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Some insights in active control of noise and vibration in aircraft cabins

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Abstract

The paper present a short overview on active control of low frequency interior noise in aircraft cabins caused by internal and external sources such as engines or turbulent air flow. For propeller driven aircraft as well as for jet powered aircraft the latter are the most dominant sources for the generation of airborne and structure-borne noise inside the aircraft cabin. Especially in the low frequency range active noise treatments can be applied effectively to reduce the interior sound pressure level. The application can be based on feed-forward controller or a feedback controller. Both structures can include self-adaptive algorithms in order to track changings of the disturbing noise field. Practical applications are known from commercial aircraft based on systems with distributed sensors and actuators. The combination of all components yields the conclusion that active control of aircraft interior noise can be interpreted as a mechatronic approach.

Keywords: active noise cancellation, aircraft interior noise, noise source, noise transmission path, adaptive control.

Некоторые идеи в области активного контроля шума и вибрации в салонах самолетов

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Аннотация

В статье представлен краткий обзор активного контроля низкочастотного внутреннего шума в кабинах самолетов, вызываемого внутренними и внешними источниками, такими как двигатели или турбулентный поток воздуха. Существуют воздушные суда с винтовым приводом и реактивным двигателем, последние являются основными источниками создания воздушного и структурного шума внутри салона воздушного судна. В частности, в низкочастотном диапазоне можно эффективно применять активные методы шумозащиты для снижения уровня внутреннего звукового давления. Применение их может быть основано на контроллере прямой связи или контроллере обратной связи. Обе структуры могут включать в себя самоадаптивные алгоритмы для отслеживания изменений мешающего шумового поля. Известны практические применения коммерческих самолетов на основе систем с распределенными датчиками и исполнительными механизмами. Комбинация всех компонентов позволяет сделать вывод, что активный контроль внутреннего шума самолета можно интерпретировать как мехатронный подход.

Ключевые слова: *активное шумоподавление, внутренний шум самолета, источник шума, путь передачи шума, адаптивное управление.*

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Introduction

Active control of aircraft interior noise can act as an effective supplement of passive noise treatments, especially in the low frequency range (below 400Hz) even if the application of this technology requires a challenging and cross-disciplinary approach in order to design a in many cases self-adaptive mechatronic system. Nowadays active control approaches are of particular importance for the aircraft system design process because of weight-optimized structural design and new engine technologies such as counter rotating open rotors. For this reason this paper presents some insights on active noise and vibration control that is far away of being complete. It is (only) aimed (i) to highlight basic noise phenomena, (ii) to provide an overview on active control systems, and (iii) to comment on flight proven applications. The references provided may be helpful for further reading.

1. Noise sources and noise transmission paths

The (overall) sound pressure level (SPL) is a relevant measure to evaluate the comfort in an aircraft cabin. In order to guarantee an acceptable noise floor, passive as well as active noise treatments are used to isolate the cabin from external noise sources or to suppress disturbances that are caused by internal sources. Because of weight-optimized structural design (based on carbon-fiber composite techniques), effective and robust control of noise and vibration phenomena is nowadays of particular importance in aircraft system technology.

To achieve a significant control profit by applying passive and/or active noise treatments, it is important to identify the dominating noise sources as well as the most relevant noise transmission paths. According to [1] it is possible to distinguish between internal and external sources. A typical internal noise source is the ventilation system, whereas external noise is mainly caused by the engines as well as by aerodynamic effects. An overview on external and internal noise sources is given by Figure 1.

