

# Experimental study of the active sound transmission reduction through a double panel test section

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## Abstract

The present study addresses the reduction of the sound transmission through an aircraft fuselage test section by means of a combined active noise and vibration control system, so as to reduce the noise level inside the passengers' cabin. Experiments prove that control loudspeakers and error microphones in the trim cavity yield higher reductions in the radiated sound power than control shakers and error accelerometers on the trim panel. This conclusion remains valid when the skin and the trim panel are mechanically connected by means of four vibration isolators, and when the cavity is filled with thermal insulation blankets. It also appears that, in case of an active cavity noise control system, there exists an almost linear relation between the reduction of the acoustic potential energy in the cavity and the reduction of the radiated sound power. The optimised control system performs much better than a control system with sensors and actuators in arbitrarily chosen positions.

## 1. Introduction

Currently, the control actuators in the most successful applications of active noise control in propeller aircrafts are loudspeakers in the passengers' cabin [1-3]. A major cost of such a system is the modification of the interior trimming of the aircraft due to the integration of the loudspeakers in the cabin interior. For this reason, other solutions were investigated in the Brite-Euram project ASANCA II [4].

A first alternative is the use of electromagnetic shakers, attached to the outer fuselage. This approach has already been successfully applied in the de Havilland DASH-8 aircraft [2,5]. One important drawback of this method is that resonant actuators are needed to achieve the high magnitudes of the control forces [6]. This implies that these actuators cannot be optimally designed for all parts of the flight envelope, as the dominating tones in the interior noise field depend on the rotation speed of the engines. A second problem is that the high forces, induced in the aircraft fuselage, might cause some fatigue problems, limiting the life time of the aircraft, or, at least, increasing the inspection costs. Recently, piezo-electric patch actuators on the fuselage skin or on the stiffeners were studied by

some aircraft manufacturers as an alternative to the loudspeakers in the cabin interior [7-9]. This solution is very attractive because important weight savings are realised in comparison with the loudspeaker-based systems. However, it has also some important drawbacks. The piezo actuators require dedicated high-voltage amplifiers, capable of handling large reactive powers. Moreover, the piezo actuators are not very efficient in the low-frequency range (around the first blade pass frequency in propeller aircrafts), and, if driven at their maximum level, they suffer from a severe harmonic distortion. For these reasons, the experiments reported by Sollo *et al.* [7] are carried out with a reduced primary field, and the broadband noise control experiments, reported by Mathur *et al.* [9], focus on the frequency range above 250 Hz, instead of above 100 Hz for the loudspeaker-based active noise control experiments. Another problem is that the piezo patches induce very high local stresses in the aircraft fuselage and stiffeners. Finally, the piezoceramic materials, that are currently used, are very brittle, and up to this moment, it is not well-known whether they will withstand the high strains in a pressurised fuselage, or not.

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As an alternative to the outer fuselage, shakers or piezoceramic actuators can also be applied on the inner fuselage, or the trim, of an aircraft. The main drawbacks of this approach are, first, the high costs due to the necessary modification of the aircraft trim, and, second, the high number of control actuators required to achieve a considerable noise reduction. This latter fact is mainly due to the relatively high modal density of the lightweight trim panels [10,11]. As the use of shakers on the trim panel is considered, this conclusion is experimentally verified in the present paper, and by simulations by Grosveld [12]. The use of piezoceramic actuators attached to the trim panels, yielding so-called “speaking panels”, is discussed by Bondoux and Garnier [6].

Next to the cabin interior, the outer and the inner fuselage, also the trim cavity is a natural choice for installing an active noise control system. A number of researchers have previously investigated the use of active noise control in the cavity to reduce the sound transmission through double panel partitions. Grosveld and Shepherd [13] reported on some very basic experiments with an active noise control system implemented in the cavity between an aluminium and a composite plate. Sas *et al.* [14,15] also investigated the feasibility of improving the insertion loss of a light-weight double panel partition by using small loudspeakers as active noise control sources inside the air gap, and presented a detailed analytical, numerical and experimental analysis of the influence of the active control system on the double panel structure. De Fonseca *et al.* [16] used the same approach to reduce the sound transmission through a double-glazed window.

