Active Control of Aircraft Cabin Noise

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ABSTRACT

The noise levels in the passenger cabin of turbopropeller-driven aircraft are typically higher than the noise levels in comparable turbofan-powered aircraft. The sources of noise in a turboprop aircraft include boundary layer flow noise, structure-borne noise due to engine vibration, and acoustic excitation of the fuselage due to the propeller, with the latter being dominant for most turboprop aircraft. Possible noise reduction approaches encompass passive methods, such as structural modification, damping treatment, and active methods, which range from synchrophasing of the propellers to control of either the acoustic field or the structural vibration transmission path.

An active noise control approach discussed in this paper is designed to weaken the coupling between the exterior and interior acoustics of turboprop aircraft. In this approach, the transmission of sound is impaired before it enters the cabin, which is superior to treating the problem further down the transmission path. Piezoceramic elements were used for structural actuation and vibration and/or acoustic sensing was employed. Full-scale testing was performed to evaluate the performance of the active noise control system. Significant reductions in noise level of up to 28 dB were achieved. Moreover the reduction in noise was global, leading to lower noise throughout the cabin. The results of this investigation demonstrate that Active Structural Acoustic Control Systems are capable of providing significant noise reduction and vibration suppression of aircraft to improve the habitability of the cabin.

1.0 INTRODUCTION

Cabin noise in turbo-propeller driver aircraft can cause crew and passenger discomfort. The noise level in the interior of turbopropeller-driven aircraft, which results mainly from the excitation of the fuselage by the unsteady aerodynamic pressure field of the propellers, is typically higher than the noise level in comparable turbofan-powered aircraft. Since the interior noise spectrum is dominated by tones occurring at integral multiples of the blade passage frequency (BPF), [1] the reduction of interior noise and fuselage vibrations at these discrete frequencies provides a significant improvement. Possible noise reduction approaches encompass passive methods, such as structural modification [2], damping treatment [3-5], and active methods which range from synchrophasing of the propellers to control of either the acoustic field [6-8] or the structural (vibration) transmission path [9,10].

Passive techniques of noise and vibration reduction for this class of problem are generally not effective for a number of reasons. Since the excitation is usually neither broadband nor resonant, the addition of damping

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material does not have a major effect on noise and vibration levels. Moreover, sound absorption materials, for which the thickness must be at least comparable to the wavelength of the sound [11], are ineffective at the low frequencies where propeller noise is significant (approximately 50 to 300 Hz). Structural damping enhancements such as constrained layer damping are also of limited use at low frequencies. Tuned Vibration Absorbers (TVA), which are located on fuselage frames and designed with a resonant frequency equal to that of the BPF, thereby reducing the fuselage vibration and noise transmission, have also been considered for aircraft application [12]. When subjected to a stationary harmonic disturbance, TVAs that are tuned accurately can be effective, but the variations in engine speed greatly limits their performance due to the required trade-off between bandwidth and peak achievable attenuation.

Active Noise Control (ANC) of the aircraft cabin through the use of secondary acoustic sources has also been demonstrated [13,14]. Such systems incorporate a large number of trim-mounted speakers along with microphones and/or accelerometers to achieve noise reduction through destructive interference between the primary (disturbance) sources and the secondary (control) sources.

An alternative approach to active noise control of turboprop aircraft discussed in this paper is to weaken the coupling between the exterior and interior acoustics. In this approach the transmission of sound is impaired before it enters the cabin. This is consistent with the well accepted rule that treating noise at or close to its source yields superior performance to treating the problem further down the transmission path. This approach of Active Structural Acoustic Control (ASAC) involves the use of structural actuators, such as piezoelectric devices, and acoustic or structural sensors to accomplish noise attenuation. There is considerable interest in the ASAC approach because of the reduction in the number of secondary (control) sources and the complexity of the control architecture required to achieve a global reduction in noise level in comparison to the ANC approach [15,16]. The resulting system is generally simpler with fewer actuator and sensors since they are required only in the propeller footprint area [11,12]. The approach followed in this investigation involves the control of local structural vibration to achieve a reduction of sound transmission. Piezoelectric actuators were mounted on the fuselage to control the propeller induced vibrations. Both feedback and feedforward control approaches were used to reduce the interior noise to improve the habitable environment of an aircraft cabin.