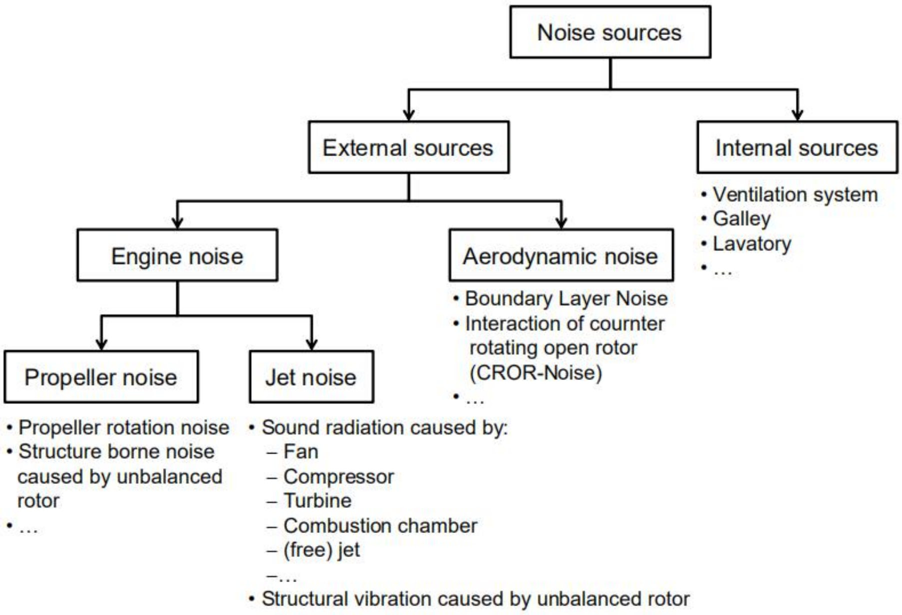

Fig. 1. An overview on external and internal noise sources

Especially for propeller driven aircraft it is possible to distinguish between engine noise caused by the propeller rotation, and power plant noise. The first generally exceeds the noise from the power plant with respect to its absolute level. Noise generated by propeller rotation causes a sound field that is highly tonal in frequency content, compare Figure 2, and highly directional in its spatial distribution.

The associated sound pressure field is deterministic and completely correlated at all points. The noise level is influenced by factors such as engine power, tip speed, number of blades, and distance between propeller tip and fuselage.

