Reducing airplane cabin and fuselage noise using active and passive control techniques

Ahmed Abu Hanieh

Mechanical and Mechatronics Engineering Department,
Birzeit University,
Birzeit, Palestine
Email: ahanieh@birzeit.edu

Abstract: The focus of this research is on making a wide discussion about the sources and control techniques of noise propagating to the passenger airplane cabin and fuselage. The first part of the document discusses the effects of vibration induced noise (vibro-acoustic) transmitted from airplane engines and aerodynamic impact on the main body of the aircraft besides to air-conditioning vibrations. These vibrations transmit noise to the cabin and fuselage causing discomfort to passengers. Finite element modelling technique is used to make this study. Two different solutions are suggested to control and get rid of these vibrations; passive control techniques using tuned mass dampers is one of the suggested solutions and the second solution is an active control technique using piezoelectric actuator and force sensor with integral force feedback compensator. The performance of the active control is much higher than that of the passive one but it is much more expensive.

Keywords: aircraft cabin noise; active control of vibrations; passive control of vibrations; tuned mass damper; integral force feedback; IFF.

Reference to this paper should be made as follows: Abu Hanieh, A. (2023) ‘Reducing airplane cabin and fuselage noise using active and passive control techniques’, *Int. J. Vehicle Noise and Vibration*, Vol. 19, Nos. 1/2, pp.67–77.

Biographical notes: Ahmed Abu Hanieh is a Professor in the Department of Mechanical and Mechatronics Engineering at Birzeit University since 2004 and worked as the Department Chairman for three years. He supervised two doctorate students in European Universities. He supervised several Bachelor graduation projects and Master theses. He is a board member in the Higher Council for Innovation and Excellence in Palestine for six years. He is the author of two books, more than 20 journal articles and more than 30 conference papers and a volunteer reviewer for more than 17 international specialised journals and conferences. His teaching interests are: mechanical vibrations, fluid power control, dynamics, measurements and sustainable engineering courses.

1 Introduction

Vibro-acoustic and aero-acoustic noise are becoming a dramatical stringent problem in most of the recent designs of vehicles, ships, trains and airplanes. Vibro-acoustic noise is a broadband disturbance caused by external functioning engines or aerodynamic contact during high speed motion. Liu et al. (2006) discuss the problem of controlling in-box noise focusing on airplane cabin noise. The authors used different passive and active techniques based on structural intensity approach. This research used the Helmholtz's integral equation to build a mathematical model for the airplane body and enhanced it with finite element analysis.

The sound pressure level reduction can be calculated using the formula in equation (1) (Abu Hanieh and Al Balasie, 2021).

$$L_p = L_N + 10\log_{10}\left(\frac{D}{4\pi r^2} + \frac{4(1-\alpha_m)}{S_a}\right) \tag{1}$$

where:

L_p Sound pressure level received by the passenger in dB.

L_N Sound pressure level produced from the jet engine in dB.

α_m The average absorption coefficient.

D The directivity coefficient.

r The distance between passenger and jet engine on the wing.

And

$$S_a = \sum_{i=1}^{n} A_i \alpha_i$$

where:

S_a The total cabin sound absorption.

A_i The surface area of each sheet in the external airplane body.

n The number of sheets.

α_i The absorption coefficient of each sheet (depends on material and frequency).

Soeta and Shimokura (2009) made a comparison between airplane and train cabin, a dummy head microphone is used to measure and control noise, this study has been made in Japan to reduce the effect of noise in national transportation. The dynamic testing and modelling of crashed aircraft cabin is discussed in Heimbs et al. (2013). Experimental tests supported by finite element analysis was done by these researchers to test the influence of crash on the body of the aircraft taking into account impact and materials in manufacturing the external body. One of the main problems of airplane noise is the effect of noise on underwater noise in oceans (Erbe et al., 2018), but this problem is not included in our research here and cannot be involved in the suggested solutions. Fernández et al. (2007) discussed an original research on the monitoring of aircraft noise using spectral patterns and neural networks, the noise level was found to be between 5 dB and 100 dB, the researchers used radar, GPS and environmental monitoring unit (EMU), all signals are acquired using central processing unit and they used *Bartlett-Welch* method for spectral elimination. Transient response and dynamic failure of aircraft skin due to fluid-metal interaction caused by explosive shock is studied by Kamoulakos et al. (1996). This study can have a great influence in the current research when talking about the influence of sudden accidents or hits on the external airplane body. Linde et al. (2004)