2.0 TEST ARTICLE

The test article was a full-scale de Havilland Dash-8 Series 100/200 fuselage without horizontal lifting surfaces, as shown in Fig. 1. The floor was fitted in the interior, which was devoid of any trim or seats. The cargo and pilot's cabin bulkheads were present. The fuselage rested on a cradle fitted trailer except during testing when an overhead crane raised the fuselage using steel cables which were attached to the fuselage at the wing-fuselage interface. This arrangement was deemed to subject the fuselage to support conditions that resemble steady level flight. The fuselage was tested in a high bay at ambient atmospheric pressure and temperature.

3.0 PROPELLER PRESSURE FIELD

The exterior propeller pressure field at the surface of the fuselage has been simulated numerically for the Series 100 aircraft by the propeller manufacturer, Hamilton Standard. The data were available for the BPF and twice the BPF at two engine speeds, 910 rpm and 1050 rpm, and included the effects of both propellers. These data were computed in the form of sound pressure level (SPL) magnitude and relative phase for a 3.5m wide band around the fuselage. The magnitude of the pressure field for a propeller speed of 910 rpm at the BPF is shown in Fig. 2**.** The objective of the present project was not to recreate the entire propeller field, but rather to represent the phase and magnitude characteristics over the key region close to the propeller plane.

The port side pressure field was considerably more intense than the starboard side field. At the BPF, the peak port side exterior (SPL) was approximately 5 dB higher than the peak starboard SPL. Moreover, the peak starboard pressure was located close to the floor of aircraft, a relatively stiff part of the fuselage, which is believed to result in the starboard side noise transmission being considerably lower than the port side noise transmission.

4.0 NOISE SOURCE

The port side exterior propeller pressure field was simulated using the sound field generated by a bank of four loudspeaker units. Each unit had two sections, a sealed plywood enclosure which formed the speaker box and a horn section which positioned the speakers at a distance of 60 cm from the mouth of the unit. Although the sides of the horn section were parallel, four tapered acoustic foam pieces produced a diverging section which increased from the speaker to the mouth. The four speaker units were connected together to form a circumferential speaker-ring which covered an arc of approximately 100° on the fuselage. The speaker-ring, which can be seen in Fig. 1, was maintained at distance of approximately 25 mm from the fuselage surface to allow for the blending of the sound from the individual speaker elements to provide a uniform sound field across the mouths of the wave-guides.

Because of the blending of sound fields from each speaker, it was not possible to directly use the desired magnitude and phase at the regions of the fuselage located adjacent to the four speakers as the magnitudes and phases of the waveforms supplied to each speaker. The approach employed here was to determine the transfer function matrix between the relative magnitudes and phases of the four speaker inputs, and the resulting magnitudes and phases of the sound field at a number of distinct locations. Using this approach, the desired and achieved relative magnitude and phase of the propeller field at fuselage exterior were found to be in good agreement. The details of the noise generation system are discussed in greater detail in reference 17.

Only the port side exterior sound pressure field was simulated using the speaker-ring unit. However, the present speaker-ring can be extended to provide a more complete simulation of the propeller field if required for further investigations.

5.0 ACTUATOR AND SENSOR DESIGN

At the relatively low frequencies of interest, up to 140 Hz, and due to the relatively large regions of high acoustic pressure on the fuselage exterior, the dominant vibrational modes will be of relatively low order. Furthermore, in most aircraft propeller noise problems, it is the low order, volumetric structural modes that are responsible for much of the noise transmission. Therefore, by designing sensors and actuators that are tailored to effectively detect and control these modes, good vibration and noise reduction performance should result.

5.1 Actuator Choice

The use of piezoelectric elements as structural actuators has a number of benefits due to their high bandwidth, low weight and distributed actuation property. The latter property is of particular interest because of the possibility of selectively imparting control authority over those structural modes that interact strongly with the acoustics of the aircraft interior. The spatially distributed nature of the resulting applied forces provides a system with high authority over structural modes which couple well with the cabin acoustics but reduces the effect on high wave-number modes which are not important for sound radiation. Thus, the energy employed in control is expended efficiently, insofar as sound transmission attenuation is concerned. The disadvantage of piezoelectric materials is their high voltage requirement. However, the required voltage can be reduced considerably by constructing a stack of thinner piezoelectric elements.

