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ACTIVE CONTROL OF CABIN NOISE-LESSONS LEARNED?

by

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ABSTRACT

The evolution of active systems applied to the reduction of aircraft cabin noise is studied. The main objective is to establish whether there are any significant lessons relative to the general use and commercialization of active noise and vibration systems.

INTRODUCTION

This paper overviews the development of active control systems designed to reduce the cabin noise in aircraft. The main purpose is to assess whether any general lessons about the application, development and commercialization of active system are apparent. If so these could be applicable to the development of future active control applications. The paper is not intended to be totally comprehensive, the examples included are chosen in order to illustrate certain points.

EARLY WORK

Perhaps the earliest demonstration of the possibility of active noise control (ANC) in propeller aircraft was work of Johnston *et al* who studied the use of synchrophasing to reduce cabin noise in a Lockheed P-3C propeller aircraft [1]. Synchrophasing is a technique in which the relative phase(s) of the propellers are adjusted in order to reduce the cabin noise. It can be seen to be related to ANC in that one propeller can be considered as the disturbance and the other propeller(s) considered as the active source whose phase is varied. Figure 1 shows the predicted interior sound levels at a number of positions for the best and worst synchrophase angles. It is apparent that for the optimal synchrophase angle, significant global sound reductions are achieved. The results thus demonstrate the possibility of using ANC to reduce interior noise. The amount of reduction is mainly limited however, by the fact that the interior field due to opposite propellers is not symmetric and of the same interior sound level.

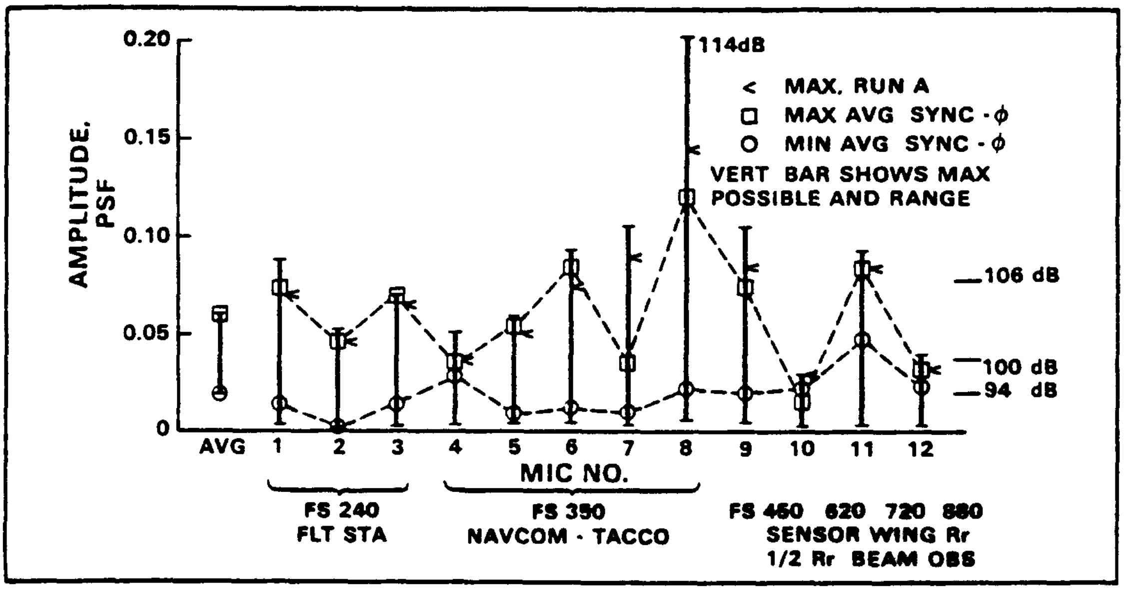

Figure 1. Predicted reduction of interior noise for various synchrophase angles (from Ref. 1)

Zalas and Tichy investigated the use of an electronic ANC system for reducing cabin noise [2]. In this case the active source is electronically generated from a signal that is coherent with the interior noise. They used a single channel feedforward LMS controller to cancel sound at a single microphone using a single active speaker. In flight tests on a Gulfstream Commander, Zalas and Tichy demonstrated reductions of 10 dB of the first six propeller tones are possible in realistic flight conditions. The best reference sensor location for the feedforward controller was found to be an exterior microphone in the propeller plane. The attenuation was limited to a small volume around the error sensor. Zalas and Tichy suggested that the volume of reduction could be increased by using multiple active speakers and error sensors.