established a virtual testing for stiffened panels of airplane fuselage, ANSYS software was used to hold the finite element analysis and compared to the buckling pattern test rig showing matching results. The design of fuselage and the crashworthy material used to construct the airplane skin is discussed by Delsart et al. (2004); this study aims at designing a new energy absorbing composite to reduce crash influence, at the same time this composite can help in reducing vibro-acoustic noise by absorbing sound energy induced by vibrations. Crash absorber has been studied by Heimbs et al. (2011) where the researchers used vertical struts with integrated energy absorbers and fibre composites. Ravettal et al. (2007) studied the aero-acoustics of landing gear in Boeing 777, The experimental set-up was tested in Virginia Tech stability wind tunnel. A 600 hp DC motor driving 4 m propeller was used in a 7 m wind tunnel to simulate the real system at a maximum speed of 180 km/h, a shock strut fairing was installed to reduce the aero-acoustic effect. Vibro-acoustics in automobile cabins is discussed by Ang et al. (2016), the researchers used here Helmholtz resonator at 200 Hz, passive sound absorption materials, viscoelastic damping treatment, dynamic vibration absorber and active controls including active control and active structural control. The acoustical society of Japan in their technical report (Bui et al., 2021) studied the effect of measured noise in military aircraft on the validity of aircraft noise in Vietnam. Lawver et al. (2001) presented a nonlinear model for the impact of airplane on reinforced concrete and steel shelters; finite element modelling is used to enhance this study. Schwinn (2015) conduced a similar study about crashworthy design. A very important research was conducted by White et al. (1997) about engine-excited vibro-acoustic noise in commercial airplanes, where a nonlinear mathematical model was tackled and compared to experimental results. Solutions and controls of the problem of noise in passenger aircraft are discussed in Kuznetsov (2003). The importance of noise reduction in vehicle structures is tackled by Qatu (2012) and Qatu et al. (2009) where the authors explain the major influence of noise and vibrations on the different structures of vehicles proving that reducing these vibrations is a stringent behaviour in all designs.

After this introduction and literature review, the skin of the airplane is studied using finite element modelling technique in the next section, the different solutions to reduce vibro-acoustic noise in airplanes is discussed in further section showing passive and active control methodologies.

2 Finite element model

Both, vibro-acoustic and aero-acoustic noise signals propagate to the airplane cabin and fuselage disturbing pilots and passengers. The noise transmission is conducted through the airplane body skin manufactured from aluminium composite material. A typical design of the airplane skin is shown in Figure 1, where it consists of 2 mm aluminium sheets curved with a radius of 2 metres. The skin is supported by 200 mm beams with a span of 50 cm.

The part of the airplane skin shown in Figure 1 has been simulated using COMSOL software finite element simulation to study the dynamic response, modes and mode shapes of the skin. Figure 2 shows the first 4 dynamic eigenfrequencies showing their frequency and displacement.

Figure 1 Typical design of the airplane body skin (see online version for colours)

