AIRCRAFT INTERIOR NOISE REDUCTION THROUGH A PIEZO TUNABLE VIBRATION ABSORBER SYSTEM

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Abstract

Turboprop aircrafts, such as Airbus A400M, are challenged amongst others by high interior noise levels due to tonal propeller-induced vibrations of the aircraft structure. One approach for interior noise reduction is the reduction of fuselage vibrations by vibration absorbers. In the case of variable propeller speed, the vibration absorbers have to be tuned to the variation of the blade passage frequency (BPF) and its harmonics. In this paper, a tuneable vibration absorber (TVA) system based on the emerging piezoelectric technology is proposed. Embedding piezoceramic elements into a GFRP leaf-spring represents the core element of a force generator amenable to direct electrical control. Depending on the control law, a tuneable vibration absorber is realized. In general, an actuator for active vibration control is achieved.

For the Piezo-TVA system proposed, piezo leaf-spring absorbers have been designed for a fundamental BPF at 87.3Hz as well as its first harmonics. Absorber prototypes are manufactured and control laws are designed, simulated and implemented into a dSPACE system. The system is tested on a realistic aircraft fuselage panel (main dimensions similar to A320) installed into a transmission loss test suite where the panel is acoustically excited. A vibration reduction performance of up to 40dB and a noise reduction performance of up to 13dB are demonstrated. Moreover, a multi-mode operation of the TVA system is presented as well as its high flexibility required for optimum system configuration during flight tests. The proposed system is extremely beneficial with respect to guaranteed performance, high flexibility and a minimum weight realization.

1 Introduction

Turboprop aircrafts, such as Airbus A400M presented in Fig. 1, are challenged amongst others by high interior noise levels due to tonal propeller-induced vibrations of the aircraft structure. One approach for interior noise reduction is the reduction of fuselage vibrations by vibration absorbers [1], [2]. In the case of variable propeller speed, the vibration absorbers have to be tuned to the variation of the blade passage frequency and its harmonics. The blade passage frequency is defined as $1BPF = n \cdot rpm / 60$, where n denotes the number of propeller blades.

Fig. 1 Airbus A400M turboprop aircraft

A tuneable vibration absorber (TVA) system based on the emerging piezoelectric technology is proposed. Embedding piezoceramic elements into a GFRP leaf-spring represents the core element of a force generator amenable to direct electrical control.

2 Requirements

Some basic requirements for a TVA system are derived from the technical specifications of the A400M, an economical turboprop aircraft with four high performance turboprops TP400-D6 and 8-blade propellers providing cruising speeds up to Mach 0.72 at 37 000ft, see Tab. 1. An efficient TVA system, comprising hundreds of vibration absorbers, relies heavily on its local TVAs generating forces of the required magnitude at a minimum weight.

	Value	Unit
Propeller speed	655	rpm
Blade passage frequency @ 655 rpm	87	Hz
Maximum propeller speed (TP400-D6)	840	rpm
Blade passage frequency @ 840 rpm	112	Hz
Relevant harmonics	1 to 3	BPF
Active mass for one TVA (1BPF)	~1000	g
Number of TVAs (1BPF)	176	Pcs.
Expected average frame acceleration reduction	14	dB
Expected noise reduction	8-10	dB

Tab. 1 TVAS requirements specification

Moreover, the local TVAs have to be automatically tuneable within the specified frequency range, and provide high reliability. For flight testing and optimum configuration, high flexibility of the TVA system is essential in order to address the question whether purely decentralized or centralized control of the TVA system is advantageous. Active masking of individual TVAs allows the identification of dispensible TVA locations. The proposed Piezo-TVA system perfectly meets all these requirements.

3 Piezo Tuneable Vibration Absorber

Based on the emerging piezoelectric technology, a piezo inertial force generator [4], [5] is realised in a dual-mass-leaf-spring configuration, see Fig. 2. Control forces are generated by the inertia of the masses subject to bending oscillations. Mass production piezoceramic stack elements are embedded into a GFRP host structure providing direct electrical control over the bending oscillation and thus over the forces induced into the attached aircraft structure. Since no moving parts are involved, this smart actuation technology comprises some highly attractive features, e.g. no wear, no friction, high life time, silent actuation, direct electrical control, extremely accurate, very high bandwidth.