5.2 Actuator Placement

The spatially distributed nature of the propeller noise field impinging on the fuselage contributes significantly to its structural response. A force distribution which has uniform phase and magnitude over a particular region, typically excites modes that are half-waves in the axial and circumferential directions which approximately match (geometrically) the pressure distribution. However, for pressure distributions with spatially varying phase and magnitude, this relationship is much more complex. Nevertheless, the spatial extent of the pressure plays a major role in determining the dominant modes which are excited. In an analogous fashion, the spatial extent of the piezoelectric elements also determines which modes can be controlled by the actuator. Therefore, the coverage of the piezoceramic actuator elements should encompass the region of high propeller pressure but need not extend beyond this region.

The vibration patterns or operating deflection shapes of the fuselage were used to determine the specific elements to be included in the actuators which then defined the circumferential limits of each actuator. The deflection shapes produced by the sound field were determined experimentally at a single axial location [18]. The deflection shape corresponding to the BPF at 910 rpm (61 Hz) is shown in Fig. 3. The agreement between this deflection shape and that measured in-flight was excellent.

5.3 Actuator Design

The one-sided or asymmetric actuation of a structure such as an aircraft fuselage by bonded piezo-ceramics will produce both flexural and in-plane vibration. For the case of noise transmission into an aircraft cabin, flexural vibrations are of greater significance due to their ability to couple with acoustic waves. For flexural vibration, the predominant actuation mechanism due to a uniform rectangular piezoelectric actuator is the presence of bending moments at its ends. This is true of both monolithic and segmented piezoelectric actuators. With this in mind, an actuator should be positioned such that its ends coincide with regions of high (and opposite) angular rotation in order to have high control authority over that particular mode or deflection pattern. If the ends are located in regions of high displacement (and hence low rotation) or if the rotations at the ends are nearly equal both in magnitude and direction, low control authority over that mode or deflection shape results. Based on this approach, the control authority over a mode can also be enhanced by appropriately reversing the electrical field of elements over regions of opposite modal displacement. These concepts are illustrated in Fig. 4.

A piezoelectric actuator is capable of inducing more strain into the host structure if the extensional stiffness of the actuator is large. The problem of controlling aircraft fuselage vibration in comparison to other piezoelectric control applications is challenging due to both the high vibration levels present and the relatively high stiffness of the fuselage. The piezoceramic actuator chosen for this application, which had a high stiffness and a thick cross-section, was therefore suited for this particular problem. However, since the total added mass is also important, actuator dimensions should be chosen no larger than needed. This implies that the piezoelectric actuators should be stiffness matched to the structure to which they are bonded, in order to achieve the most effective actuator for minimum mass.

In the present work, 199 Type I d_{31}-mode ceramic piezoelectric elements each measuring 25 mm by 25 mm by 6 mm were bonded to the fuselage although the number of actuators could easily be changed by altering the connecting wiring. The dimensions of the individual actuator elements were chosen to minimize the bond line thickness, and therefore the loss of actuator effectiveness, due to the attachment of the flat piezos to the curved fuselage. Based on the above methodology and the measured deflection pattern at 61 Hz, three piezo actuators were designed by connecting all the elements located between points A and C in Fig. 3 in parallel.

5.4 Actuator Installation

The actuators were bonded to the fuselage using a conductive epoxy, Bipax BA-2902, manufactured by Tra-Con Inc. This allowed the fuselage itself to be used as a common ground plane for all actuators, and avoided the difficulty of making an electrical connection to the lower actuator surface without interfering with the bond. Since high strains were desired, and the piezoelectric actuators used were relatively thick, high voltage levels were required. A Trek HV Model 50/750 amplifier capable of producing 1500 V in uni-polar operation was used. It should be emphasized that in an actual application, such a large voltage requirement would not be necessary, since there are possible modifications to the actuator design which would reduce the necessary voltage.

5.5 Sensor Selection

The output of a sensor must be well correlated to the performance variable, which in this case was the interior sound level. The minimization of this sensed variable must ensure that noise transmission was also being minimized. Moreover, the sensor must also be spatially distributed in order to be insensitive to high wave-number vibrations, while being responsive to the acoustically critical low wave-number vibrations. For these experiments, discrete structural sensors distributed over the length of the actuator were used. Signals from each sensor were averaged to provide a single equivalent sensed variable. A judicious choice of sensors can simplify the control design procedure, which requires a transfer function model between actuator and sensor. By sensing fuselage strains that are approximately collocated with the actuators, the transfer function between actuator and sensor became relatively simple, due to the duality of the pair.