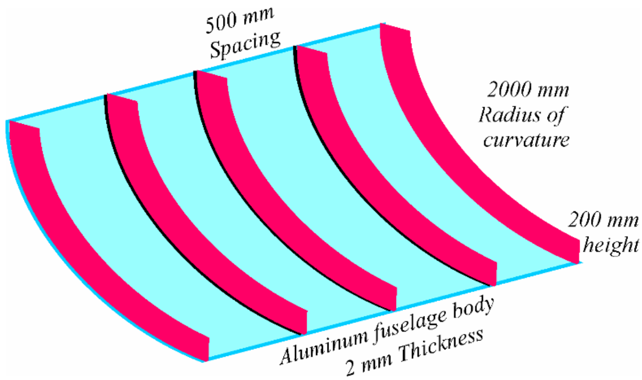
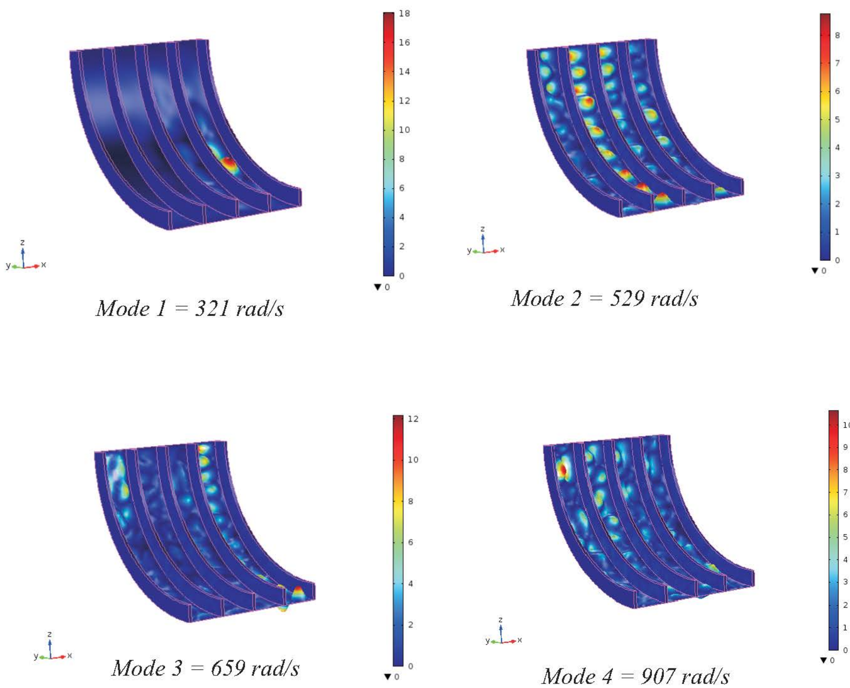


Figure 2 Eigenfrequencies of shell representing the airplane skin (see online version for colours)



To widen the airplane body model, a complete model for fuselage has been tested using finite element analysis in COMSOL software. Figure 3 shows the CAD design of fuselage section with the aircraft deck using the same parameters of the previous sub-model where the skin thickness is 2 mm and the whole diameter is 4 m.

The modes and mode shapes of the fuselage finite element model are shown Figure 4. It is clear that the maximum strain energy and deflections lie between the supporting beams. These are the most important places where control can be placed to reduce the vibrational motion leading to reduce the acoustical transmission through the skin.

Figure 3 CAD design of aircraft fuselage section (see online version for colours)

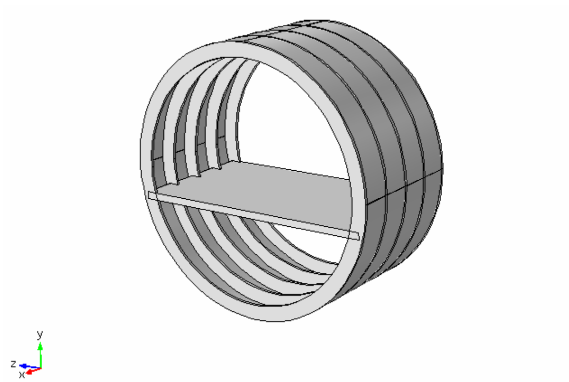
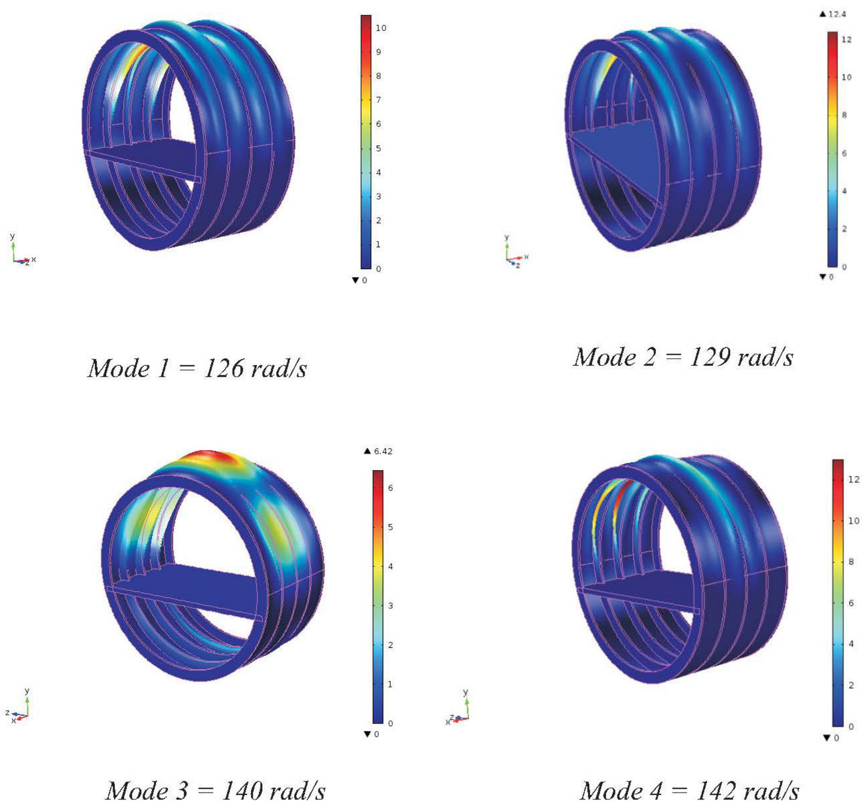