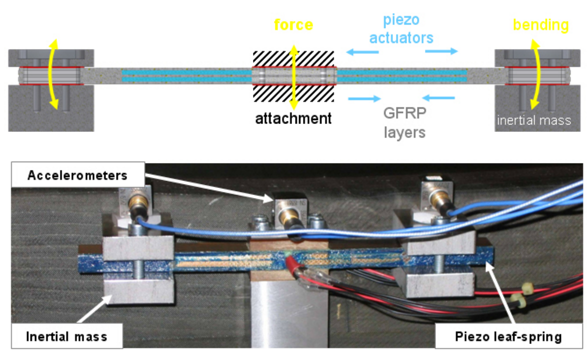

Fig. 2 Piezo-TVA working principle and hardware realization

Fig. 3 shows the prototype line designed and manufactured at EADS CRC ranging from preliminary test articles, over endurance test articles, single-mass as well as dual-mass devices up to large scale devices for helicopter vibration control.

The piezo inertial force generator is suitable for any active vibration and noise control system, e.g. active control of structural response (ACSR).

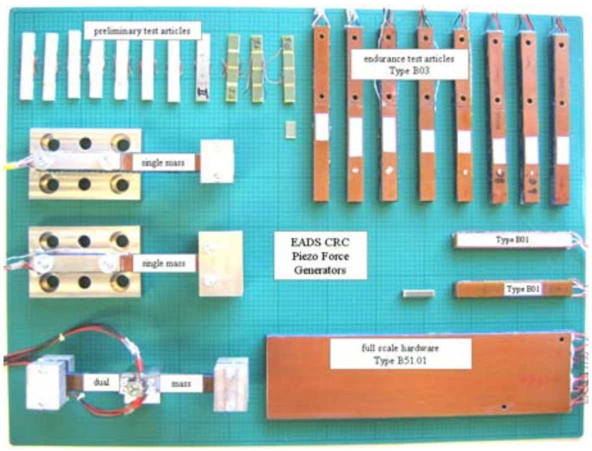

Fig. 3 Piezo-TVA prototype line

In the case of a local feedback loop, a piezo tuneable vibration absorber is realised. When the piezo actuators induce active forces into the piezo leaf-spring in phase with the bending deflection (through feedback control), the stiffness of the piezo leaf-spring and thus the eigenfrequency is affected. Inducing active forces in phase with the bending velocity affects the damping and thus the quality factor of the TVA.

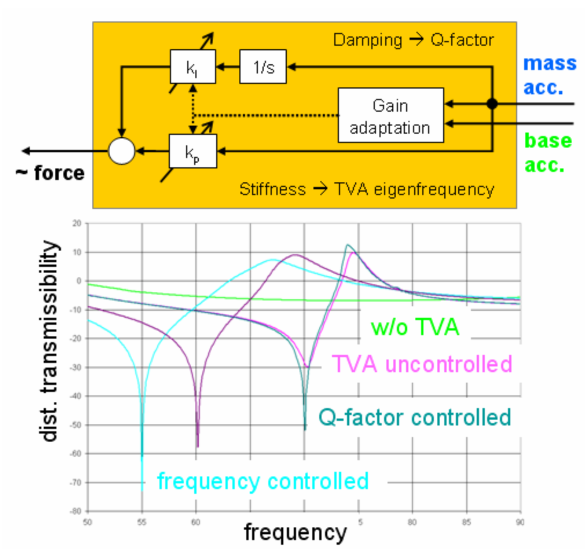

Fig. 4 Adaptive PI-control

Adaptive PI-control [6], [8], see Fig. 4, based on acceleration sensors as well as robust disturbance rejection control (RDRC) [3], [7], see Fig. 5, based on the internal model principle can both be applied in order to achieve the required transmission zero in the disturbance transmissibility. A local vibration reduction at the location of the TVA attachment is achieved.

Whereas adaptive PI control shifts the natural transmission zero, i.e. the natural eigenfrequency of the absorber to the disturbance frequency, RDRC introduces an additional transmission zero at the disturbance frequency.

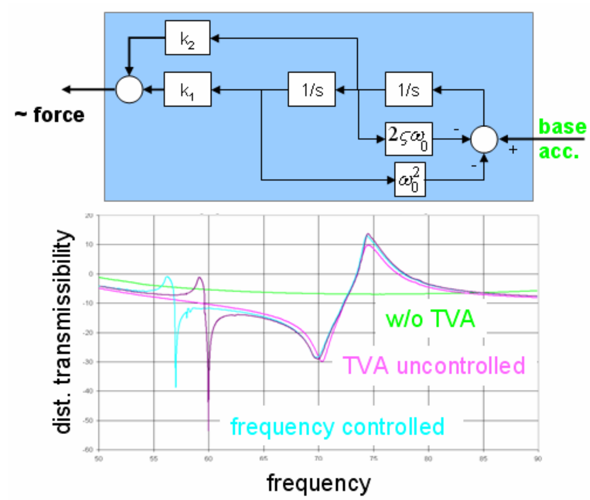

Fig. 5 Robust disturbance rejection control

The natural eigenfrequency of the absorber is sensibly chosen in the vicinity of the variation of the fundamental disturbance frequency (1BPF). Higher harmonics of the disturbance frequency (2BPF, 3BPF, …) can be attacked with RDRC introducing zeros at respective frequencies. Including higher harmonics is referred to as multi-mode TVA. This is especially attractive since for the control of the higher harmonics no additional absorber hardware is required.