5.6 Sensor Design

Since the goal of this work was to correlate the radial structural deformation with transmitted noise into the cabin, the primary sensors used was an accelerometer. Accelerometers were attached at various locations in the actuator plane on the fuselage. Since the internal noise was transmitted principally by radial vibrations, the accelerometer measured a quantity in some sense closer to the desired performance metric (internal noise) than the strain gauges. Unfortunately, the transfer function between the actuator and accelerometer sensor became more complicated. However, measurements taken in this experiment indicated that this may not be a significant problem.

The noise attenuation performance of the control system was monitored by microphones placed at multiple locations inside the cabin, that were representative of the areas of highest internal noise and the likely location of passengers.

6.0 CONTROL STRATEGIES

Both feedback and feedforward control approaches are currently being used in various active vibration and noise control applications [13-16]. In the present program, adaptive feedforward strategies were developed and implemented based on the filtered-x LMS algorithm, which incorporated off-line identification of the secondary path between actuator and error sensor. For the present investigation, a second order feedback compensator was also implemented for the control loop. The objective was to design a control system to demonstrate that segmented piezo actuators and structural velocity feedback can be used to significantly attenuate structural vibration and interior noise in turboprop aircraft simultaneously.

7.0 EXPERIMENTAL RESULTS

The closed loop performance of the system was verified by subjecting the port side of the aircraft to simulated propeller noise using the speaker-ring system described earlier. The first case explored was control at 61 Hz (910 rpm, BPF) using accelerometer feedback to control the three actuators discussed earlier. Four accelerometers were placed over the region of high open loop vibration at each of the three axial locations where piezoelectric actuators were bonded. Averages of each set of four measurements were used as the sensed quantities for both feedback and feedforward control approaches. The feedback control system was designed with peak loop gains of between 25 and 30 dB, gain margins of between 8 and 15 dB, and phase margins of between 14º and 50º, for the diagonal elements of the transfer function matrix. The feedforward approach used filtered-x LMS adaptive control. An IIR filter with 15 forward and 14 recursive filter coefficients was used to model the secondary path using a band limited random signal between 55 and 75 Hz for off-line LMS system identification of the plant. The control filter was chosen to be a FIR filter with 15 coefficients.

The reductions in the vibration levels for the twelve accelerometer locations as well as for the 3 average acceleration values are given in Table 1. It can be seen from the vibration attenuation data that the feedback and feedforward cases yielded similar results, both in individual sensor and averaged data. There were specific differences between individual results although the trends were similar. The peak reduction in vibration in both cases occurred at the same accelerometer position. For the feedforward control case, spectra for the control-on and control-off data for accelerometer 3 are shown in Fig. 5.

In order to monitor the noise reduction performance, microphones were positioned at the seated head height for the two port side seats and at standing height for the aisle center for seat rows 1, 2 and 3. The noise attenuation data using the ASCS system implemented with both feedback and feedforward control algorithms defined above for vibration error sensing, are presented in Table 2, together with the results for microphone error sensing which will be discussed later. The control-on and control-off noise level spectra at the aisle seat in row 1 for the vibration error sensing feedforward case are presented in Fig. 6.

The resulting attenuation in the interior noise levels was also significant. The peak reduction, which was almost 28 dB, occurred at the aisle seat in row 3. The reductions in row 2, which was close to the plane of the propeller, were 11 dB for both the aisle and row seats. Only one location, corresponding to the window seat at row 1, exhibited a very small increase in noise level. This location had exhibited the lowest open loop sound pressure, and therefore the slight increase was of little significance. The reductions in both the noise and vibration levels were essentially global with significant reduction in the noisiest cabin areas.

The noise control performance for the feedback and feedforward cases of active control with vibration sensing were not identical in results, since the peak reduction in each case occured at different locations. These differences can be attributable to a number of factors, the most significant of which was probably the fact that although the sensor and actuator arrangements were identical in both cases, the control design approaches were completely different. For the feedback approach there were significant differences in peak gains for the three loop transfer functions considered. In contrast, for feedforward control, the only user specified parameters for the system identification and control processes were the convergence coefficients, which were chosen to be the same for all channels. The results also highlighted the highly sensitive dependence of noise reduction performance on vibration reduction; the differences in residual vibration in both cases were small compared to the differences in residual noise levels. This is consistent with fact that the vibrational modes that were responsible for much of the noise transmission may not be those that dominated the vibration field. Therefore, two seemingly similar vibrational fields may actually have produce substantially different interior noise fields.