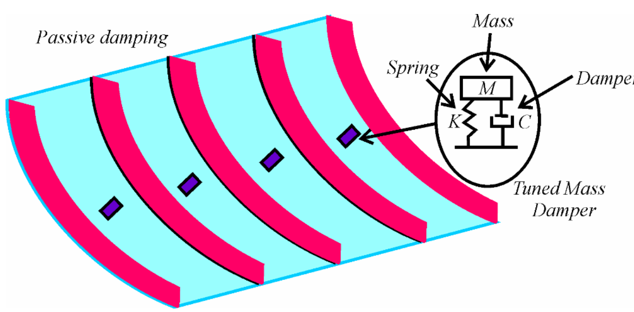
Figure 4 Modes and mode shapes of fuselage skin in finite element model (see online version for colours)



3 Active and passive control of vibrations

Noise induced in airplane cabin and fuselage are transmitted mainly by vibrations of airplane body skin by the external disturbance coming from either the airplane jet engines or aerodynamic effect from the contact between wind and airplane body. These vibro-acoustics and aero-acoustics can be reduced and prevented from propagating to the cabin by eliminating the vibrations of the skin. Vibrations of skin can be reduced or eliminated using passive or active techniques. The first passive technique is by using tuned mass dampers (TMD) as shown in Figure 5, TMD is a simple oscillator unit consists of a mass; spring and damper adhered to the skin of the aircraft on the maximum strain energy spots to act passively against the vibration of that part. The natural frequency of the TMD is selected to be close to the mode required to be damped and damper works to reduce the overshoot of that mode. One of the drawbacks of using TMD solution is that it needs adding more masses on the skin of the aircraft but it is cheap and very easy to use and install.

Figure 5 Passive tuned mass damper TMD to damp vibrations of skin (see online version for colours)



The second method is to use active damping method; this can be implemented by installing an active strut between a fixed frame and the skin of the airplane as shown in Figure 6. The active strut (Figure 7) consists of collocated piezoelectric actuator and force sensor connected from both sides by flexible joints to avoid lateral moments or forces that can break the piezoelectric stack. The drawback of this method is that it is expensive and costly but it gives much higher control authority than TMD solution.