	Value	Unit
TVA type	1	BPF
Induced force @ 97.3 Hz	195	N
Natural eigenfrequency	100.0	Hz
Tuning range	87.3 – 97.3	Hz
Low level signal capacity	2x12	µF
Max. required voltage for one TVA	100	V
Max. required effective power for one TVA @ 87.3 Hz	2.4	W
Active mass for one TVA	2x300	g
Mass of piezoceramics	144	g
Mass of GFRP spring	124	g
Free length of leaf spring (half side only)	120	mm
Width of leaf spring	40	mm
Thickness of leaf spring	9.0	mm
Total weight for one TVA	868	g

Tab. 2 Design parameters for Piezo-TVA

4 Experiments

In order to investigate the noise & vibration reduction performance of the Piezo-TVA including controls, the TVA is implemented into a realistic test environment, see Fig. 6. This includes a representative aircraft fuselage panel into a transmission loss test suite between two reverberation chambers. The fuselage panel (dimensions 2.3 by 2 m) is derived from the Airbus-D fuselage panel design that is one part of the TANGO barrel. It is completely manufactured in CFRP and its main dimensions are similar to A320. The panel is acoustically excited by two speakers installed in the sending chamber. The Piezo-TVA is installed at the fuselage frame as shown in Fig. 6. An accelerometer bonded to the TVA attachment measures the structural vibrations whereas three microphones installed in the receiving chamber measure the sound pressure level. The control algorithms are implemented on a rapid control prototyping system.

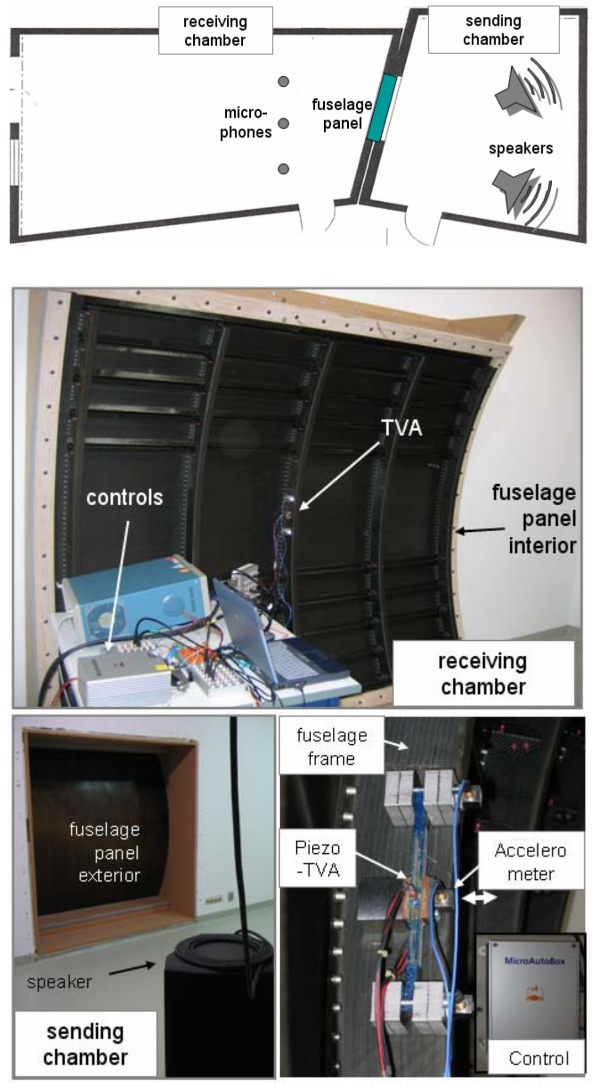

Fig. 6 Transmission loss test suite

The vibration reduction performance of a single Piezo-TVA at low noise cruise propeller speed (655 rpm) is presented in Fig. 7. As seen from the experimental data for an acoustic excitation of the panel at 87.3Hz, the structural vibration at the TVA attachment point can be reduced up to -40dB when the 1BPF controller is on. When the 2BPF controller is on, a vibration reduction of -35dB is achieved, and when both control loops are closed, simultaneous vibration reduction at 1BPF and 2BPF is achieved. These results clearly proof the multi-mode performance of the Piezo-TVA technology. The transient behaviour due to a step change in the excitation frequency is given in Fig. 8. The time history shows the TVA attachment acceleration when the TVA is tuned to 87.3Hz and a step change in the excitation frequency to 97.3Hz is applied at about t=4s. The TVA reaches the steady state within about 1.5s.