Based on the promising results obtained in these studies, this possibility is further investigated here for reducing the sound transmission through a stiffened double panel partition, serving as a model for a typical aircraft fuselage section. The use of control loudspeakers in the cavity is compared with the use of shakers on the trim panel. For this purpose, a model of the active control system was first developed and combined with a finite element model of the considered vibro-acoustic system. This yields an integrated simulation model of the actively controlled structure, allowing both structural and acoustical control. Second, the number, the type (structural or acoustical) and the locations of the control actuators and the error sensors were optimised in order to increase the performance of the active noise and vibration control system in terms of the reduction of the radiated sound power, averaged over the frequency band of interest. These

numerical simulation and optimisation studies are reported in references 17 and 18.

After the extensive simulation work, a detailed experimental study of the dynamic behaviour of the actively controlled double wall partition has been performed, and the results of it are reported in this paper. A filtered-X LMS algorithm is used to minimise the quadratic controller objective function, which consists of the sum of the squared error signals. Tests have been carried out with loudspeakers in the trim cavity and with shakers on the trim panel. The use of shakers on the stiffened skin panel has been discarded here, because the simulations [17,18] indicate that the required control forces are too high for the available actuators. As mentioned before, resonant actuators should be used for this kind of applications, but this is in contradiction with the desired performance over a broad frequency range in the present study. Both accelerometers on the trim panel and microphones in the trim cavity have been considered as error sensors.

## 2. Description of the experimental arrangement

The basic test set-up consists of a double wall partition, formed by two plane, parallel aluminium panels, clamped to a 10 mm thick and 100 mm high rectangular steel framework. The free dimensions of the plates are 1460 mm x 760 mm. This partition is mounted in the upper opening of a rigidly walled enclosure, which is built in the floor of a semi-anechoic room. A loudspeaker placed in this enclosure provides the acoustical excitation of the double wall structure. In this way the lower panel represents the outer fuselage of the aircraft, the skin panel, and the upper panel represents the inner fuselage, the trim panel. The free space above the upper panel can be seen as the passengers' cabin, while the loudspeaker simulates the propeller excitation. Figure 1 shows the position of the double wall on top of the enclosure.

In order to have a representative fuselage model, the dimensions and spacing of the so-called frames (i.e. the circumferential stiffening of the fuselage) and the stringers (i.e. the axial stiffening of the fuselage) on the plate on the incident side of the structure, the skin panel, are based on those found in a real aircraft. Two L-shaped aluminium beams are glued in the shortest direction of the skin panel, serving as frames. In the other direction, three rows of Z-

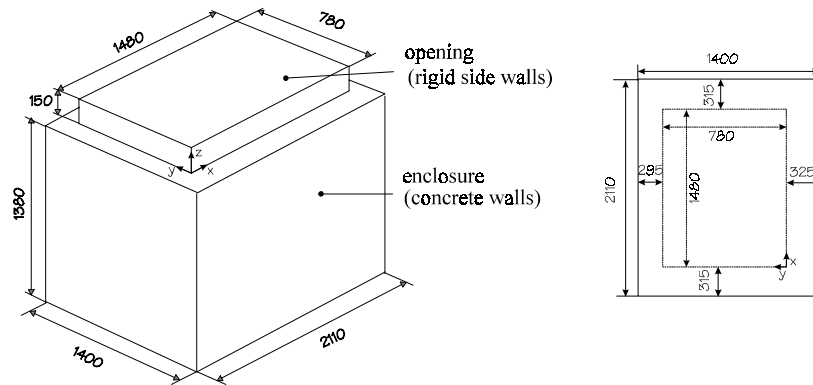


Figure 1 : Double wall set-up on top of the source enclosure.

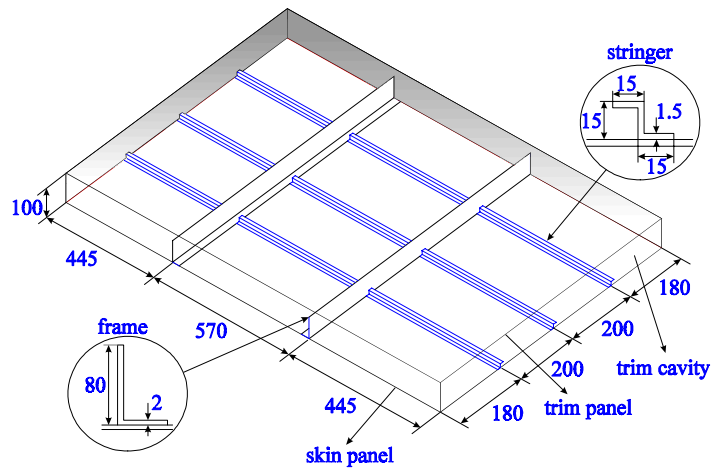


Figure 2 : Fuselage test section with the stiffened skin panel.

shaped aluminium beams are glued on the panel as stringers.