When noise reduction was chosen as the performance metric or criterion, the results obtained using microphone error sensing were generally superior to those for vibration sensing. The control at 61 Hz was explored with the identical actuator design, but using the three microphones in seat row 2 as the error sensors. The noise reduction obtained using microphone error sensing were superior to those for vibration sensing. The results, which are given in the last column of Table 2, demonstrated the superiority in this noise reduction performance when compared to vibration sensing results. The arithmetic average of the reductions at all microphone locations was over 2 dB higher than the average when accelerometer error sensing was employed. The reductions were also global in nature.

Noise reduction for other flight conditions was also achieved successfully applying the actuator design approach described earlier and using vibration sensing. The operating deflection shape (ODS) for deformation of the fuselage at twice the BPF at 910 rpm (121 Hz) which had a greater number of nodes than the previous case of the 61 Hz ODS, is shown in Fig. 7. For this case, two actuators were implemented at each axial location to accommodate the higher mode shape. The piezoelectric elements between points A and B as shown in Fig. 3 at all three axial locations were grouped together to form one actuator, while the elements between points B and D at all three axial locations formed a second actuator. The lack of piezoelectric coverage precluded the coverage from extending to point C, the point of higher slope. Had this been possible, one would expect even higher controllability over the vibration field. Six accelerometers between points A and B (2 per axial location) were averaged to form two effective error sensors, while another six between B and D (also 2 per axial location) were averaged to form another pair of sensors. Using the feedforward control algorithm described previously, the achieved vibration and noise reduction was again significant. The vibration reduction data are given in Table 3, while the noise reduction results are presented in Table 4. The vibration and, in particular, the noise reduction performance was slightly reduced compared to the performance for vibration sensing and there were a few microphone locations that exhibited slight increases in noise levels. Nevertheless there were significant reductions in the key locations of high noise as well as a general global noise reduction in the cabin.

8.0 CONCLUSIONS

The use of an Active Structural Acoustic Control (ASAC) system was successfully applied to reduce interior noise and vibration in a full-scale aircraft fuselage to improve the habitable environment. This was achieved using a control system that incorporated segmented piezoelectric actuators bonded to the fuselage and either acoustic or vibration error sensing. The results of this investigation suggest that through judicious actuator and sensor design, ASAC systems using bonded piezoelectric actuators and vibration or acoustic error sensors are capable of simultaneously providing significant propeller noise reduction and vibration suppression in the passenger cabin of a turboprop aircraft. The reduction in the passenger cabin noise was significant with the peak measured attenuation over 28dB. The attenuation observed was essentially global through out the cabin. Moreover, an optimized system has been shown to provide a significant reduction of other modes that may be present. Most importantly, such an active system can be adaptively modified in-situ to address changes resulting from operating conditions to provide a time varying optimized system of vibration and noise control to improve the habitability of the aircraft cabin.

9.0 ACKNOWLEDGEMENT

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Table 1 Vibration attenuation at 61 Hz, vibration sensing

Accelerometer	Vibration Attenuation (dB)	
	Feedback Control	Feedforward Control
1	7	8
2	9	13
3	16	21
4	4	4
5	0	5
6	10	16
7	9	14
8	6	7
9	2	5
10	11	18
11	16	19
12	8	11

Table 2 Interior sound attenuation at 61 Hz, acoustic sensing

Microphone Location	Noise Attenuation (dB)		
	Fdback, vibration sensing	Fdforward vibration sensing	Fdforward noise sensing
Row 1, window seat	-3	2	1
Row 1, aisle seat	9	24	9
Row 1, standing aisle	2	6	19
Row 2, window seat	11	10	11
Row 2, aisle seat	11	9	18
Row 2, standing aisle	4	7	20
Row 3, window seat	6	14	7
Row 3, aisle seat	28	10	13
Row 3, standing aisle	5	6	13
Average	8.1	9.8	12.3

Table 3 Vibration attenuation at 121 Hz, vibration sensing

Accelerometer	Vibration Attenuation (dB)
1	5
2	23
3	-1.5
4	10
5	14
6	13
7	14
8	9
9	13
10	10
11	4
12	4

Table 4 Interior noise reduction at 121 Hz, acoustic sensing

Microphone Location	Noise Attenuation (dB)
Row 1, window seat	5
Row 1, aisle seat	4
Row 1, standing aisle	-2
Row 2, window seat	13
Row 2, aisle seat	-0.5
Row 2, standing aisle	-1.4
Row 3, window seat	7
Row 3, aisle seat	2
Row 3, standing aisle	0.3
Average	3.0