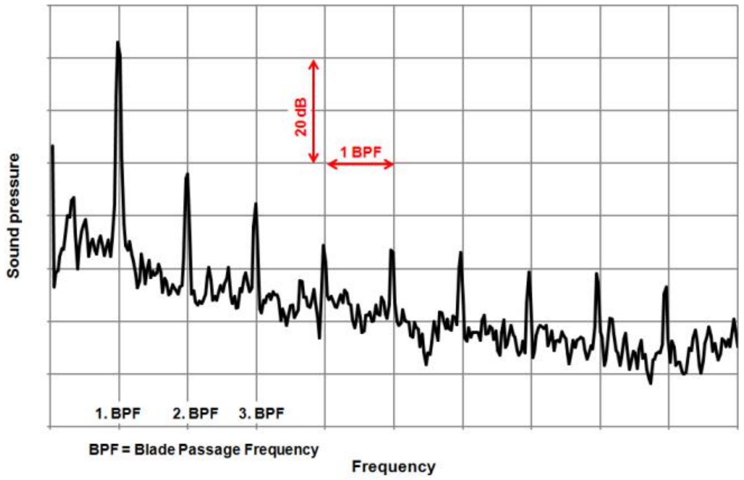

Fig. 2. Power spectral density measured in a propeller driven aircraft

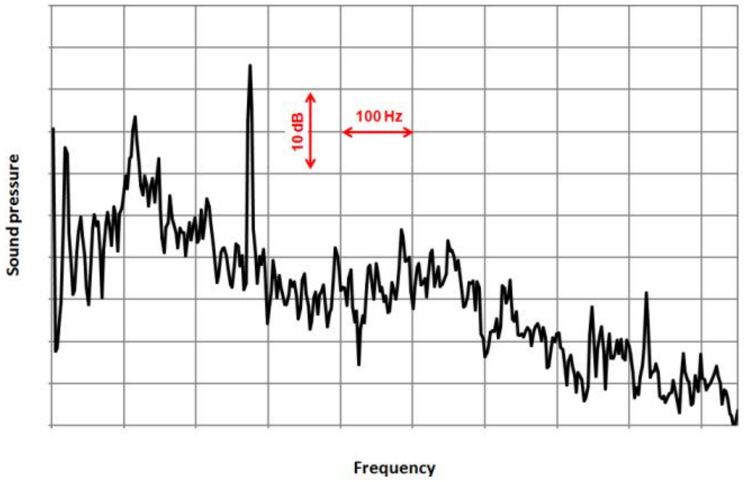

Fig. 3. Power spectral density measured in a very light jet

Power plant noise was originally restricted to the exhaust noise of reciprocating engines. Nowadays gas turbines (turbo-jet, turbo-prop, and turbo-fan) are of practical importance, see [2]. For jet noise generated by these power plants, the acoustical field on the airframe is random, and can be an efficient exciter of structural vibrations at low frequencies. In addition engine unbalance forces can also cause tonal components of cabin noise in a jet powered aircraft, compare Figure 3. Furthermore, forward radiated noise from a jet engine fan inlet consists of broadband and dominant tonal components at various frequencies (known as buzz-saw noise).

According to [2], aerodynamic noise is generated by the airflow over the aircraft surfaces. For smaller aircraft airflow noise is important at higher frequencies. For larger, jet powered, well streamlined aircraft, high speed flow generates significant levels of turbulent boundary layer noise that is usually the most important source of cabin noise for these types of aircraft. Results of in-flight measurements of the fluctuating pressure acting on the fuselage surface beneath the boundary layer taken from a large jet aircraft, operating at speeds from 138 to 242m/s at an altitude of 7620m, clarified that the pressure was broadband and contributed significantly to the cabin noise between 100Hz up to frequencies above 2kHz. It was found that increasing airspeed (from Mach 0,45 to Mach 0,78) resulted in an increasing pressure spectral density of about 7dB.

The different types of noise sources can also be classified in respect of the disturbance that is emitted by the source. Following this approach, compare [2], it is possible to distinguish between airborne noise (fluctuation of the acoustic pressure caused by an acoustic source that radiates sound) and structure borne noise (caused by a structural source that emits mechanical vibrations). These different mechanisms of noise generation are illustrated by Figure 4.

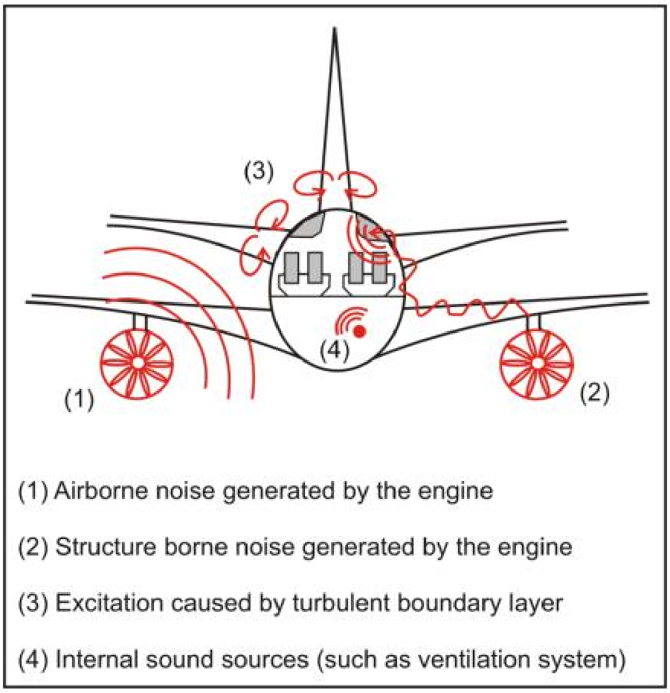

Fig. 4. Mechanisms for sound generation

Consequently, it is necessary to distinguish between different noise transmissions paths. These are the airborne path and the structure born path, see Figure 5. The first is responsible for cabin noise that is transmitted through the fuselage sidewall from sources that exert directly on the exterior of the fuselage. The second transmits noise caused by mechanical forces or by the aerodynamic pressure acting on distant regions of the airframe. Disturbances caused by these excitations are transmitted through the structure and radiated into the fuselage as acoustic sound. Examples, see [3], are:

- Cabin sidewall path (not well defined/distributed, transmission of airborne noise),
- Pressure bulkhead path (well defined/localized, transmission of airborne noise),
- Engine mount path (well defined/localized, transmission of structure borne noise into fuselage),
- Fuselage path (not well defined/distributed, transmits structure borne sound through fuselage).

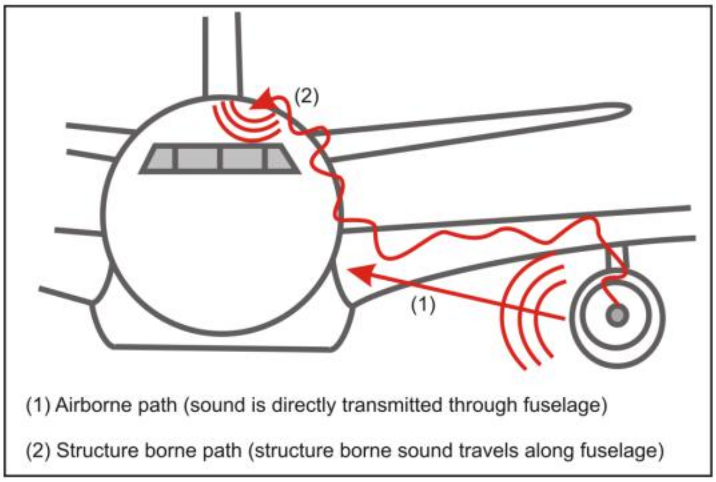

Fig. 5. Sound transmission paths

2. Structure and functional principle of active systems

As outlined in section one, the cabin noise field is excited by airborne noise as well as by structure born noise. In order to (i) limit the emission of a specific source, (ii) reduce the transmission along a specific path, and/or (iii) reduce the remaining sound pressure in the cabin, passive noise control is in the majority of cases (especially in the mid and high frequency range) a very effective, robust and cheep approach that is easy to implement and causes a negligible maintenance effort.

However, especially in the low frequency range (below 400Hz) it can be necessary to support passive treatments by active noise and vibration control techniques that are based on the concept of active noise control (ANC) proposed by Dr. Paul Lueg, see [4], [5]. The original idea of this approach is given by destructive interference of noise and anti-noise, as illustrated in Figure 6. Nowadays, active control approaches can also be based on more advanced concepts such as active control of the system input power or the maximization of acoustic dissipation. These concepts are summarized in [6].

Regardless the enormous variety of engineering applications that range from noise canceling headphones to active silencers, active control of interior noise can be interpreted as a mechatronic approach, because an ANC system consists of loudspeakers as actuators, microphones as sensors, and a real time processor for fast signal processing. The basic system is given by the air filled cavity, compare Figure 7. This elastic continuum can be described by the wave equation for the acoustic pressure - a partial differential equation. Therefore, the plant consists of a distributed parameter system. It behaves linear, if high sound pressure levels as well as over-modulation of loudspeakers are avoided. The optimization of sensor and actuator positions however results in a nonlinear problem. ANC is carried out to control the acoustic potential energy.

As reported in [6], it is also possible to apply alternative control strategies such as active structural acoustical control (ASAC – control of sound radiation), and active vibration control (AVC – control of kinetic energy). ASAC can be applied with active tuned vibration absorbers, see [7], whereas AVC has been realized using active mount systems, compare [8]. However, in many situations it is impossible to meet the requirements without the application of ANC, compare Figure 8.

