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Review of Active Techniques for Aerospace Vibro-Acoustic Control

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This paper presents a review of active techniques for aerospace vibro-acoustic control. First, the mechanisms of airborne or structure-borne sound generation and transmission in aerospace vehicles are briefly reviewed. The main approaches of passive and active noise/vibration control are then summarised, and three examples of active systems that have already been developed into practical aerospace applications are briefly described. Finally the actuator, sensor, and control system requirements for aerospace applications are discussed.

I. Introduction

VIBRO-ACOUSTIC control is an important issue in the design of aerospace vehicles. Fuselage or airframe vibration cause several types of problems. For example, aircraft fuselage vibration can generate high levels of cabin noise that affect passenger comfort.[1] The vibration and noise levels in supersonic aircraft are so high that acoustic fatigue phenomena could damage the aircraft structure and also the mechanical or electronic apparatus used for flight control.[2] During liftoff of space launchers, the noise of the rocket boosters is reflected by the ground and strongly excites the fairing structure so that it generates high levels of structural vibration and internal noise that can damage the payload inside the fairing.[3,4]

Vibration and noise control in aerospace vehicles is a challenging problem. Passive isolation treatments are successfully used to reduce the vibration and noise transmission in the so-called "mid-" and "high-frequency range."[1] Active control systems can be integrated with passive treatments for the reduction of low-frequency vibration or noise disturbances. These systems are generally composed of a set of structural or acoustic actuators, which are mounted on the airframe or fuselage structures. The actuators are driven by a control unit in such a way as to create a vibrating or acoustic field that destructively interferes with the unwanted disturbance field. Vibration control systems are arranged to reduce either the vibration transmission from the airframe to the fuselage or to reduce the noise transmission and radiation by the fuselage wall. Acoustic control systems are instead set to reduce the cabin noise directly.

Although actuators and sensors are often not embedded in the fuselage skin or in the airframe structure, they can be regarded as the active part of large and complex "smart structures," which are indeed the airframe or the fuselage wall structures. In this paper the concept of smart structure is therefore associated with large parts or even the whole framework of the aerospace vehicles and with any type of sensor/actuator equipment forming the active control system.

In the following sections the main sources of vibration and noise of aerospace vehicles are reviewed. The passive isolation methods are then briefly described with the intention to highlight the main features of vibration and noise isolation in aerospace vehicles. In parallel, active control systems that could be integrated to the passive control means are described.

Three types of control systems that have been successfully developed by the aircraft industry are considered in more details. The first example is an adaptive tuneable vibration absorber, which has been designed by Barry Control Aerospace and Hood Technology Corporation to reduce the fuselage vibration induced by the tonal excitations of the aft engines of DC-9/MD-80 aircraft. The second example considers a smart strut, which has been studied by Westland and Agusta helicopter manufacturers for the isolation of the main rotor and gearbox vibration transmission to the cabin of the EH101 large helicopter carrier. The last example describes an active noise vibration control system, which has been developed by Ultra Electronics for the reduction of sound in the cabin of turbopropeller aircraft as for example the Havilland Dash-8 Series 200.

The features and requirements of the actuators, sensors, and control systems that could be mounted on aircraft or aerospace vehicles are also reviewed. This analysis principally addresses effectiveness, cost, and safety issues.

II. Structure- and Airborne Noise Transmission to Aircraft and Spacecraft Interior

Interior noise or airframe vibration in aircraft or spacecraft vehicles is a problem that assumes specific features for each type of vehicle. Noise is an intrinsic effect of propulsion systems (propeller and jet propulsion), engine-induced vibration (reciprocating, turbofan, and jet engines), airflow over the vehicle fuselage (boundary-layer turbulence), wings and aft tail vibration (caused by vortex generated by exhaust or propeller wakes), and running equipment (hydraulic servomechanism and air conditioners). These sources of noise are called "airborne noise" when they directly affect the cabin or payload of the aerospace vehicle. The cabin/payload noise caused by the airframe vibration is instead called "structure-borne noise."[1]

The principal sources and transmitting paths of noise in aerospace vehicles are briefly reviewed in this section. More details about the mechanism of noise generation analyzed here can be found in Chapter 16 of Ref. 1.

A. Turbulent Boundary-Layer-Induced Noise

The airflow over the aircraft surface generates high levels of turbulent boundary-layer-induced noise that, quite often, is the most significant source of noise in the cabin during flight conditions. For all types of aircraft or spacecraft vehicles, the airflow over the fuselage surface is characterized by a turbulent boundary layer that generates a fluctuating pressure, which excites the fuselage skin. The nature of this excitation is random both in frequency and spatial domains. The boundary-layer pressure field is convected in the direction of the airflow. The convection speed is proportional to the aircraft speed such that at certain cruise speeds "hydrodynamic coincidence" occurs. In this case the phase of the boundary-layer-induced pressure matches the phase of the bending wave vibration of the fuselage skin. This phenomenon generates large vibrations of the fuselage wall and therefore large sound levels in the aircraft cabin.