Figure 2 shows the stiffened skin panel. It's a 2,5 mm thick aluminium plate (1480 mm x 780 mm, if the loss of 20 mm due to the clamping devices is not taken into account). The stringers are 760 mm long and 2 mm thick. Their L-shape is 80 mm by 25 mm. The frames are 445 or 570 mm long and 1,5 mm thick. All their sides are 15 mm long.

The trim panel is an aluminium plate of 1,5 mm thick, 1480 mm long and 780 mm wide, covering the entire upper plane of the trim cavity.

The investigated frequency range in the active control measurements goes from 50 Hz to 250 Hz in order to cover the blade pass frequency (i.e. around 100 Hz) and its first harmonic. The double panel test set-up has about 80 coupled eigenmodes in this frequency band of interest. Due to this relatively high modal density, the response of the system is often dominated by more than one eigenmode at a single frequency. This increases the difficulty of the control task, and consequently, the selection of the control actuator and error sensor locations becomes more important.

An implementation of the filtered-X feedforward algorithm in the Digisonix [19] environment has been used for all tests. The controller hardware is based on a TMS320C40 digital signal processing board. The reference signal for the feedforward algorithm is the driving signal of the loudspeaker in the enclosure below the double panel. This choice for the reference signal is analogous to the situation in a propeller aircraft where the tachosignal from the motors is used as a reference. In some preliminary tests, also a microphone in the box was used as a reference, but the acoustical feedback from the control loudspeaker to this reference microphone deteriorated somewhat the performance of the active control system. Therefore, the subsequent tests were conducted with as reference the electrical signal to the primary sound source, which is not influenced by the control action.

The double panel partition was excited tonally by driving the primary sound source with a stepped sine wave signal with a frequency going up from 50 to 250 Hz with a 1 Hz resolution. The actual measurements were carried out over 16 cycles for each frequency line, after a stabilisation period of

16 cycles (in order to eliminate the transients due to the frequency step). This measurement set-up is similar to the situation in a real aircraft where the propeller excitation is also harmonic, but its frequency content changes during flight, depending on the flight condition (e.g. take off, climb, cruise, high speed cruise, approach, landing, ...). Moreover, a harmonic excitation was also tacitly assumed in the simulations [17,18], which were all carried out in the frequency domain.

The performance criterion, which has been used to evaluate the quality of the different active control configurations, is based on the sound pressures in nine evaluation microphones in a plane about 1.5 m above the trim panel :

$$\Pi_e(f) = \frac{1}{9} \sum_{i=1}^9 |p_i(f)|^2 . \quad (1)$$

This performance criterion is proportional to the sound power radiated by the trim panel, under a far field assumption. It is called the ‘experimental objective function’ in the remaining part of this text, because of its relation with the ‘theoretical objective function’ used in the numerical simulation and optimisation studies in [17,18].

### 3. Combined active noise and vibration control

#### 3.1 Discussion of the measurement results

Combined active noise and vibration control refers to all control systems with either loudspeakers or shakers as control actuators, and with either accelerometers or microphones as error sensors. Six different sets of error sensors have been used, three of them being microphones and the other three accelerometers. Also three different sets of control loudspeakers and three different sets of control shakers have been used. Each set of control actuators contains two speakers or two shakers, and each set of error sensors contains four microphones or four accelerometers. The first set of loudspeakers and the first set of microphones are the result of the numerical optimisation process [17]. In the second set, the loudspeakers are located in the two opposite corners of the trim cavity, which can be considered as a good configuration based on some engineering judgement. The first set of control shakers and error accelerometers are also the result of an optimisation process, allowing only structural exciters and transducers. All other sets are arbitrarily chosen.