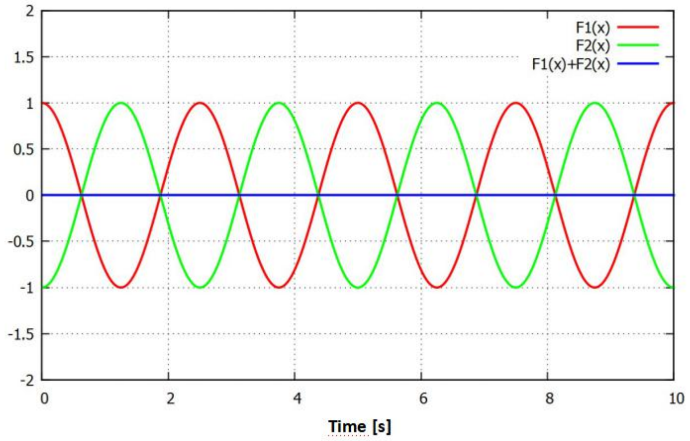

Fig. 6. Destructive interference of noise (red) and anti-noise (green)

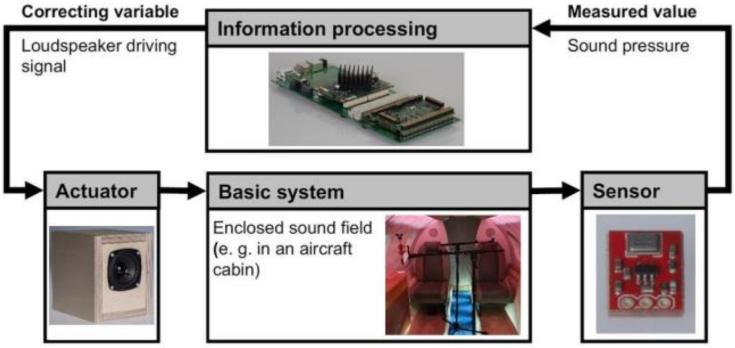

Fig. 7. Active control of aircraft interior noise interpreted as mechatronic approach

