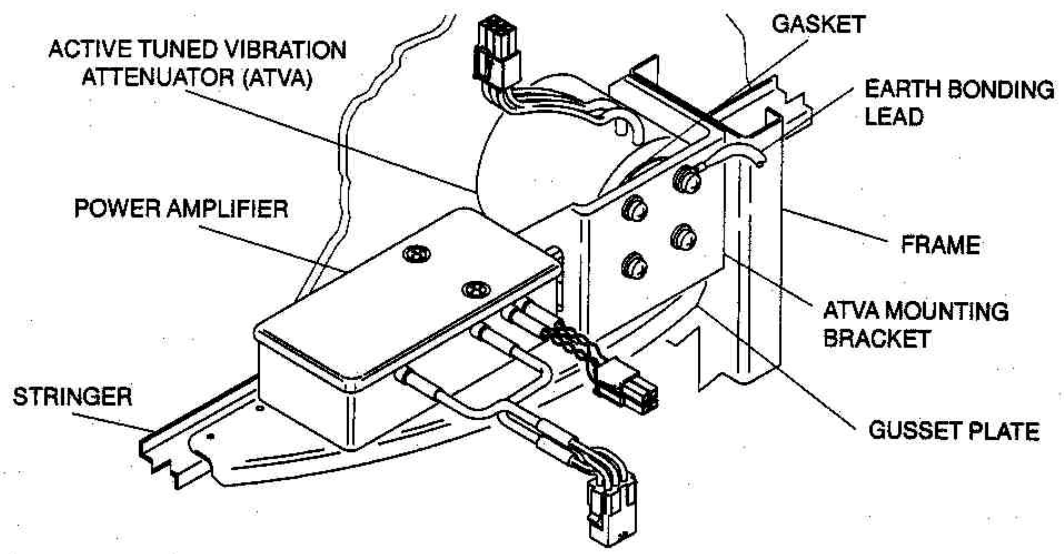

Figure 3 – ATVA mounting method

A survey of potential sensor locations was also conducted to determine locations where microphones or accelerometers could be installed. The locations where microphones were actually installed were chosen to give an even spread of microphones throughout the aircraft. Microphones were installed along the aircraft in seven rows and positioned at equi-spaced axial locations. These seven rows corresponded to just above window height on both sides of the aircraft, near the back of the overhead bins on both sides of aircraft, near the front of the overhead bins on both sides of aircraft and along the centreline of the aircraft ceiling panel. Accelerometers were positioned along the aircraft at equi-spaced locations down the seat-rails. In total approximately 150 microphones and 40 accelerometers were installed at ‘control’ locations.

The superset installation also required the installation of an Active Noise Control Unit (ANCU) and the associated wiring connecting the actuators, sensors, tachometer signals and pressure signal to the ANCU, along with power wiring for the power amplifiers.

SUPERSET INSTALLATION INITIAL ACOUSTIC MEASUREMENTS

The purpose of the initial acoustic measurements for the superset installation is identical to that performed during the initial testing. Namely, to determine the primary sound field within the aircraft and determine the secondary sound fields produced by the installed ATVAs.

The aircraft was instrumented in exactly the same way as for the initial measurements, with an array of microphones with two microphones positioned at each seated head height location. A test flight was then performed at the same flight conditions used during the initial testing and measurements taken at all microphones (both measurement and control locations) simultaneously. A further test flight was performed with identical flight conditions to identify variability between flight conditions and any anomalies with the data.

The transfer function between each ATVA drive signal and the response at all the microphones within the aircraft (positioned at the exact same locations used during the test flights) was determined across the required frequency range, with the aircraft on the ground and pressurised to a level that provides the same pressure differential across the aircraft skin as experienced during typical cruise conditions.

ANALYSIS OF SUPERSET ACOUSTIC DATA

The primary sound field data was analysed to determine the sound amplitude and phase at each microphone location for each of the eight frequencies at which noise control is required. Similar analysis was also performed on the secondary sound field transfer function data.

Computational analysis was then performed to identify the optimum set of actuators and control sensors, and the optimum propeller synchrophase angle required to minimise the average sound pressure level at each seat throughout the aircraft across a broad range of flight conditions. This analysis was performed using a model of the active control system to determine suitable control sensor locations and optimise the performance parameters used in the controller active noise algorithm. As in the preliminary analysis the calculations used constraints relating to the maximum allowed drive level from each actuator, the maximum allowed residual tonal level at a given seat location, which flight conditions were most important and how many actuators were allowed.