Fig. 1 The de Havilland Dash-8 S-100/200 aircraft

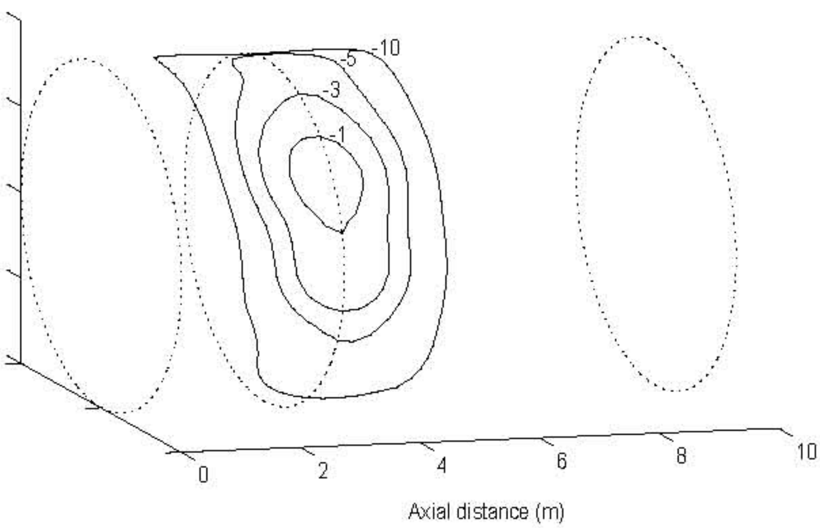

Fig. 2 Port-side propeller pressure distribution

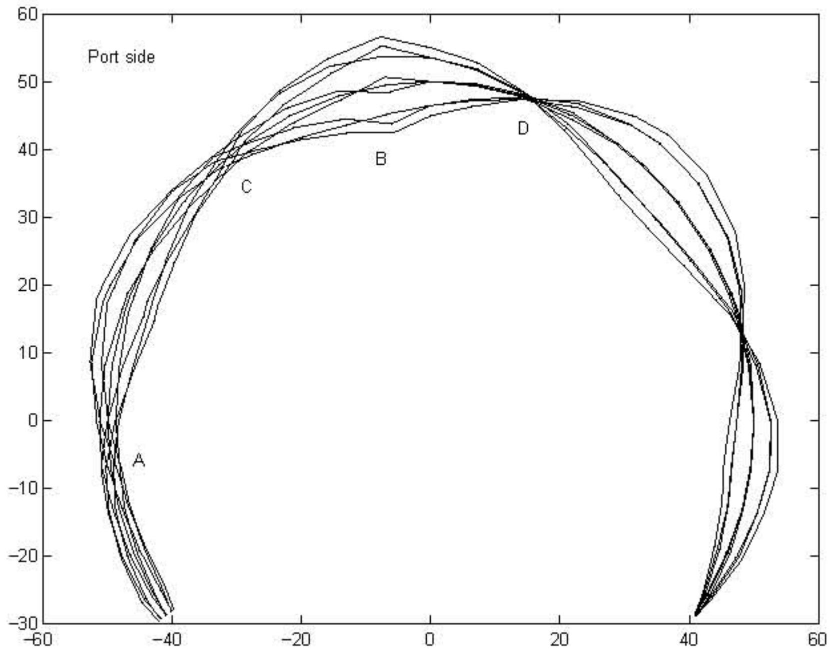

Fig. 3 Measured operating deflection shape due to simulated propeller noise, BPF, 910 rpm (61 Hz)