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B. Propeller Noise

Propeller noise is generated by the propeller blades rotating through air. This source of noise is deterministic because the sound field generated is correlated to the rotational speed of the propeller. There is a second, but less important, mechanism of random broadband noise generation, which is caused by the boundary-layer turbulence in the airflow over the blade surfaces. Propeller noise is determined by a number of factors that are as follows: first, the power produced by the propeller; second, the blade tip speed; third, the number of blades; fourth, the blade shape; and fifth, the uniformity of airflow into the propeller (as a result of the angle of attack of the propeller). The spectrum of the noise generated by a propeller is characterized by very distinctive tones. The largest one coincides with the blade-passage frequency, and the others coincide with higher harmonics. The highest noise levels are generated in the plane of the blades; thus, this type of noise mainly affects that part of the cabin closest to the propellers. Helicopter tail- and main-rotor blades also generate large acoustical excitations whose tones occur at very low frequencies.

C. Engines Noise

The sound radiation from jet engines is principally caused by the high-speed and high-temperature jet gases turbulent flow in the engine and their mixing with the air flowing behind the engine. This source of noise mainly affects the cabin section behind the engines, and it is particularly strong during takeoff, at cruise climb, and during thrust reversing of landing maneuvers. High-bypass jet engines have a relatively low-velocity gas flow from the exhaust system. Therefore, the mixing of the jet gases with the air flowing behind the engine is less intense, and consequently the noise radiation is also reduced. However, the inlet compressors of these engines generate a lot of fan buzz saw noise, which is radiated toward the front part of the aircraft. Jet noise is the dominating source of noise in aerospace vehicles. During liftoff of aerospace launchers, the engine noise reflected by the ground strongly excites the rocket structure and the payload bays. Jet engine noise is similar to boundary-layer noise excitation; it is in fact a random and broadband noise with a small convective pattern in the direction of motion of the aircraft or aerospace vehicle. In some cases the noise radiated from the vibration of the cage of reciprocating or jet engines could also affect the cabin of an aircraft.

D. Structure Borne Noise

Both reciprocating and jet engines are rigidly mounted on the wings or the airframe of an aircraft. Therefore, the fuselage structure is excited by the vibration of the engines either directly or through the wings. This type of structural excitation could be relatively large, particularly when the rotating components of the engine and the propulsion system are critically unbalanced. In a propeller aircraft the front and tail wings are also excited by the wakes detached from the propeller blades. The rocket boosters are rigidly fixed to the space launcher structure so that a large amount of vibration is transmitted to the fairing bay. The vibration of helicopters gearbox and main rotor generates intense structural excitations at low frequencies. All of these types of excitation are transmitted to the helicopter cabin via the rigid struts connecting the gearbox to the fuselage, and this causes an additional level of noise in the cabin. This type of noise is called structure-borne noise because it is originated by the vibration of the airframe.

E. Other Sources of Cabin Noise

There are many other sources of noise in an aircraft among which the most important are given by the operation of the hydraulic servomechanism for the positioning of the flaps or the release of the wheels and by the operation of air-conditioning systems in order to maintain fresh air in the passenger cabin.

III. Passive and Active Approaches to Noise and Vibration Reduction in Aircraft and Spacecraft

The control of vibration and interior noise in aerospace vehicles is usually classified either as "source" or "transmitting path" noise/vibration control. A third class of noise control includes control means that directly act on the cabin acoustic field. These three approaches are briefly reviewed considering both passive and active control means used for aerospace vehicles.

A. Side-Wall Vibration and Noise Reduction

Among many passive methods of airborne noise control, the most common consists of fuselage double-partition constructions with acoustic insulation coating.[5–7] The fuselage wall is furnished with fiberglass blankets and impervious septa that are placed in the space between the fuselage skin and the interior trim panels. This is a double-wall construction that control the sound transmission by means of two mechanisms: first, the "mass-spring-mass" coupling of the fuselage wall with the trim panel (the two masses) given by the air in the gap between the two partitions (the spring); and second, the acoustic dissipation effect of the absorbing material confined between the fuselage skin and the trim panel. Double-wall partitions provide good transmission loss, particularly at frequencies above the so-called "mass-air-mass" double-wall resonance frequency where both the dissipative and double-wall coupling mechanism are effective.[8] Additional transmission loss can be obtained by means of fuselage wall treatments. Mass, damping, and stiffness treatments on the fuselage skin are suitable for the reduction of noise transmission and radiation to the fuselage interior.[9,10] Damping treatments reduce the sound transmission controlled by the resonances of the fuselage wall. Stiffness treatments are effective at low frequency but are difficult to implement in practice because they require modifications of the airframe structure. The effect of added mass is usually a byproduct of damping and stiffness treatments. Except for the stiffening treatment, none of these treatments are very effective in the so-called "low-frequency band."[1]

The poor sound transmission loss at low frequencies of aircraft wall constructions can be improved with active sound transmission control (ASTC) systems. For example, the sound transmission/radiation by the fuselage wall to the interior of aircraft or spacecraft vehicles could be reduced with active structural acoustic control (ASAC) systems.[11,12] This control approach improves the transmission loss of the fuselage wall by driving structural actuators mounted on the fuselage skin or frame structure (Shakers, PZT Lead zirconate titanate patches, PVDF Polyvinylidene fluoride films) in such a way as to minimize the vibration components of the fuselage wall that mainly contribute to the radiation of sound to the interior.[13–15] These vibration components, also called radiation modes,[16] could be efficiently excited and measured by means of shaped piezoelectric foils that are embedded in the fuselage skin.[17,18]

Active control systems are also used to reduce the sound transmission through the small cavity confined between the fuselage skin and the trim panel.[19–24] Three types of control actuators could be employed: first, a set of small loudspeakers placed within the double-wall partition; second, structural actuators (shakers, PZT patches, PVDF films) acting on the trim panel; and third, smart foam elements.[25–27] The sensors can be either a set of microphones placed within the cavity or a set of accelerometers attached to the trim panels. The actuator could be driven to control either the sound in the cavity between the two panels or the structural vibration of the trim panel. Both types of actuators can also be driven to minimize an estimate of the sound radiated into the cabin which is measured with a relatively large number of microphones.