The results from the initial stages of this computational process were used to determine the number of ATVAs required to provide good tonal performance. Figure 4 shows the predicted A-weighted tonal reduction, normalised with the predicted reduction with 96 ATVAs, for a typical cruise condition.

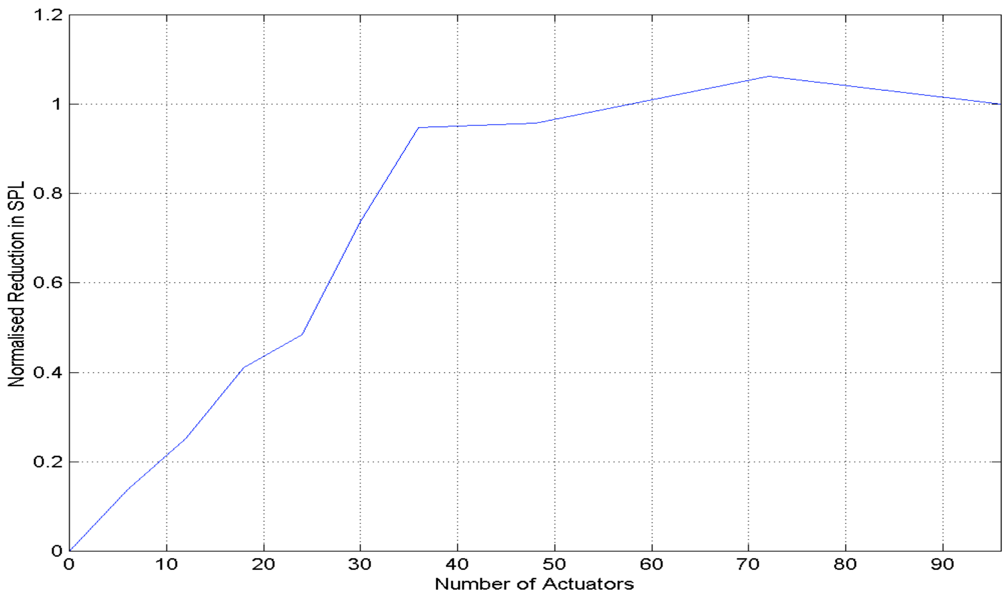

Figure 4 - Effect of Number of Actuators on Tonal Reduction at Seated Head Height.

As can be seen the tonal performance improves significantly with number of actuators up to approximately 36 ATVAs and flattens out above this number of actuators. The choice of the number of actuators to use in a production system is then a compromise between the robustness of the system across a variety of flight conditions (which increases with number of ATVAs) and the cost of installing more ATVAs. The data measured suggested a system size with between 40 and 48 ATVAs would be suitable.

CONTROL FLIGHTS

Once a suitable set of actuators and sensors had been identified from the calculations a flight was performed to confirm the measured system performance against the predicted performance. Spatial comparisons of the predicted and measured residual sound fields for typical cruise conditions show good agreement between the two sound fields. The cabin average measured and predicted residual SPL are within 0.2dBA for typical cruise conditions. Across all normal flight conditions the measured and predicted sound fields are within 1.0dBA.

The good agreement between the measured and predicted sound fields confirmed that the calculation process accurately predicted the performance of a given set of actuators and sensors. Three further test flights were performed in order to investigate the advantages of using different numbers of actuators and to refine the performance parameters within the active control algorithm. These test flights also confirmed the robustness of the system performance across a wide range of flight conditions.

Once a final system of actuators and sensors had been determined the unused actuators were removed from the aircraft and a further test flight was performed. This final flight confirmed that the unused ATVAs were not acting as passive TVAs and contributing to the system performance.

PRODUCTION SYSTEM

The active noise system defined by the above process resulted in a system comprising 42 ATVAs and 84 sensors, of which 80 are microphones. There are currently 53 Q400 aircraft in service throughout the world, all with the active noise system installed. The measured performance on these aircraft is in close agreement with the trial system. This large number of aircraft meeting the performance requirements has proven the design process is robust to the variability inherent within a production installation.

SUMMARY

Ultra Electronics, in collaboration with Bombardier Aerospace, have applied active control to the Q400 turbo-prop resulting in cabin noise at the same levels as seen in regional jets.

The design process has proved reliable with predicted system performance matching the measured performance extremely well. The performance of a trial system was within 1dB of that predicted by the optimisation process in normal flight conditions, and the 53 aircraft currently in service are in close agreement with the trial system. This large number of aircraft meeting the performance requirements has proven that the design process is robust to the variability inherent within a production installation.