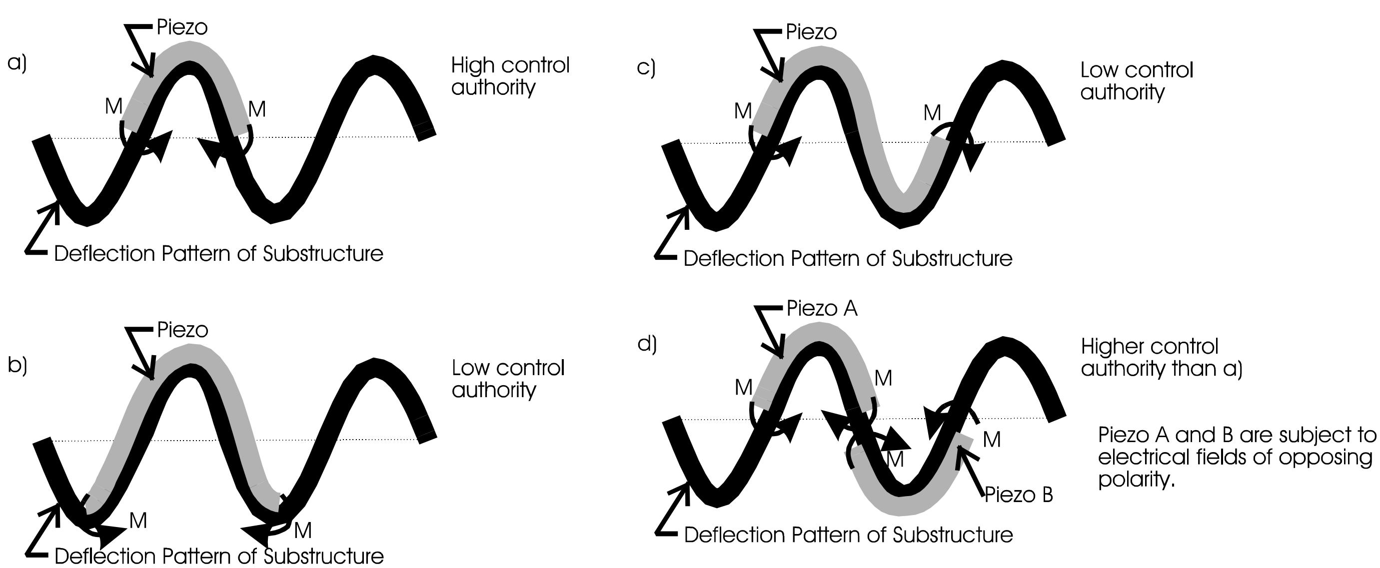

Fig. 4 The effect of actuator positioning on modal control authority

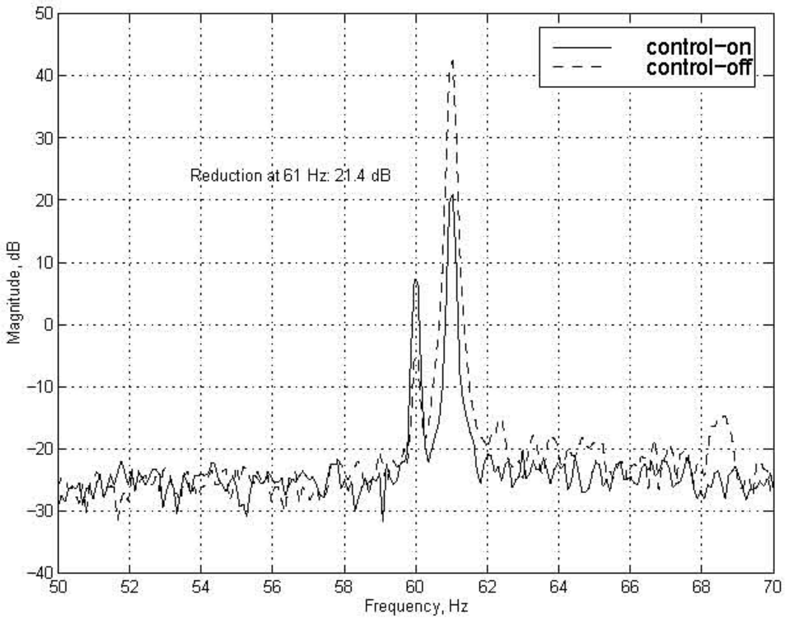

Fig. 5 Acceleration spectra for accelerometer 3, feedforward control, vibration sensing, 61 Hz