The results of the experiments with combined active noise and vibration control are summarised in table

1, which gives the reduction in the objective function for different control systems with four error sensors and two control actuators.

As appearing from table 1, active noise control in the trim cavity is more efficient for reducing the sound transmission through the double panel partition than active vibration control on the trim panel. The modal density of the cavity is much lower than that of the trim panel, which makes that the sound pressure waves in the cavity are much easier to control with a limited number of actuators (two) than the vibrations of the trim panel. Due to the relatively high flexibility of the trim panel, the active vibration control system has only a local control effect in the close neighbourhood of the error sensors, without reducing the vibration level of the entire trim panel. Figure 3 shows the spectrum of the experimental objective function for the double wall without active control (solid line), with an active noise control system (dash-dotted line) in a configuration, which has been optimised by means of the simulation model (loudspeaker set 1 and microphone set 1), and with an active vibration control system (dotted line) on the trim panel, also in an optimised configuration (shaker set 1 and accelerometer set 1). The active noise control system in the cavity reduces the sound transmission through the double wall structure much more than the active vibration control system.

		Loudspeaker set			Shaker set		
		1	2	3	1	2	3
Micro- phone set	1	6.6	4.7	1.5	-1.7	-4.8	-4.7
	2	6.2	4.3	0.1	-2.2	/	/
	3	4.6	2.3	0	-1.8	/	/
Accele- rometer set	1	2.9	/	0	2.3	-4.3	0
	2	3.7	3.2	-1.6	1.1	-2.8	/
	3	3.5	/	-1.3	1.8	/	-2.3

Table 1 : Average reduction [dB (ref.  $2.10^{-5}$  Pa)] of the experimental objective function between 50 and 250 Hz.

In general, loudspeakers in the trim cavity perform better than shakers on the trim panel for controlling the sound transmission through the double panel partition, as well with microphones in the cavity as error sensors, as with accelerometers on the trim panel.

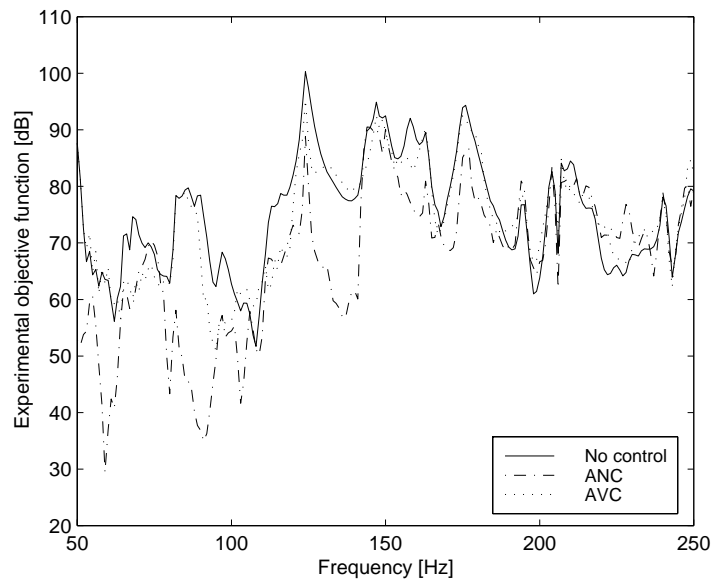


Figure 3 : Comparison of active cavity noise control (dashed line) with active trim panel vibration control (dotted line)

### 3.2 Interpretation of the results

The measurements presented above prove that the active noise control using control loudspeakers and error microphones in the cavity provide a very efficient means for reducing the sound transmission through the double wall. This active cavity noise control system essentially reduces the acoustical potential energy in the cavity of the double panel partition, but, due to the vibro-acoustic coupling, this also results in a reduced sound radiation. To illustrate this, figure 4 shows the relation between the reduction of the radiated sound from the upper panel, averaged over the frequency band of interest, and the averaged reduction of the acoustic potential energy in the cavity, for all tests that have been carried out with different numbers of control loudspeakers and error microphones in different locations in the cavity. This acoustic potential energy is calculated from the measured sound pressures in nine microphones in the cavity. The error microphones were always chosen amongst these nine cavity microphones. The distribution of the results in figure 4 shows that there exists an almost linear relation between the (linear) reductions in the acoustic potential energy and the (linear) reductions in the radiated sound power. The correlation coefficient of the linear regression equals 97 %. This linear relationship indicates that the dominating control mechanism, in the application being considered, is modal suppression of the cavity modes [20]. This explains why the reductions in figure 3 are much higher in the lower frequencies than in the higher frequencies (from

180 Hz on). Below 180 Hz, the sound field in the cavity is dominated by only a few eigenmodes that can easily be controlled by two control sources. Above 180 Hz, the modal density becomes higher and the control system is not able anymore to reduce all modes simultaneously.