ACTIVE NOISE CONTROL

In order to extend the ANC system to multiple active speakers, it was necessary to develop the appropriate control paradigm. Elliott *et al* [3] extended the feedforward Filtered-x approach to multiple input-multiple output and derived theory for the optimal convergence parameter. This control approach was then used by Elliott *et al* [4] and Dorling *et al* [5] to demonstrate, in a flight test of a BAe 748, global control (i.e. through an extended volume) of interior noise. The system of Ross, for example, used 24 active speakers and 72 error sensors and gave reductions of the order of 10 dB as shown in Table 1. Dorling and his co-workers also measured the transfer functions between the control sources and the error sensors and used this in conjunction with a measurement of the noise field at the error sensors to predict the ANC performance. The predicted attenuations are also given in Table 1 and good agreement is apparent. Thus these two projects demonstrated a number of important achievements, (1) a controller with many control transducers is feasible, (2) global control of the interior noise in real aircraft applications is possible, (3) performance decreases with frequency or complexity of the interior field and (4) analytical models or measurements can be used to predict and thus optimize the control system arrangement and performance.

Table 1. Averaged interior sound level reductions (from Ref. 5).

Frequency (Hz)	Reductions (dB) Predicted	Reductions (dB) Measured
88	9.1	8.3
176	14.5	13.2
264	13.2	11.5

Lester and Fuller [6] developed an analytical model of ANC in a propeller aircraft based upon an infinite cylinder analysis . The basic assumption is that vibrations and interior noise decay quickly away from the propeller plane due to interior acoustic and fuselage damping. Their model predicted that the sound transmission occurred primarily in the propeller plane and was controlled by low order circumferential modal response (in contrast to panel transmission models). Thus the best location for the ANC sources are in the propeller plane and arranged circumferentially. The number of required sources was predicted to be at least twice the order of the dominant highest order circumferential mode. Figure 2 shows the arrangement of the ANC sources used by Elliott *et al* [3] in the propeller plane and it is apparent that of the total 16 active sources, most are in the propeller plane and arranged in a circumferential pattern. Other work on interior fields which use a full modal type model tend to indicate that the active sources should be distributed more evenly throughout the interior space (since the response does not decay axially). Thus the above works demonstrate the importance of capturing the major physics of the problem when modeling it.

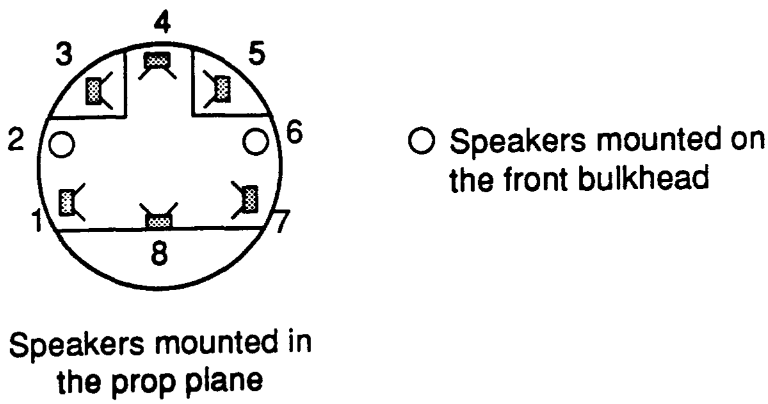

Figure 2. Locations of active speakers in the propeller plane of flight tests of Elliott *et al* (from Ref. 3)

More recently Ross [7] and Emborg [8] have developed the first commercially available ANC system for aircraft interior noise reduction in a SAAB 340 and 2000. Figure 3 shows the attenuations achieved for an increasing number of control sources. It is apparent that the reduction increases with the number of sources and reaches a plateau at around 20 active sources. However, in the commercial system reported by Ross [9] significantly more