In general, trim panels are rigidly mounted on the airframe because of safety requirements. In certain cases, for example in helicopters, the high levels of airframe vibration are transmitted to the trims with a consequent increase of sound radiation into the cabin. Active isolators could be used to reduce this type of vibration transmission. Inertial actuators mounted on top of the mounting system can be driven by a local feedback analog control system in such a way as to minimize the velocity measured at the top of the mount.[23]

For both ASAC and double-panel control systems different control architectures can be used depending on the characteristic of the primary noise to be cancelled. Propeller noise, that is, tonal noise, is usually controlled with a feed-forward control system that uses a reference signal from a tachometer mounted on the aircraft engine. Boundary-layer noise or jet noise, that is, random noise, is better controlled with a feedback control system.[28,29]

The low-frequency vibration of the fuselage structure caused by tonal disturbances (engine structure-borne and airborne excitations) is often controlled by means of tuned vibration absorbers (TVA).[1] These devices are distributed over the fuselage surface and are tuned to the frequency of the tonal excitation. When the dynamic absorbers are perfectly tuned to the unwanted disturbance, they act on the fuselage skin in such a way as to block the vibration at the points where they are mounted. An accurate choice of their position and tuning frequency can give good reductions of the fuselage vibration and of the sound level in the interior.[30] However, their effectiveness is limited by the requirements of perfect matching between the tuning frequency and the tone to be controlled. For example, when they are used to control structure-borne noise caused by the unbalanced engines, they can be effective only for a specific rotational speed of the engine. Usually they are set to perform at the cruise flight condition so that during any type of maneuver (landing, takeoff, change of altitude) they produce very small or no benefits. This problem is bypassed when an active system is used, in which case the tuning frequency is continuously matched to the disturbance tone. These devices are called adaptive tuneable vibration absorbers (ATVA) and are set to minimize a cost function that estimates the sound level in the cabin. The absorbers are therefore tuned to rearrange the fuselage vibration in such a way as to minimize the sound radiation rather than to minimize its vibration level.[31]

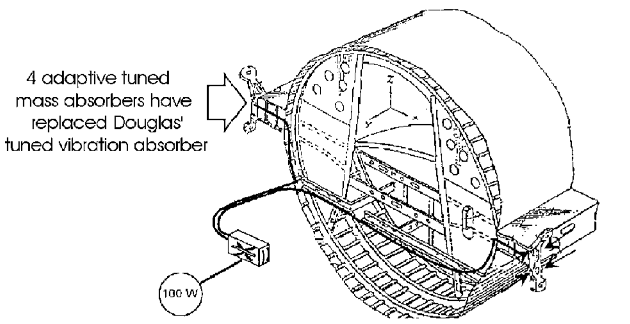

Fig. 1 Barry Controls Aerospace Adaptive Tuned Vibration Absorber System for Douglas DC9 aircraft (reproduced with permission of Barry Controls Aerospace and Hood Technology Corporation).

Adaptive tuneable vibration absorbers have been used to control the noise in the aft cabin of Douglas aircraft DC-9 and MD-80 twin-jets.[32,33] On these airplanes the two jet engines are mounted to the aft fuselage structure. This causes the engine vibration to be transmitted to the fuselage, which then radiates a high level of noise in the aft cabin. These engines have two rotors that when not perfectly balanced can generate large tonal excitation at their rotation speeds N_1 and N_2 and higher harmonics. Initially, Douglas solved the problem by mounting a set of four tuned vibration absorbers to the engine yoke, as shown in Fig. 1. The vibration absorbers were tuned in order to neutralize the vibration transmission at the two rotation speeds N_1 and N_2 when the plane is at cruise flight conditions. Barry Controls and Hood Technology Corporation extended the effectiveness of these systems by developing adaptive tuneable vibration absorbers to be mounted in place of the four tuned vibration absorbers. These systems consist of a set of independent vibration absorbers commanded by a small control box, which adapt their tuning during flight. They reduce both the N_1 and N_2 engine tones of about 25 dB at the noisiest seat, over the rpm range of 65–100%. With this system the engine tones cannot be recognized by the passengers. Figure 2 summarizes the typical performance of ATVAs at the aft seats.