Figure 6 Active control method using active strut (see online version for colours)

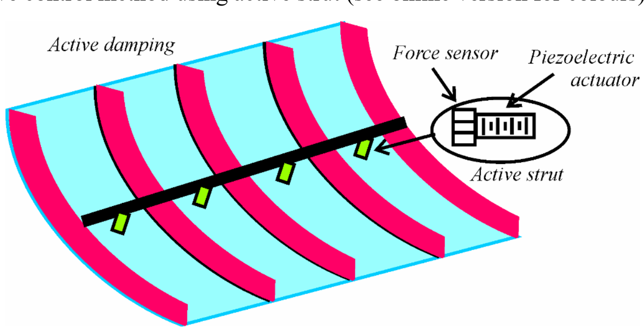


Figure 7 Active strut

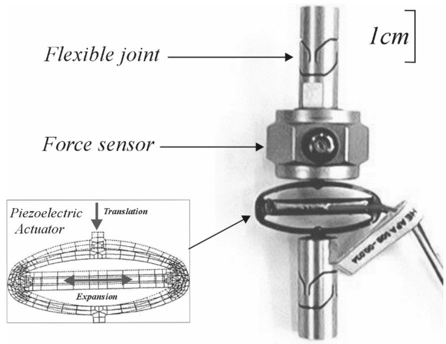


Figure 8 Free body diagram of the TMD system

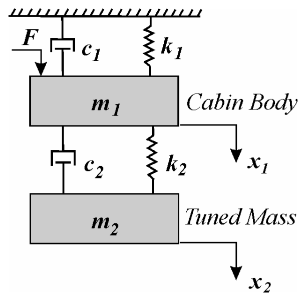
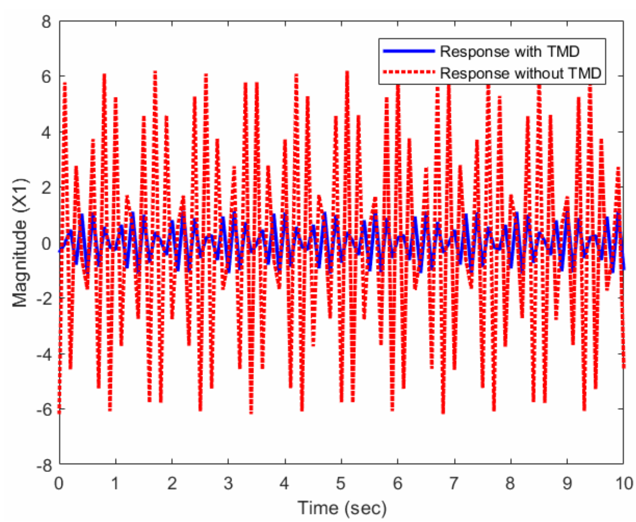


Figure 9 Time response of body skin displacement x_1 (see online version for colours)



4 Passive tuned mass damper control results

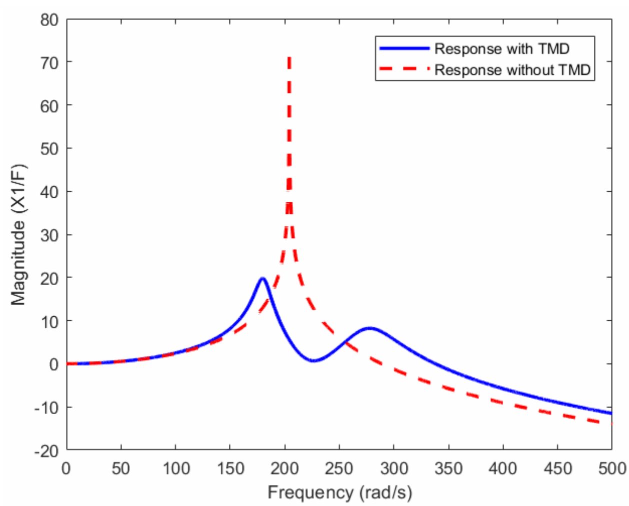
TMD is simply a mass attached to an elastomer where the elastomer provides the stiffness and damping of the system. Figure 8 shows a free body diagram of the systems where m_1, k_1, c_1 are respectively the mass, stiffness and structural damping of the aluminium skin of the airplane; and m_2, k_2, c_2 are respectively the mass, stiffness and passive damping of the TMD. F is the external disturbance force exerting on the airplane skin.

The equations of motion of the system read:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} F \\ 0 \end{Bmatrix} \quad (2)$$

The time response of the cabin body skin x_1 with and without using TMD is shown in Figure 9. The frequency response function between the excitation force as an input and the displacement of the cabin body as an output is depicted in Figure 10.