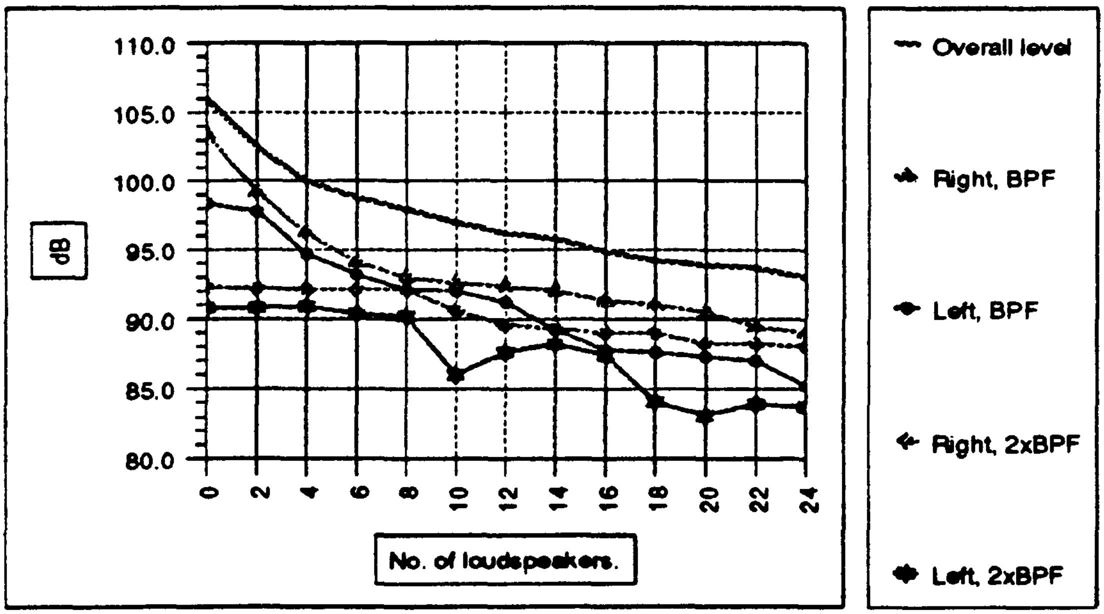

Figure 3. Average cabin SPL versus number of active speakers (from Ref. 8)

active sources are used. This is due to a number of reasons, primarily, (1) the sources have to be compact enough to fit behind the trim and thus, in order to achieve the required control volume velocity, it is necessary to have an increased number of (smaller) sources, (2) due to limitations imposed by the arrangement of the present trim the active sources have to be in non-optimal locations and thus more of them are needed and (3) the ANC system performance is more robust to a failure of a transducer. Nevertheless, impressive performance of around 6-8 dB at the fundamental and first harmonic is typically achieved as shown in Table 2. Many of these ANC systems marketed by Ultra Electronics are in use around the world today.

Table 2. Active control in a Dash - 8 (from Ref. 7).

	Noise Reduction (dB)			
	1 BPF	2 BPF	3 BPF	4 BPF
ASAC	10.5	7.6	4.4	3.0
ANC	8.0	6.6	3.6	0.4

An interesting outcome of the use of an ANC system is that it will tend to predominantly cancel the sound from the dominant engine. The residual field will then be composed of relatively equal levels from each engine, thus making synchrophasing an attractive technique for further sound reduction. Pla *et al* have studied the use of an active syncrophasor to reduce interior noise in a flight test on a OV-10 propeller aircraft [8]. The system arrangement is shown in Figure 4 while typical performance results are given in Figure 5. The results show high attenuation of sound in the cabin and confirm the potential of synchrophasing. Thus it is interesting that the use of one technique (ANC) increases the potential of another (synchrophasing) implying that active systems may ultimately be a hybrid of different techniques.