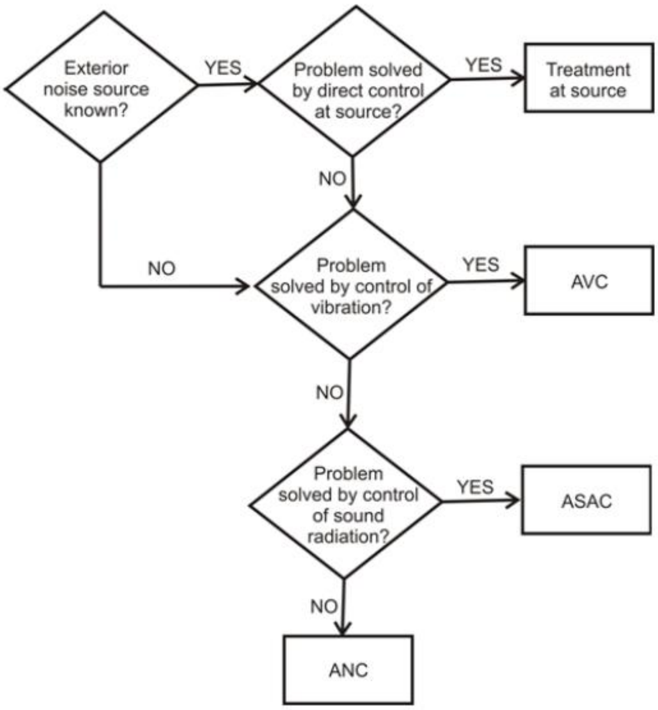

Fig. 8. Decision making during ANC system design

Common to all concepts is the necessity of measuring physical values (e.g. the cabin sound pressure), and the generation of cancelling signals that can be used to reduce disturbing quantities by a set of actuators. Information processing is – for every concept – needed, in order to evaluate the measured values as well as to calculate the command signal. It can be either adaptive or non-adaptive. Non-adaptive information processing uses the physical measure provided by sensors to drive the actuators by manipulating the sensor signal with a constant gain. On the one hand, this is a robust approach, but on the other hand it is impossible to take into account for misadjustments that might be caused by a slight shift of the excitation frequency, but also by a breakdown of sensors and/or actuators, if non-adaptive control is applied. The dramatic effect of especially phase errors on the control profit is shown in Figure 9.

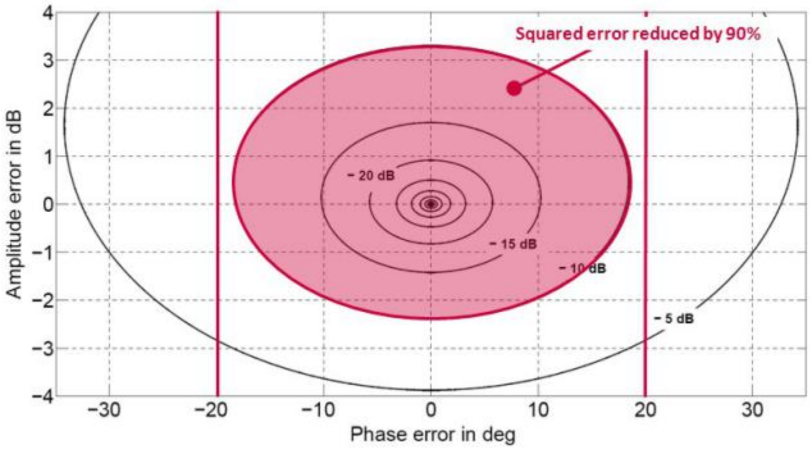

Fig. 9. Effect of errors on the control profit

Adaptive signal processing is capable of redefining the control gain according to a change of the disturbance or to variations in the plant. Adaptive control can be realized with preview (known as the feed-forward approach) and without preview (known as the feedback approach), see [9]. Both concepts are shown in Figure 10.

Feed-forward control (Figure 10 – left) is based on the reference signal x and the disturbance signal d. The latter is fed to the controller to compute the actuator signal u. This controller is only able to cancel that part of the desired signal d which is correlated to the reference signal x. The error signal e is used to adjust the feed-forward controller.

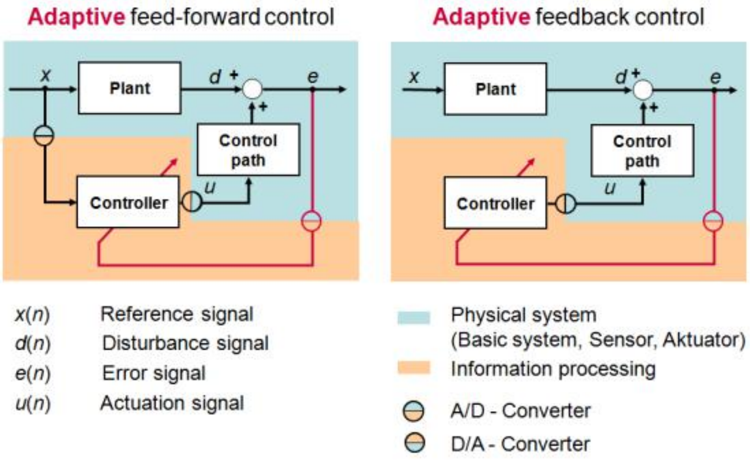

Fig. 10. Information processing in control systems

The second control schema is the feedback structure, see Figure 10 – right. Here, no reference signal x is required to provide the actuator signal u. Only the error signal e is fed into to the controller. However, the missing reference can be approximated using an internal model of the cancelling path. Applying feedback control it is possible to cancel the deterministic part of the desired signal d. However, the delay between sensing and actuation must by small compared to the sampling time to realize a significant control profit. For this reason application of feedback control leads in many situations to co-local control approaches as known from Skyhook-dampers, see [10]. Finally, it should also be noticed that the hybrid control strategy (a combination of feed-forward and the feedback control) combines the advantages of both control structures.