B. Vibration Transmission Isolation

Structure-borne sound reduction in aerospace vehicles is generally focused on the control of engine-to-airframe transmission of structural vibration. The effectiveness of resilient isolator systems for aircraft engines or helicopter rotor-gearbox blocks is limited by the stiffness requirements of the mount elements. A mount has to

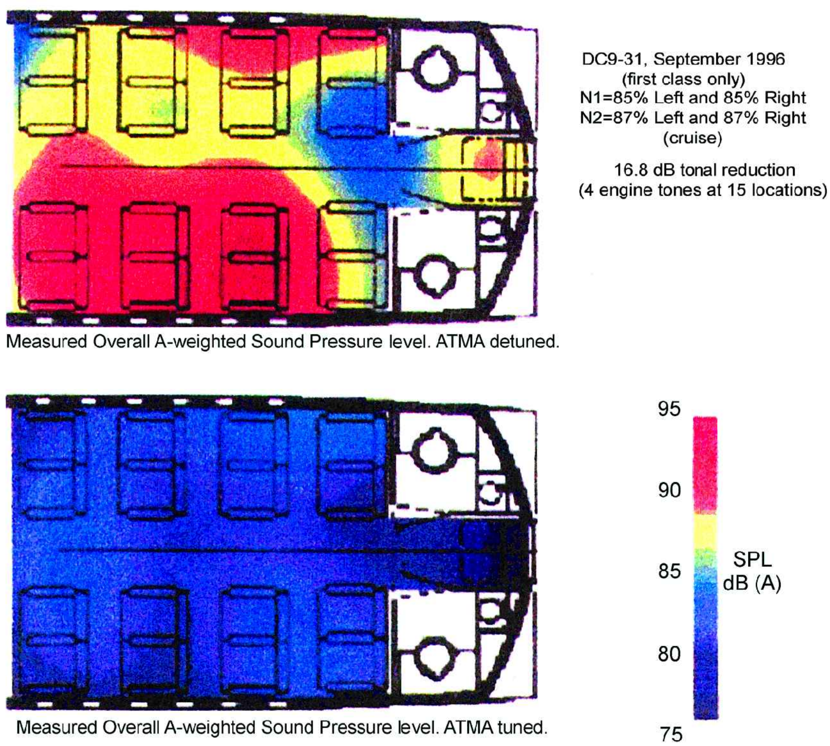

Fig. 2 Measured overall A-weighted sound pressure level at the aft of a Douglas DC9 aircraft. Top graph, ATVA detuned; bottom graph, ATVA tuned (reproduced with permission of Barry Controls Aerospace and Hood Technology Corporation).

satisfy two conflicting objectives: to support the engine at the most severe flight conditions and to reduce the structural motion caused by the engine vibration. Therefore, the isolator system has to be statically as stiff as possible (to connect) and dynamically as soft as possible (to isolate).[34] The impossibility of finding elastomeric materials able to provide simultaneously the required static stiffness and the compliant properties for the vibration isolation has often left no option other than the design of a very stiff mount, which gives very little vibration isolation. A certain compromise between the static and dynamic stiffness has been achieved with "fluid mounts."[35] In these mounts an additional isolation effect is generated by the flow of fluid between two flexible chambers. The motion of the fluid through the orifice connecting the two chambers provides additional damping and produces a tuned absorber effect for the control of the fundamental resonance of the aircraft engine-mount system.

A good compromise between static and dynamic stiffness can be achieved with active or semi-active mounting systems. An active mount is composed of three main elements: first, a reactive or inertial actuator; second, a sensor system; and third, a controller. If a reactive actuator configuration is used, the control force can be adjusted in such a way that the total force transmitted through the mount caused by the active and passive components is zero, then the receiving structure will be not excited. The dynamic vibration of the source machine will then be the same as if the source structure alone was floating freely in the space.[36] The reactive actuator can be placed either in series or in parallel with the connecting element. In the first case the actuator must bear the entire static load of the supported machine. The second solution does not present this problem; nevertheless, in order to drive the system it requires an actuator able to overcome the stiffness of the passive connecting element.[34,37] Depending on the intrinsic properties of the actuator element (free velocity and blocked force), the actuator is usually coupled to either a force or displacement amplification device.[36] As an alternative to reactive actuators, inertial shakers can be mounted at the connecting point between a passive mount and the airframe structure. In this case the control capability can be limited by the excessive actuator force requirements at the natural frequency of the mount-engine system.[38] In general the control actuator is driven to cancel the velocity measured at the connecting point of the mount with the airframe. In some cases the control of alternative cost functions based on the measurement of the velocity or/and force parameters can give better results.[39,40] Feed-forward control architecture is used for tonal disturbances where the reference signal is taken with a tachometer from the engine spool. The control of random disturbances requires instead feedback control system.

A dominant source of structure-borne noise in a helicopter cabin is the meshing of the gears in the main rotor gearbox.[41,42] In large helicopters, such as for example the Westland/Agusta EH101, the gearbox is connected to the helicopter airframe via a set of four long struts, as shown in Fig. 3. These struts are rigidly connected to

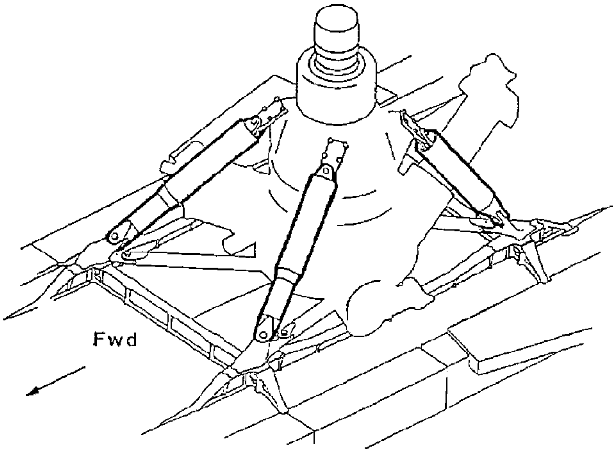

Fig. 3 Helicopter main rotor gearbox installation, showing the location of the support struts.