Figure 10 Frequency response function between the force as input and skin displacement as output with and without using TMD (see online version for colours)



5 Active control with integral force feedback (IFF)

The other suggested control method is the active control technique shown in Figure 11. The technique consists of an active strut of linear piezoelectric actuator ($ka + \delta$) collocated with force (F) sensor, the strut is connected to the body skin on a maximum strain energy spot to oppose the vibrations of the skin (M), k and c are the structural stiffness and damping of the aluminium skin. The active control is implemented here by measuring the force signal coming from the force sensor and feeding it back to the piezoelectric actuator through an Integration compensator; this is why this technique is called IFF.

Figure 11 Free body diagram of active control with IFF

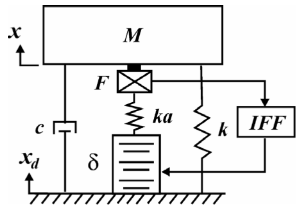
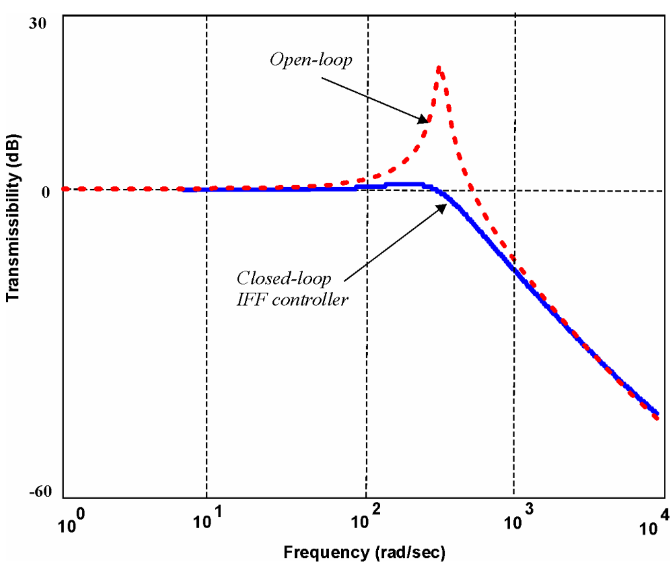


Figure 12 shows the transmissibility frequency response function between the disturbance displacement x_d and the skin displacement x with and without control. It is clear from this figure that the overshoot at the natural frequency has completely disappeared in keeping the attenuation at high frequency; this property is done by the influence of using active control with IFF controller. The impact and performance of the active control is much higher than that of the passive control besides that this control method is robust and safe.

Figure 12 Transmissibility frequency response function between the disturbance displacement x_d and the skin displacement x with and without control (see online version for colours)



6 Conclusions and recommendations

The foregoing research tackled the problem of eliminating vibro-acoustic and aero-acoustic noise induced in the cabin and fuselage of a passenger aircraft. The study assumes that the noise is generated in the jet engines and aerodynamics and propagates into the cabin through the aircraft body aluminium skin by vibrating these metal sheets. Two solutions were suggested; one is passive by using TMD and distributing them on the skin of the aircraft from inside. This method is an economic method but it adds more weight to the airplane. The second solution is the active control method. In the active control method piezoelectric actuator and force sensor are installed in a collocated place to ensure stability and robustness. The active control techniques are stable and efficient but it is expensive. It is recommended to use a mixture of the two techniques where active struts can installed in the most important places and the passive mounts can be installed in the less important ones.

References

Abu Hanieh, A. and Al Balasie, A. (2021) 'Noise and vibrations reduction of stone cutting factories', *International Journal of Mechanical & Mechatronics Engineering*, Vol. 21, No. 1, pp.48–63.

Ang, L.Y.L., Koh, Y.K. and Lee, H.P. (2016) 'Acoustic metamaterials: a potential for cabin noise control in automobiles and armored vehicles', *International Journal of Applied Mechanics*, Vol. 8, No. 5, p.1650072.