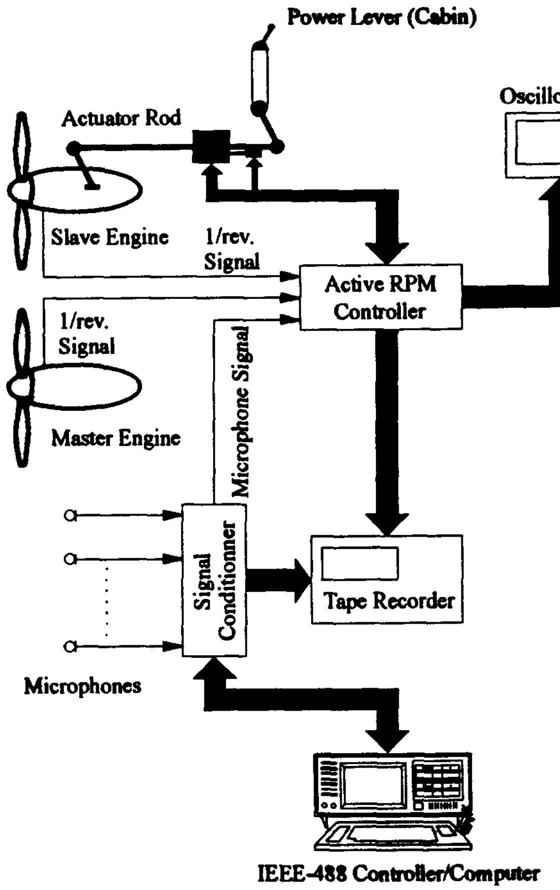

Figure 4. Experimental setup used by Pla *et al* in synchrophasing tests (from Ref. 8)

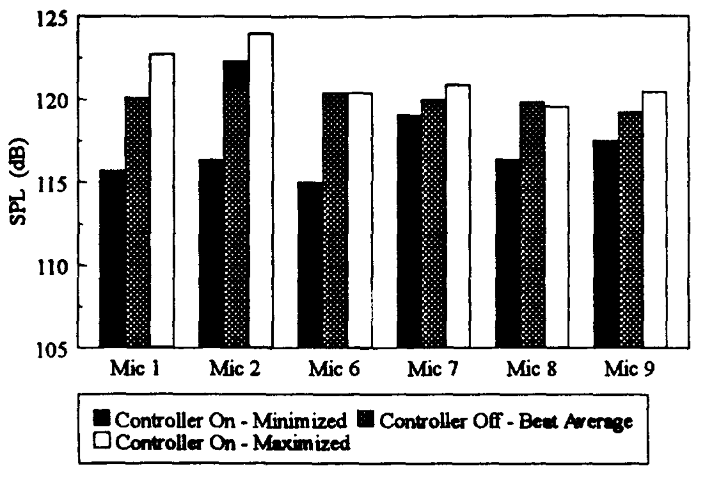

Figure 5. Cabin SPL corresponding to the arrangement of Fig.4 (from Ref. 8)

All of the ANC approaches discussed above employ a feedforward control approach. The intent in these approaches is to create a spatial and temporal match of the noise field throughout the cabin, thus creating global reduction. This usually requires a coherent reference signal and a fully coupled MIMO controller making the system sensitive to causality and lack of spatial coherence. In a different approach, Carme [10] has developed the ANCAS seat, which uses individual active speakers and microphones located in the seat headrest in conjunction with a feedback control approach. The system provides a zone of quiet around the passengers' head. This system thus requires at least two speakers for each seat and does not provide reduction throughout the cabin, but does eliminate the need for a wiring harness and the DSP that the feedforward systems use. In addition, the feedback approach enables reduction of random broadband noise due to the exterior boundary layer. Thus there are different viable approaches to the solution of the problem depending upon the nature (spatial and temporal) of the noise to be canceled. Choice of a suitable system is based upon a number of factors apart from solely performance; cost and weight perhaps being the most significant.

There has also been commercial ANC systems developed for high end general aviation aircraft such as the Beech King Air [13]. One of the largest challenges in such a system is to achieve a significant *perceptible* reduction in noise. Since the propeller fundamental is very low, a large attenuation in overall SPL is often achieved, while A-weighted SPL does not change as significantly. The result is a reduced passenger perception of the control effect. The solution to this problem is to use frequency weighted error signals or band-limited control.