As also reported in [9], the filtered-reference least mean square algorithm (FxLMS) is most widely used for adaptive tonal and broadband active noise and vibration control applications. The name of the algorithm is derived from the fact that the known or approximated reference signal x is filtered with a model of the secondary path. The main advantage of the algorithm is its simplicity and robustness. However, one drawback is the relatively slow convergence and tracking performance which depends on the secondary path and the signal statistic. To improve the performance, different variations such as the power normalized FxLMS algorithm are used in practice. In some applications remote control is required, because it is not possible to observe the sound pressure at the desired location. As – in great detail – reported by Kestell in [16] adaptive control based on forward-prediction virtual sensor techniques can be applied. Because the spatial discretization applied in this approach is based to a finite number of nodes and only in one direction, the control profit could be limited in the mid and high frequency range.

3. Comments on Flight-Proven Applications

Johansson, see [11], states that two companies, Ultra Electronics (England) and Saab Aircraft (Sweden), developed the first commercially-available ANC system for reduction of propeller induced noise in aircraft cabins. The first commercial aircraft in the world in which this technique was used is the SAAB 340 and its successor, the SAAB 2000.The first SAAB 340 was delivered in the spring of 1994, and the first SAAB 2000 was delivered later the same year. The ANC system in the SAAB 340 uses 48 control microphones and 24 loudspeakers. The system in the SAAB 2000 consists of 72 control microphones and 48 loudspeakers. The functional principle of these systems is illustrated by Figure 11, whereas the effect on the cabin noise field (evaluated at a single position) is shown in Figure 12.