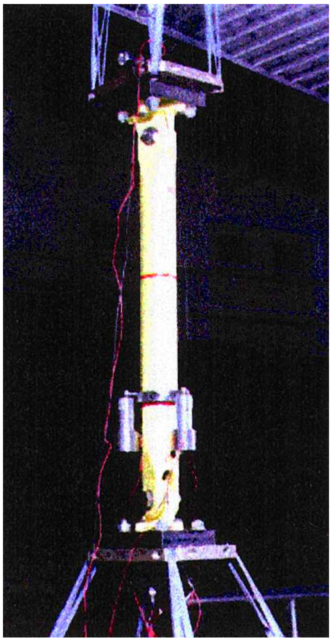

Fig. 4 Experimental rig used for strut active control measurements. The three magnetostrictive actuators are attached to the strut externally by means of a collar.

the gearbox and to the cabin so that they constitute the main structural vibration transmitting path to the helicopter cabin for both the low-frequency vibration generated by the main rotor blades (approximately 20 Hz) and the vibration generated by the gearbox, which covers a frequency range between 500 Hz and 2 kHz. The mechanism of high-frequency vibration transmission by the strut is quite complex and includes the effect of coupled longitudinal and bending wave propagation along the strut.[43] These struts are subject to severe load conditions because they have to carry the in-flight quasi-static load of the helicopter. Therefore it is not possible to introduce elastomeric parts at the junctions between the strut and the cabin or gearbox points that could provide some vibration isolation. Westland and Agusta have considered the possibility of building a smart mounting system where a set of three reactive actuators are fixed with a collar to each strut, as shown in Fig. 4. The actuator is a small magnetostrictive cylindrical element, which is connected to the strut collar on one side and to a mass on the other side. The three actuators are oriented in parallel to the strut and are disposed in a triangle. In this way they can be driven to generate an axial force and two bending moments for the control of longitudinal and flexural waves propagating along the strut. The three actuators are driven to minimize the kinetic energy of a small and rigid block of material fixed at the base of the connecting point between the strut and the cabin. The block is equipped with a set of six accelerometers positioned and oriented in such a way that the three linear and three angular velocities of the mass are measured. With these velocities it is then possible to estimate the total kinetic energy of the block mass. Figure 5 shows the reduction of the kinetic energy of the block mass that can be achieved using the three reactive actuators measured on the experimental rig shown in Fig. 4.

C. Interior Noise Absorption/Cancellation

The level of noise in an aircraft interior is controlled by the amount of acoustic absorption material used in the cabin.[1] Indeed, acoustic absorption is provided by the treatments of the interior surfaces of the aircraft cabin (side walls, ceiling panels, bulkheads, and floor) or by the passenger seats and baggage containers. The design of these elements is often dictated by considerations other than acoustic absorption, such as, for example, mechanical resistance, ease of cleaning, or stylistic appearance factors. This involves cabin side surfaces with low acoustic absorption. However, there are few furnishing elements that are designed by taking into account acoustic absorption, such as, for example, side sound-absorbing panels. These panels consist of a perforated inboard, which faces the interior of the cabin, a flow-resistive partition, a honeycomb core, and

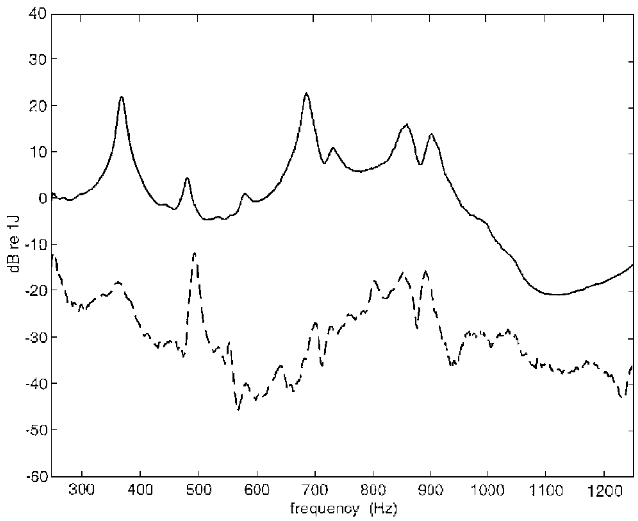

Fig. 5 Kinetic energy of the lower endplate assembly: ——, without control; – – –, with active control using three secondary actuators.

an impermeable outboard. This multilayer panel construction produces good absorption of the impinging sound waves to the panels in the mid- and high-frequency bands. When thin panels are used, some benefits caused by the membrane vibration of the panels are also achieved at low frequencies.