ACTIVE STRUCTURAL ACOUSTIC CONTROL

Research work as in Ref. 6 has shown that low frequency sound transmission into aircraft cabins is due to a few dominant circumferential modes. This observation suggested an alternative approach, termed Active Structural Acoustic Control (ASAC), in which the control inputs are actuators applied to the fuselage structure while the error sensors are microphones in the cabin interior [11]. Such an approach will reduce the dominant acoustically coupled structural modes resulting in (hopefully) global sound reduction with fewer active sources. Preliminary experiments by Simpson *et al* on applying ASAC to a DC-9 fuselage demonstrated its potential [12]. Figure 6 shows the experimental arrangement while Figure 7 presents typical measured results. Since the DC-9 is a turbofan powered

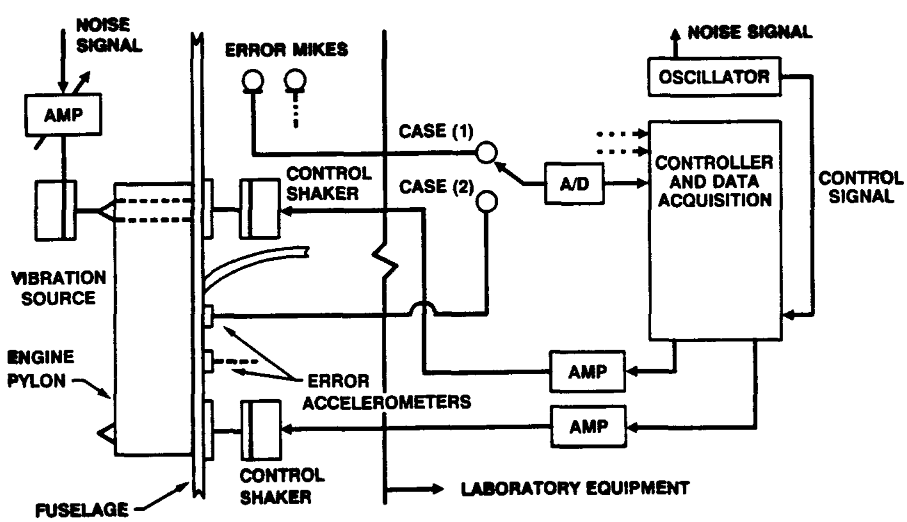

Figure 6. Experimental arrangement used by Simpson *et al* (from Ref. 12)

aircraft, the disturbance was simulated by a vibration input at the engine pylon. The active inputs were shakers applied to the fuselage near the pylon as shown. The excitation frequency is significantly higher than the propeller application but the results of Figure 7 demonstrate about 10 dB of averaged reduction. Recently two commercial versions of ASAC systems have become available. Ultra Electronics have applied an ASAC system to a de Havilland Dash 8. The system consists of electromagnetic actuators attached to the fuselage frames while the error sensors are microphones located on the trim. The control approach is a feedforward LMS. Table 2 presents typical results and impressive attenuations are achieved in this aircraft. A comparison with ANC in Table 2 reveals that the ASAC system outperforms an ANC system for the Dash -8. Thus good performance can be achieved with less transducers and a simpler controller. However, this is likely to be application specific and is likely to vary for other applications. According to Ross [9] when the excitation is localized in the propeller plane, then it is suitable for an ASAC approach. In another ASAC application Lord Corporation is marketing a system which consists of