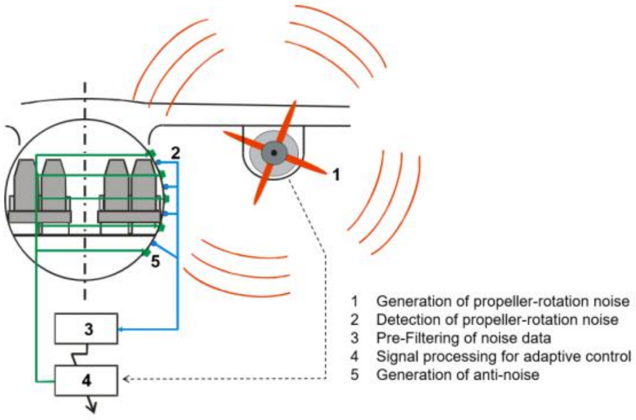

Fig. 11. Structure of noise cancellation system in a propeller driven aircraft

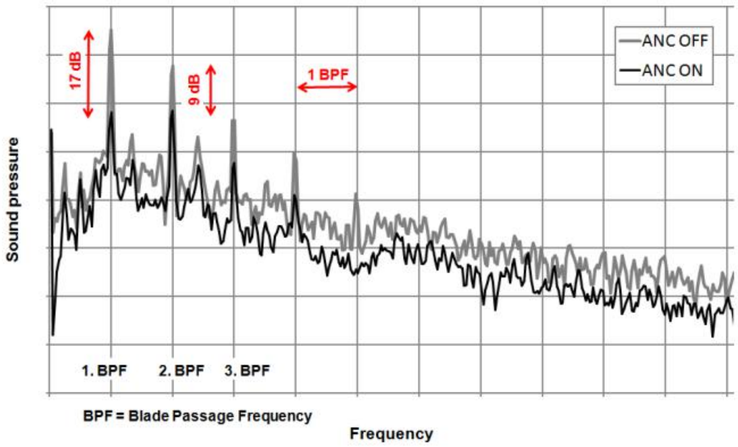

Fig. 12. Principle of active noise cancellation in an aircraft

According to the manufacturer, see [12], the Ultra-system has up to now been adopted on the Bombardier Q100, Q200, Q300 and Q400, Bombardier Challenger 601 and 604, Lockheed Martin C-130, Beech King Air 350, and Saab 2000 and 340. According to Elliott Aviation, see [13], an Ultra-system in a King Air 200 with 12 loudspeakers achieves a mean noise reduction of 6-9 dB(A). Hansen, see [14], reports an Ultra-system with 96 input channels (error and reference sensors) and up to 48 output channels for actuators. The error sensors were mostly microphones, located just above the aircraft windows in the cabin lining as well as in the centre of the ceiling lining and in the head racks. Performances of 10dB, 7dB and 3dB are given for noise reduction of the fundamental frequency and the first two harmonics (spatially averaged reduction determined at passenger head-level).

Billoud, see [8] reports on the AVC system developed by the Lord Corporation that was applied to reduce helicopter floor vibrations. This system uses up to 16 accelerometers as sensors and is capable of driving up to four force actuators. In [8] Billoud also reports on an ASAC application of Lord's technology in which the accelerometers were replaced by microphones. Two jets, a Douglas DC-9 and a Cessna Citation X, were equipped with active dampers at the engine mounts.

In both cases, the turbines were mounted on the rear fuselage and the error sensors were distributed in the cabin lining in order to achieve global reduction. No absolute reduction performance values are given for the Citation X. According to Billoud [8], a reduction of up to 8dB(C) at 120Hz and 170Hz was reached for the rear 45 seats of the DC9.

Other examples of flight-proven systems are noise-cancelling headphones, see [15], with analogue feedback control. Because active headphones are able to act close to the error sensor these systems provide a significant noise reduction. An active attenuation of 25dB in the frequency range 25 to 500 Hz was reported for a closed headphone. Open headphones reach an attenuation of approximately 10dB in a frequency range between 400Hz and 1kHz.

Conclusions

The present paper was intended to provide some insights on active control of aircraft interior noise. However, the topics mentioned in this article are only a percentage of the whole story. Furthermore, the list of references is far from being complete. The author therefore apologize to any colleague not mentioned in spite of their important contributions to academic and/or applied research on passive and/or active control of aircraft interior noise.

It has been shown that the main sources for cabin interior noise are the engines and the turbulent air flow. Interior noise with dominant harmonic contributions is caused by the rotating machinery of a propeller-driven aircraft. The noise signature in a jet-powered aircraft is mainly broadband, because of the jet noise and the aerodynamic noise. It has also been introduced that the interior noise field is caused by both airborne noise (directly transmitted through the fuselage into the cabin) and structure-borne noise (resulting from sound radiation from the structure into the cabin after wave propagation in the structural parts).

As outlined in this contribution, active control of sound is applied especially in the low frequency range to save both, weight and volume. It is usually applied, if passive noise treatments are not suitable to reduce the interior noise level to a specified limit. The main idea is based on the principle of destructive interference of primary noise with the canceling signal. In most situations microphones are used as sensors and loudspeaker as actuators. In order to adjust an active control strategy to changings in the primary noise field and/or changings in the secondary paths, adaptive control is applied, based on feed-forward or feedback control implemented on a digital signal processor.

Commercial applications are known from propeller driven aircraft as well as from jet powered aircraft. Global control – especially adjusted to single acoustic modes of the aircraft cabin – can be applied successfully for propeller-driven aircraft. Local control of sound around human head is possible for tonal as well as broadband noise and can therefore be found in both aircraft types. The design of active noise control systems is a mechatronic approach and requires expertise in the fields of engineering acoustics, digital signal processing and model based system engineering.

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