Active control systems have proven to be effective also for cabin noise control. There are three active control approaches to cabin noise: the active noise control (ANC), the active noise and vibration control (ANVC), and the active boundary control (ABC). The first approach uses acoustic sources (loudspeakers), which are driven to create a control acoustic field that destructively interferes with the acoustic field in the cabin.[28,44] The second approach employs structural actuators (electromagnetic shakers or PZT patches) that shake the fuselage structure in such a way as to reduce and rearrange the vibration of the fuselage skin so that the sound field in the cabin is attenuated.[45] The third approach uses smart trim panels that have stiff segments which are driven to suppress near-field radiation from the trims themselves.[46,47] In principle, all of these control approaches could be set to control the sound in the cabin as a result of any type of structure- or airborne noise source, not just the sound transmitted and radiated by the fuselage wall. The ANC and the ABC approaches use only microphone control sensors, whereas the ANVC uses both acoustic and structural sensors (microphones and accelerometers). Interior noise caused by propellers is controlled with feed-forward control systems that use a reference signal of the rotational speed taken from the engines main rotor shafts. The adaptive feed-forward control of random-type interior disturbances, caused, for example, by boundary-layer noise, jet noise, and air-conditioning noise, is limited by the requirement of reference signals with early information on the unwanted disturbance.

The three control approaches just described have also been considered for the control of noise in the payload section of launch vehicles during liftoff. For example, a control system using both acoustic and structural actuators has been studied for the reduction of noise inside the Ariane 5 payload fairing.[48] With this system both ANC and ANVC control approaches are employed to reduce the noise inside the fairing. A set of detection sensors placed in the vicinity of the jet engines provide, with good time advance, reference signals correlated to the fairing interior noise so that an adaptive feed-forward controller can be used. Two types of ABC systems have also been studied. The first is an active blanket with many locally feedback controlled collocated actuator and pressure-velocity sensor pairs covering the fairing.[49] The second consists of arrays of distributed active vibration absorber (DAVA) that have been distributed over the fairing internal surface.[50]

Figure 6 shows one of the structural actuators of the ANVC device developed by Ultra Electronics, Ltd., for propeller aircraft. The fuselage skin is excited by means of inertial electromagnetic actuators, which are actually working as active vibration absorbers.[45] The actuators have been fixed on frame-stringer intersections on the circular frames close to the propeller plane, with the line of action oriented radially. The control microphones have been placed on cabin trim walls, overhead bins, aisle ceiling, and seat backs. The location of the microphones is chosen with reference to a compromise between ease of installation and maintenance, proximity to passenger ear locations, distribution, and data acquisition requirements. The control accelerometers have been located as close as possible to the actuators driving points and were radially oriented. Figure 7 shows the distribution of sound levels in the cabin when the ANVC system is either switched off or on. This type of control approach has been proven to be more effective than ANC by about 2 dB, in particular at relatively low frequencies where the fuselage structural modes are well coupled with the cabin modes.

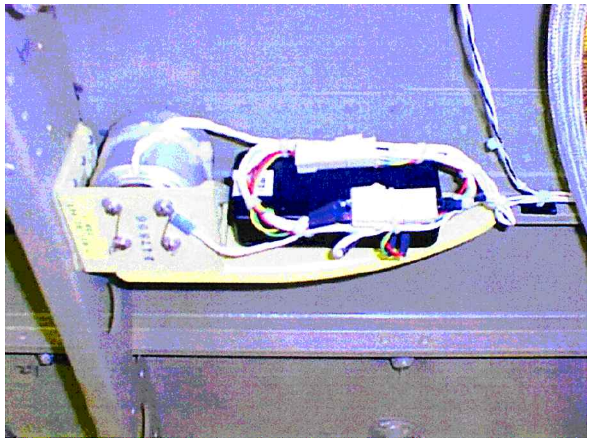

Fig. 6 Inertial actuator for active noise and vibration control system for propeller aircraft (reproduced with permission of Ultra Electronics, Ltd.).

IV. Actuators, Sensors, and Control System Requirements

The feasibility and success of a control system for vibration or noise control in aerospace vehicles depend on a number of factors that could be grouped into three main categories: first, effectiveness and reliability; second, costs; and third, safety issues. In the majority of cases, the effectiveness of a control system is limited by cost and safety problems. The following two subsections analyze the advantages and disadvantages that actuators, sensors, and control architectures have with reference to these three topics.

A. Actuators

Weight is a major issue in the design of an aircraft because it directly affects the flight costs.[1] Piezoelectric actuators (PZT patches or PVDF films) are by far the most light structural actuator that can be used for active mount devices or can be applied to the fuselage skin or airframe structure for the control of airborne and structure-borne sound transmission/radiation.[12,51–53] The possibility to embed directly to the mounting element or to the fuselage frame or skin structures has made these type of actuators very attractive because precious space can be saved.[54,55] However, they have some important drawbacks. Piezoeletric actuators require dedicated high-voltage amplifiers capable of handling large reactive powers. Although they are capable of generating large force excitations, they cannot be driven at the maximum levels because they suffer from severe harmonic distortion. Also, their actuation strength is limited at low frequency by the length of the piezoelectric element. The forcing mechanism of piezoelectric patches is confined to small areas of a structure so that they produce localized very high stress fields on the structure in which they are embedded. Finally, piezoceramic actuators are very brittle, and in some cases they are not able to bear the relatively large strain deformations of the fuselage