Bui, T.L., Nguyen, T.L., Morinaga, M., Morihara, T. and Hiraguri, Y. (2021) 'Effect of measurement-based noise source model of military airplanes on the validity of aircraft noise estimation in Vietnam', *Acoustical Science and Technology*, Vol. 42, No. 1, pp.50–57.

Delsart, D., Joly, D., Mahe, M. and Winkelmuller, G. (2004) *Evaluation of Finite Element Modelling Methodologies for the Design of Crashworthy Composite Commercial Aircraft Fuselage*, Office National D Etudes Et De Recherches Aerospatiales Onera-Publications-TP 188.

Erbe, C., Williams, R., Parsons, M., Parsons, S.K., Hendrawan, I.G. and Dewantama, I.M.I. (2018) 'Underwater noise from airplanes: an overlooked source of ocean noise', *Marine Pollution Bulletin*, December, Vol. 137, pp.656–661.

Fernández, L.P.S., Pogrebnyak, O., Rodríguez, J.L.O. and Guerra, S.S. (2007) 'Noise pattern recognition of airplanes taking off: task for a monitoring system', in *Iberoamerican Congress on Pattern Recognition*, Springer, Berlin, Heidelberg, pp.831–840.

Heimbs, S., Hoffmann, M., Waimer, M., Schmeer, S. and Blaurock, J. (2013) 'Dynamic testing and modelling of composite fuselage frames and fasteners for aircraft crash simulations', *International Journal of Crashworthiness*, Vol. 18, No. 4, pp.406–422.

Heimbs, S., Strobl, F. and Middendorf, P. (2011) 'Integration of a composite crash absorber in aircraft fuselage vertical struts', *International Journal of Vehicle Structures & Systems*, Vol. 3, No. 2, p.87.

Kamoulakos, A., Chen, V., Mestreau, E. and Lohner, R. (1996) *Finite Element Modelling of Fluid/Structure Interaction in Explosively Loaded Aircraft Fuselage Panels using PAMSHOCK/PAMFLOW Coupling*, European Space Agency-Publications-ESA SP 386, pp.831–844.

Kuznetsov, V.M. (2003) 'Noise control problems of passenger airplanes (a review)', *Acoustical Physics*, Vol. 49, No. 3, pp.241–262.

Lawver, D., Nikodym, L., Tennant, D. and Levine, H. (2001) 'Non-linear numerical modelling of aircraft impact', *International Journal of Crashworthiness*, Vol. 6, No. 4, pp.451–470.

Linde, P., Pleitner, J. and Rust, W. (2004) 'Virtual testing of aircraft fuselage stiffened panels', in *Proceedings of ICAS.*

Liu, Z.S., Lee, H.P. and Lu, C. (2006) 'Passive and active interior noise control of box structures using the structural intensity method', *Applied Acoustics*, Vol. 67, No. 2, pp.112–134.

Qatu, M.S. (2012) 'Recent research on vehicle noise and vibration', *International Journal of Vehicle Noise and Vibration*, Vol. 8, No. 4, pp.289–301.

Qatu, M.S., Abdelhamid, M.K., Pang, J. and Sheng, G. (2009) 'Overview of automotive noise and vibration', *International Journal of Vehicle Noise and Vibration*, Vol. 5, Nos. 1–2, pp.1–35.

Ravettal, P.A., Burdisso, R.A. and Ng, W.F. (2007) 'Screening of potential landing gear noise control devices at Virginia tech for QTDII flight test', *13th AIAA in CEAS Aeroacoustics Conference*, AIAA.

Schwinn, D.B. (2015) 'Parametrised fuselage modelling to evaluate aircraft crash behaviour in early design stages', *International Journal of Crashworthiness*, Vol. 20, No. 5, pp.413–430.

Soeta, Y. and Shimokura, R. (2009) 'Comparison of noise characteristics in airplanes and high-speed trains', *Journal of Temporal Design in Architecture and the Environment*, Vol. 9, No. 1, pp.22–25.

White, J.L., Heidari, M.A. and Yantis, T.F. (1997) 'A study of engine excited non-linear vibro-acoustics in commercial airplanes', in *Proceedings-SPIE the International Society for Optical Engineering*, SPIE International Society for Optical, pp.1503–1509.