The modal suppression control mechanism is most efficient for systems with low modal densities, the first reason therefore being that the number of dominating modes in the system determine the required number of actuators. Next to this physical reason, there is also a second, more practical, reason. The feedforward algorithm uses FIR filter models of the impulse response functions from the control actuators to the error sensors over the entire frequency band of interest. The higher the modal density, the more complex these impulse response functions are. The accurate experimental identification of complex impulse response functions is difficult, and the corresponding FIR filters are long, which results in high computational loads for the digital signal processor. Therefore, an FIR filter based control system can control a system with a low modal density much more efficiently than a system with many modes in the frequency band of interest, even when a sufficient number of actuators are available.

These two obvious reasons indicate that in a noise transmission problem the active noise or vibration cancellation system is preferably installed in the subsystem of the transmission path with the lowest modal density. In the double panel set-up, the subsystem with the lowest modal density in the transmission path from the disturbing source in the

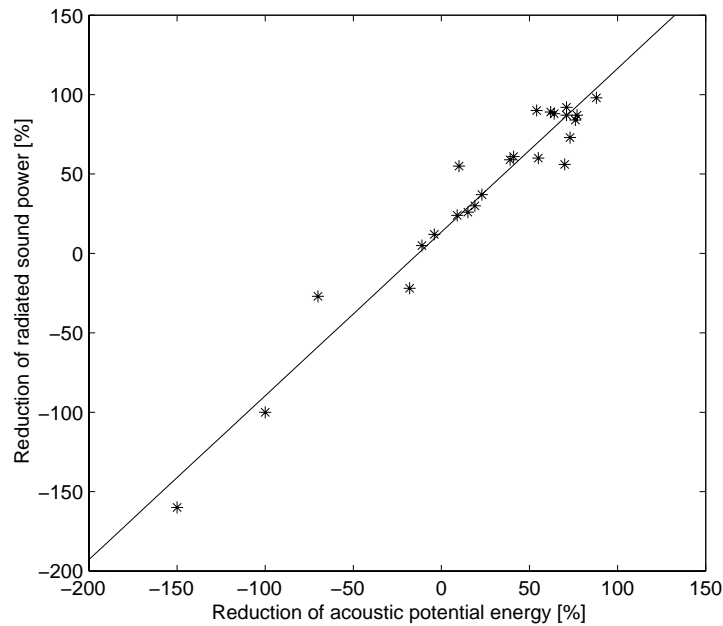


Figure 4 : Relation Between the reduction of the radiated sound power from the upper panel and the reduction of the acoustic potential energy in the cavity

enclosure to the radiated field, is the cavity. For that reason, the active noise control in the cavity yields much better results than the active structural acoustical control on the trim panel.

The sound transmission through the trim cavity in a propeller aircraft is most important in the area around the propeller plane. Due to the thermal insulation material and the circumferential stiffeners, which divide the trim cavity in more or less uncoupled compartments, this local excitation of the acoustic medium in the trim cavity does not propagate very much in the axial direction of the plane. Therefore, an active trim cavity noise control system can be concentrated in that area, instead of covering the entire aircraft. This local installation results in important savings in electrical wiring from the controller to the control loudspeakers. Moreover, due to the weak coupling between different compartments in the trim cavity, one might diagonalise the controller, or even use a modular control system design. Depending on the customer's requirements, more independent modules can then be added to the active control system to provide higher levels of acoustical comfort in the passengers' cabin.