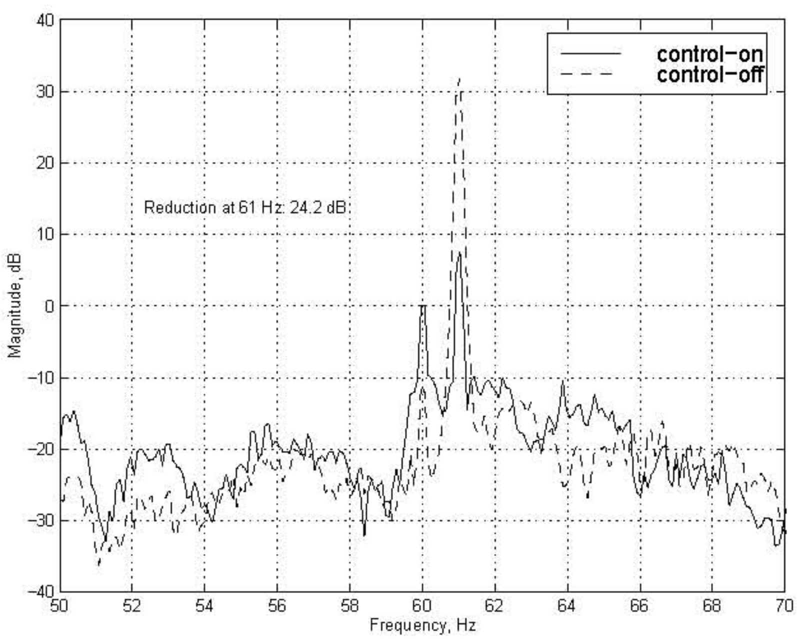

Fig. 6 Sound level spectra for row 1 aisle seat, feedforward control, vibration sensing, 61 Hz

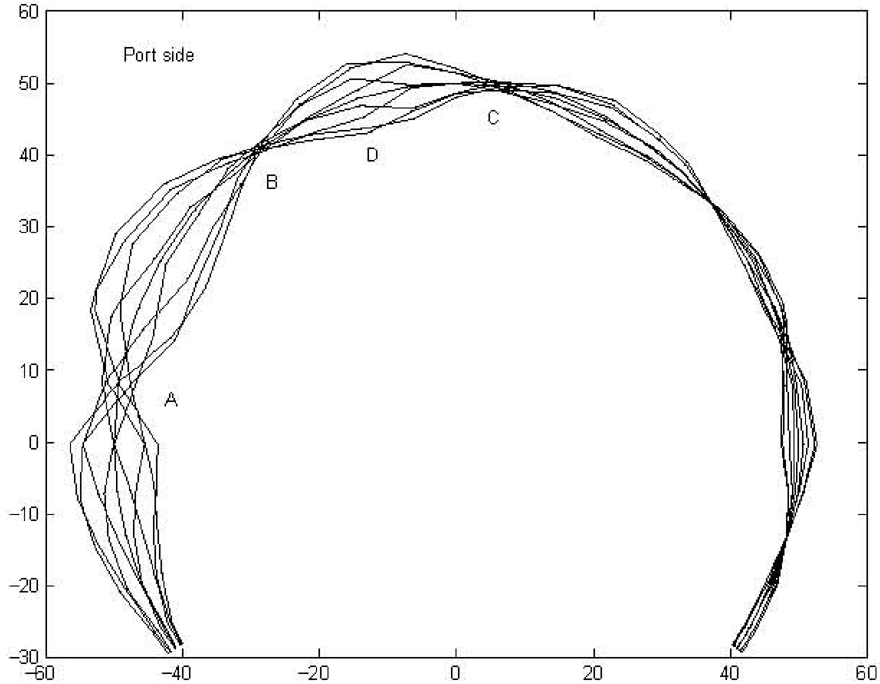

Fig. 7 Measured operating deflection shape due to simulated propeller noise, 2×BPF, 910 rpm (121 Hz)

Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P20 D.G. Zimcik 'Active Control of Aircraft Cabin Noise', (NRC, CA)

With this third presentation devoted to the reduction of the noise and vibration levels of turbo-propeller-driven aircrafts (see also paper 11), the author concludes on the significant noise reduction (global attenuation of 28dB) thanks to active structural acoustic control (ASACS) systems weakening the coupling between the exterior and interior acoustics.

Discussor's name: K. Kowalczyk
Q. Could you please put some comment on sensor placement? How do you optimize the position?
R. Sensor placement was established based on measured Operational Deformation Shapes (ODS) of the fuselage and acoustic survey of the cabin. Based on these test data, sensor locations were chosen to provide high signal to noise measurement of the parameters (displacement or noise) to be measured.

Discussor's name: S.J. Van Wijngaarden
Q. Can you inform us about the cost (for instance, in terms of weight or power consumption) of using an ASCS System to suppress noise?
R. This proof-of-concept demonstration was not directed forward establishing a production system. Selection of actuator design and placement will be critical for establishing an optimized operational design. Developments in switch-mode amplifiers have shown promise of reducing power requirements significantly, as well as component size of the amplifiers. Finally use of dedicated electronics (such as ASCS) to implement the control algorithm will result in small electronic packaging. However, each system will be a unique design for the specific application.