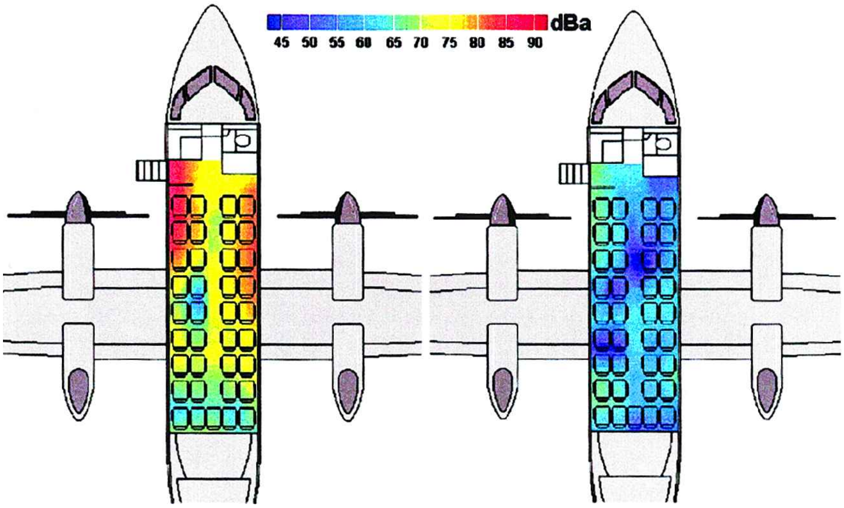

Fig. 7 Measured overall sound pressure level in a propeller aircraft cabin. Right without active control; left with active noise and vibration control (reproduced with permission of Ultra Electronics, Ltd.).

wall caused by the cabin pressurization. The same type of problem arises when they are mounted on helicopter struts or aircraft engine mounts. The load on the mount produces large deformations that cannot be matched by piezoceramic plates. Therefore, the choice of piezoelectric actuators has to take into account a number of problems, which involve the following: first, the limitations of control strength caused by distortion effects; second, their operative costs caused by inspection routines of the structures where they are mounted and the subsequent replacement of damaged patches, and third, safety and certification issues mainly related to the high voltage with which piezoelectric elements are excited and related to the high stresses generated on small areas of the structure where they are mounted.[31,46]

In some cases electromagnetic or magnetostrictive actuators constitute a valid alternative to piezoelectric actuators even if their weight is relatively larger, their unit cost is higher, and they require modifications of the structure on which are mounted. They constitute a reliable excitation system that can be successfully used in active mounting systems or inertial actuators for structural vibration control.[36,56] Electromagnetic actuators generate relatively small blocked forces and large free displacements, so that, in order to have the required vibration force, they may need some kind of system that enables force magnification. Magnetostrictive actuators generate instead relatively large blocked forces and small free displacements, and in this case the required stroke may need to be obtained with some kind of system for displacement magnification. The complete actuator system may therefore be composed of a large number of elements all of which have to satisfy the restrictive design and safety issues of aerospace constructions. The electrical power consumption of electromagnetic or magnetostrictive actuators can be relatively high, and this is a major limitation for ANVC systems, where a large number of actuators is required. This problem has been partially solved by using ATVA systems.[31,57] These devices have very little power consumption and can be set in such a way as to exert significant reactive force on the fuselage wall at a specific disturbance frequency. Therefore they are limited to the control of tonal disturbances caused by engine vibration transmission or to propeller noise.[58]

A major problem that arises when structural actuators are applied to the fuselage skin or airframe structure is fatigue. In particular, when ASAC is implemented the overall vibration level of the fuselage wall could be increased, and this can cause serious structural problems. In general the excitation mechanism of structural actuators generates localized stresses that can produce cracks in the fuselage structure. The periodic nature of the excitation tends to enlarge these fissures and therefore can bring the structure to failure. Therefore, the application of structural actuators on the airframe structure of fuselage wall requires extra certification procedures and additional maintenance routines to monitor the presence and size of cracks. For this reason active noise control or active boundary control represents an important alternative to active sound transmission control. ANC and ABC methods use loudspeakers,[28] smart trim panels,[21,59] and "speaking panels,"[46,56,60,61] as actuators. Thus there are no problems related to structural failure. In return they are limited by other issues such as effectiveness and cost. ANC requires a large number of loudspeakers, which means an increase in both weight and cost. Trim panels are relatively flexible elements so that in order to control their vibration for ANC or ABC control purposes a large number of structural actuators is required. Speaking panels or rigid segmentation of trims can represent a good solution to this problem although there could be a certain limitation in the capability of generating the required sound field caused by distortion problems of the actuation mechanism.