Of course, the active cavity noise control approach has also some important drawbacks. In comparison with the use of piezo-electrical control actuators, the weight of the loudspeakers is one important drawback of the active trim cavity noise control. Also the space requirements of the control loudspeakers in the trim cavity are subject to similar

limitations as in the case of a classical active noise control system in the cabin interior. There, the back cavities of the control loudspeakers are generally also incorporated in the cavity behind the trim panel. Finally, it can be expected that a larger number of small loudspeakers will be needed to achieve a specified cabin noise reduction than for a classical speaker-based cabin noise control system. However, a proper diagonalisation of the controller should in that case limit the increased computational load.

### 3.3 Relation with other research work

The experimental results presented in the previous section agree well with the conclusions drawn by other researchers. From extensive simulations with a coupled FEM/BEM model of an aircraft, Grosveld [12] finds that acoustic control sources in the trim cavity yield higher reductions in the interior sound field, due to an exterior acoustic source, than point forces either on the outer or on the inner fuselage. Similarly, Gardonio and Elliot [21] conclude from active noise control studies on a simulation model of a double panel partition that loudspeakers in the cavity yield a much higher transmission loss than active mounts between the two panels. Based on experimental active noise control studies on a symmetrical double wall, Bao and Pan [20] also show that an active control system in the cavity between the panels is often superior to a vibration control system with a shaker on the radiating panel.

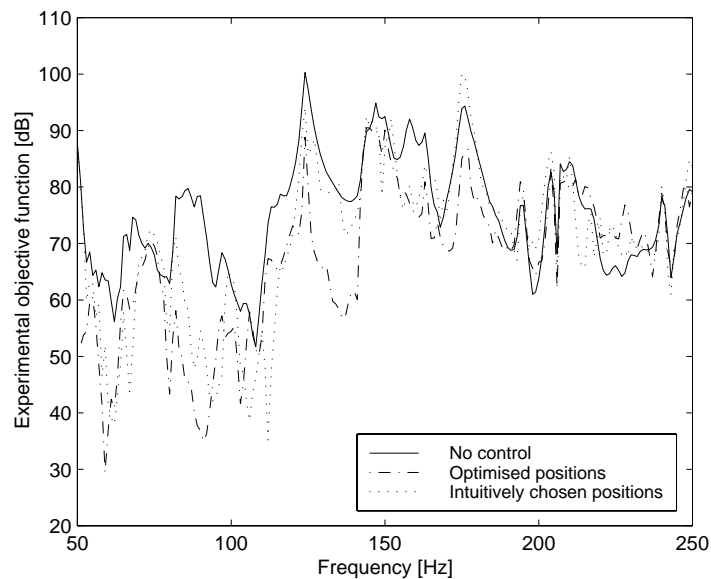


Figure 5 : Performance of an active noise control system with two loudspeakers in optimised positions (dashed line) and in intuitively chosen positions (dotted line)

#### 4. Validation of the optimisation studies

The control configurations which have been optimised by means of the integrated simulation model perform much better than the arbitrarily chosen configurations. This is true, on the one hand, for the type of error sensors (microphones in the trim cavity or accelerometers on the trim panel) and control actuators (loudspeakers in the trim cavity or shakers on the trim panel). The results of the numerical optimisation [17] also indicated that acoustic control in the trim cavity is more efficient than structural control on the trim panel.

On the other hand, the acoustical control system in the trim cavity with loudspeakers and microphones in optimised locations gives better results than the same control system with loudspeakers and microphones in arbitrarily chosen positions. Figure 5 compares the performances of a control system with two control loudspeakers in optimised positions (dashed line) and in intuitively chosen positions (dotted line). The control system has four error microphones in positions which were optimised together with the optimised control loudspeaker positions. The optimised control configuration is clearly much better than the one with the loudspeakers in two opposite corners of the set-up, which could have been selected as ‘good’ positions with some engineering judgement.

Also when other error microphone positions are used, the performance of the control system with

optimised loudspeaker positions is still better than with intuitively chosen loudspeaker positions.

The experimental validation of the optimised control configurations is very important in light of the conclusions drawn in the previous section. If one would compare the active trim panel vibration control approach using the shaker set 1 and accelerometer set 1 with the active cavity noise control approach with loudspeaker set 3 and any of the microphone sets, the conclusion would unavoidably be that active vibration control on the trim panel is better suited to reduce the sound transmission through the double panel than active noise control in the cavity. However, when comparing the optimised configurations for both approaches, one must conclude the opposite. This indicates that conclusions drawn from comparisons between non-optimised control system configurations (e.g. [12,20]) should be taken with some care.