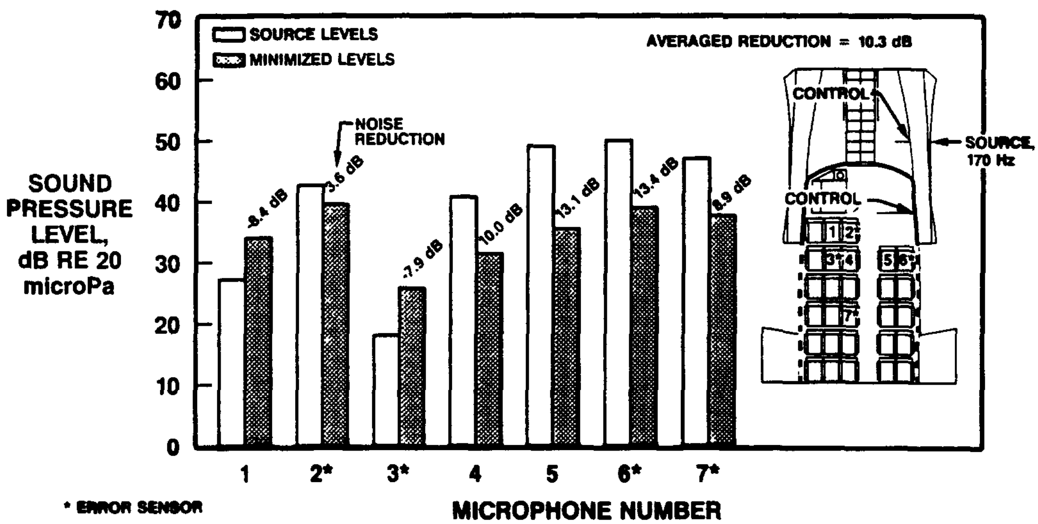

Figure 7. Cabin SPL corresponding to the system of Fig.6 (from Ref. 12)

electromagnetic shakers acting on the back of the engine mounts of Cessna Citation X turbofan business jet [13]. The error sensors again are microphones in the cabin interior while a feedforward controller is used. Such an approach minimizes the actuator control force/displacement requirements since it only needs to reduce the acoustically significant vibrations at the engine mounts. One potential disadvantage of the ASAC approach is that even though cabin levels are reduced, the fuselage vibration can sometimes increase [11], which has implications in terms of passenger vibration comfort and fuselage fatigue. In addition, applying actuators to the pressure hull of an aircraft has larger implications in terms of certifications than ANC.

An alternative approach is being marketed by Barry Controls and Hood Technology. This approach is not purely active, rather it replaces the actuators with adaptive (tunable) vibration absorbers (ATVA's) [14]. An ATVA has the ability to adapt its properties (usually stiffness) and so adjust its resonant frequency to track the disturbance. In this manner a lightweight, high Q ATVA can be installed which gives high vibration reduction at its mount point. Tuning is achieved through a controller which adjusts the stiffness to achieve the required resonant frequency. Barry Controls have successfully developed a commercial system, which is being installed on DC-9's for cabin noise reduction. An advantage of such a system is its relative simplicity in that no error microphones and wiring harness need be installed in the cabin. All installation occurs on the engine mounts, a factor that appears to be significant to airlines in terms of installation downtime and maintenance. However, TVA's previously used for cabin noise reduction have a reputation for fatigue failure since the high force from a lightweight device comes about from large deflections of the active mass. It remains to be seen whether the new ATVA's will suffer this problem.

CONCLUSIONS

In conclusion, we try to draw from the above evolution some general lessons about the commercial application of active systems to sound and vibration reduction. Since some of these are well known to present ANC practitioners, we will split the lessons into two categories; more obvious and less obvious.

More obvious lessons learned:
(1) Cost, complexity, robustness, performance achieved (and for the aircraft application weight and size) are the most significant factors.
(2) System modeling of an ANC system is very useful, but should capture the major physics.
(3) Optimal design is important using validated models.
(4) Different ANC approaches should be considered, depending upon the spatial and temporal form of the noise, as well as performance requirements.

Less obvious lessons learned:
(1) Customer perception of the control effect is crucial.
(2) A hybrid of ANC approaches is viable since use of one system will often enhance the attractiveness of another.
(3) Adaptive or active-passive control approaches in which the passive properties of the system can be adjusted to reduce noise should be considered, since they require minimal control power.
(4) New, improved control approaches can often be obtained by examining the physics of the problem.
(5) The final arrangement of the optimal ANC configuration is limited in practice by the physical constraints of the application with a result that reduced performance may occur.

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