B. Sensors and Control Architecture

The choice of sensing system and control architecture also plays an important role in the success of a control system. If the objective of the control system is the reduction of aircraft/helicopter cabin or space launcher fairing interior noise with ANC, ANVC, and ABC systems, then the most robust control approach is given by setting the controller to minimize an estimate of the interior sound level measured with a set of microphones placed in the cabin or fairing cavity. This control strategy represents a good solution for control systems using either structural or acoustic actuators. However, its implementation has some drawbacks. The minimization of sound in a relatively big cavity requires a large number of microphones and a large number of actuators so that a multi-input multi-output (MIMO) controller is required.[28,29,62] As a result, the whole control system turns out to be heavy and expensive. In fact, in addition to the cost and weight of the actuators and sensors the cost of a sophisticated control system (including both the computer unit and the power supply units for the actuators) and the weight of all of the cables to connect the sensors and the actuators to the control unit has to be added up. Also, because the sensors and actuators are distributed all around the cabin the plant responses required in the controller filters, that is, the measured transfer function between the sensors and actuators, are affected by a number of factors influencing the acoustics of the cabin. For example, the change of the air physical parameters (caused by changes of the cabin pressurization, humidity, and temperature) or the change of the geometry of the acoustic field is caused by the movement of the passengers.[63] Adaptive feedforward control[29] is well suited to the control of tonal noise due to airborne noise (propeller tones), or structure-borne noise (airframe vibration generated by airflow wakes impinging on the front and tail wings) in which case the rotational speed of the engines main rotor shaft can be used as a reference signal.[29,64] The adaptive algorithm must, however, be robust to the changes in the plant response discussed above.

A more simple control architecture can be used for the control of noise transmission through the side walls of the vehicle. If distributed sensors are used, which are able to detect volume velocity vibration components of sections of the fuselage skin or trim panels and distributed actuators able to generate uniform forces over the same fuselage/trim panel sections,[65,66] then single-input single-output (SISO) control systems can be used to implement active structural acoustic control. The collocated positioning of the sensor and actuator elements allows the implementation of both adaptive feed-forward and feedback control architectures.[29,67] In this case the stability and robustness of a feedback control system could be limited by flanking paths caused by cross-structural or acoustic excitation between fuselage sections next to each other. Although this approach has given promising results, the use of distributed sensors is very delicate and has some drawbacks. First, distributed strain sensors are not capable of detecting rigid-body motions, and this could be a problem when they are bonded on trim panels that are connected to the airframe via soft mounts. Second, the control effectiveness of a collocated and distributed sensor–actuator pair could be disrupted at certain frequencies by control spillover phenomena.[17] This problem could be solved by using matched sensor actuator pairs. However these must be designed with particular care because shaping errors and coupling between the sensor and actuator via in-plane vibration of the panel on which they are bonded could deteriorate the stability of a feedback controller.[18] These two problems could be solved by using a grid of miniaturized accelerometers whose output is combined in such a way as to provide a signal proportional to the volume velocity vibration component of the panel on which they are mounted.[15,68]

As an alternative approach, smart structures for active structural acoustic control can be built with very large numbers of sensor–actuator pairs, each of which constitute a decentralized self-contained control system.[68,69] In this case each sensor–actuator pair is set to locally control the vibration of the fuselage skin or trim panel. These smart structures can be built in such a way as to integrate micro-electro-mechanical systems (MEMS) transducers (sensors and actuators) and MEMS controllers. Decentralized control systems have also been developed to control the airborne sound transmission through double-wall partitions.[70,71] For example, von Flotow[72] has proposed to insert a set of decentralized feedback control unit consisting of a loudspeakers with a collocated microphone in the small cavity between the fuselage skin and the trim panel.

The three control approaches just described indicate that scientists have gone through a full circle since they started: by studying control systems with a large number of sensors and actuators controlled by a powerful multiple channel feed-forward controller; have then considered single-channel feedback control system using one distributed and collocated sensor actuator pair; and, finally, went back to develop a system with a large number of sensor and actuator pairs, which are controlled individually by simple decentralized analog feedback controllers.

MIMO feed-forward control architectures are also used for the active control of harmonic vibration transmission through mounting systems or connecting struts.[34,37,38,73] The control actuators are driven to minimize an estimate of the cabin noise that is measured with a set of microphones. A reference signal of the unwanted disturbance is taken from the main rotor shaft of the engine[74] or gearbox[41–43] elements to be isolated. However, with collocated sensor and actuator pairs it is possible to implement feedback control systems in which case random disturbances can also be isolated.[39,75,76] Of particular interest is the development of decentralized mounting systems,[77] which are particularly suited for active suspension of trim panels[23] or for active isolation of racks with delicate electronic equipment.[78]

V. Conclusions

A review of active techniques for aerospace vibration and noise control has been presented. First, the mechanisms of airborne or structure-borne sound generation and transmission in aerospace vehicles are reviewed. The main approaches of passive and active noise/vibration control are then summarized, and three examples of active systems that have already been developed into practical aerospace applications are briefly illustrated. Finally the actuator, sensor, and control system requirements for aerospace applications are discussed.

The review has covered several control approaches and has highlighted the way in which researchers have gone through a full circle by considering three different families of control systems. The first type of system that was developed consisted of a feed-forward multichannel controller driving a set of control sources (loudspeakers or shakers) to minimize the sound inside the aircraft cabin measured with a relatively large number of microphones. The second family of control systems considered modular systems for the control of sound transmission through panels composed by distributed sensor–actuator pairs driven by a relatively simple single-channel feedback controller. Finally, a third generation of control system has been developed in which a relatively large number of sensor–actuator pairs are driven by decentralized feedback controllers. Thus, the evolution of active control of noise and vibration systems has started from systems with one MIMO controller and a large number of sensors and actuators, then has moved to a system with SISO controllers and one sensor–actuator pair, and finally has reverted to systems with a large number of sensors and actuators, which are working in pairs using simple SISO controllers.

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