#### 5. Influence of the boundary conditions

Figure 6 compares the performances of the same optimised active noise and vibration control system configurations as in figure 3, but for a slightly modified test set-up. The trim panel is now connected to the frames by means of four vibration isolators, identical to those used in airplanes. The measured spectra in figure 6 show that the optimised active noise control configuration still performs much better than the optimised active

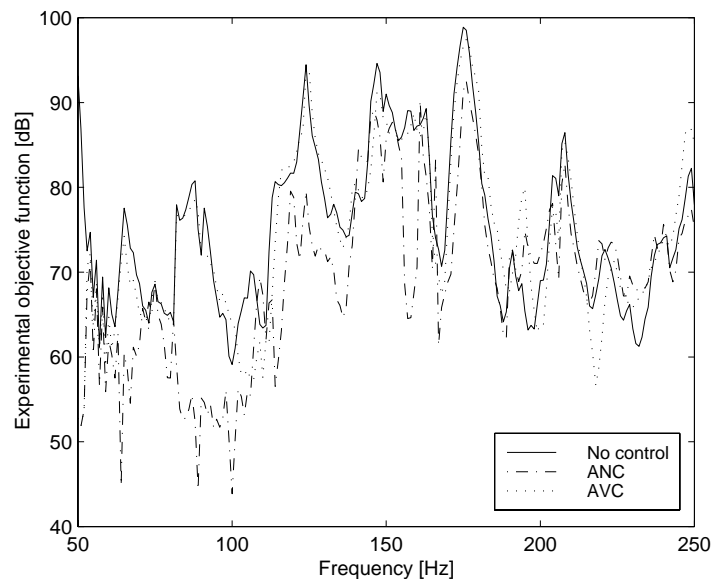


Figure 6 : Comparison of active cavity noise control (dashed line) with active trim panel vibration control (dotted line) on the test set-up with vibration isolators between the skin and the trim panel.

vibration control configuration, which hardly succeeds in reducing the radiated sound power. Despite the mechanical connection between the skin and the trim panel, the active cavity noise control system still provides significant reductions in the sound transmission through the double panel partition. This indicates that the air-borne sound transmission path is far more important than the structure-borne path, and, hence, that the vibration isolators successfully prevent the energy to be transmitted from the skin to the trim panel via the mechanical connection.

The influence of porous thermal insulation blankets in the cavity on the performance of an active cavity noise control system was investigated in some preliminary tests, conducted on the same test set-up but with a different active control configuration. These tests clearly showed that the porous material does not provide any improvement in the sound transmission characteristics of the double wall in the low-frequency range (below 200 Hz), and that the performance of the active cavity control system in that frequency range remains almost unaffected. Gardonio and Elliot [21] come to exactly the same conclusion from an extensive simulation study of the active reduction of the sound transmission through a double panel system representing a section of a civil aircraft fuselage.

## 6. Conclusions

A detailed experimental study of the possibilities for reducing the sound transmission through an aircraft fuselage test section by means of an active noise and vibration control system is presented in

this paper. A previously developed simulation model has been used in an optimisation process, based on a genetic algorithm, to select the best spatial configuration, in terms of the reduction of the radiated sound power, for the error sensors and the control actuators.

The experimental analysis shows that the control configurations which have been optimised, perform much better than the arbitrarily chosen configurations. On the one hand, this is true for the type of error sensors and control actuators. On the other hand, the acoustical control system in the trim cavity with loudspeakers and microphones in optimised locations gives better results than the same control system with loudspeakers and microphones in arbitrarily chosen positions. This conclusion remains valid when the skin and the trim panel are mechanically connected by means of four vibration isolators, and when the cavity is filled with thermal insulation blankets.

It also appears that, in case of an active cavity noise control system, there exists an almost linear relation between the reduction of the acoustic potential energy in the cavity and the reduction of the radiated sound power.

Finally, it can be stated that a successful implementation of an active noise and vibration control system on a complex vibro-acoustic structure requires a detailed study of the considered system and its interaction with the control system. The present work illustrates that the optimisation of the positions of the control actuators and the error sensors undoubtedly forms one of the critical success factors of such a detailed study.

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