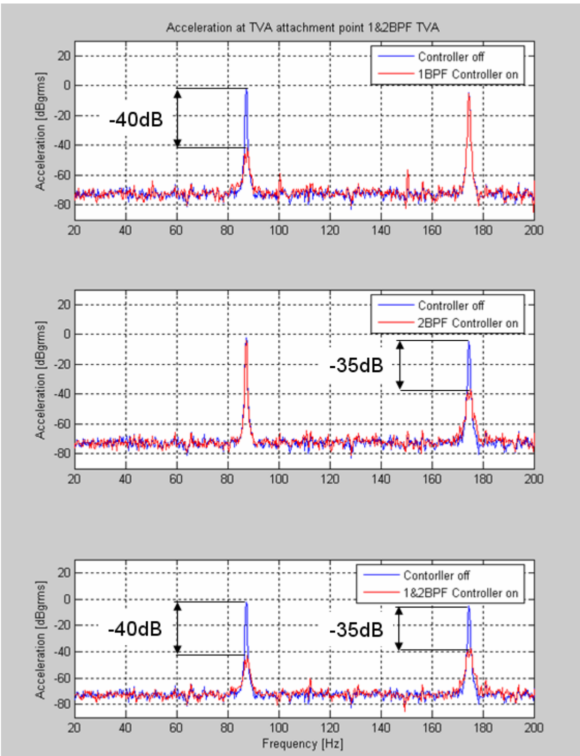

Fig. 7 Vibration reduction of 1BPF-TVA in multi-mode operation at 655rpm

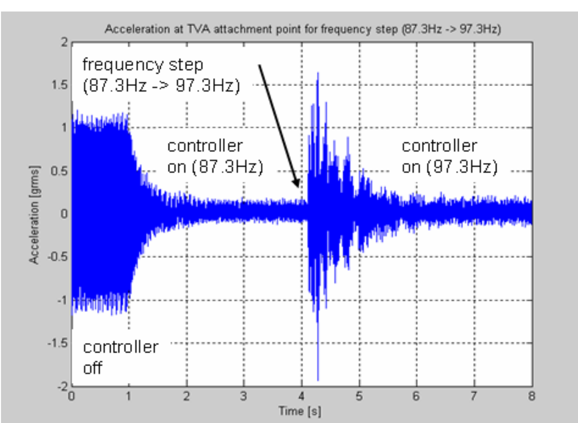

Fig. 8 Transient behaviour due to step change in excitation frequency

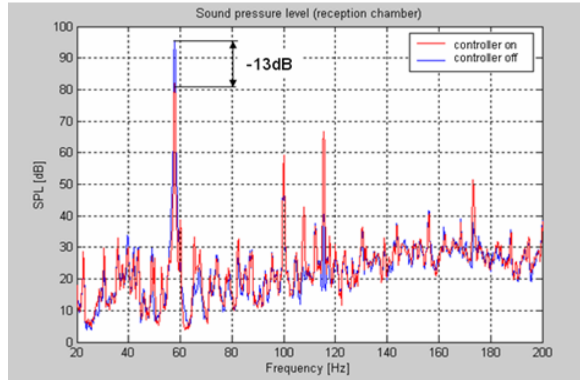

Fig. 9 Noise reduction of 1BPF-TVA at 58Hz

Fig. 9 demonstrates the noise reduction performance of the Piezo-TVA. The fuselage panel excited acoustically through two speakers installed in the sending chamber is forced to structural vibrations and transmits noise into the receiving chamber measured through three microphones. The sound pressure level averaged over the microphones is compared for the controller status OFF and the controller status ON. Although the Piezo-TVA achieves excellent local vibration reduction, one single TVA installed at the panel centre can only lead to a moderate reduction of the noise transmission since the local vibration at those frequencies is not correlated with the actual sound radiation of the panel. This is different when the first flexural eigenmode of the panel at 58Hz is attacked. Here, the local vibration reduction with a single TVA leads to a global reduction of the sound pressure level in the reception chamber of about -13dB. This clearly demonstrates the noise reduction performance when the TVAs are installed at proper locations and spacing at an aircraft fuselage panel.

5 Conclusions

A tuneable vibration absorber system based on the emerging piezoelectric technology has been proposed for active aircraft interior noise reduction. This technology offers outstanding benefits, such as:

Guaranteed performance: The proposed Piezo-TVA technology permits direct electrical control without any mechanical displacement. As a result, the frequency tuning can be realized precisely. In addition, the quality factor can be adjusted in operation. Thus, a high absorption performance can be guaranteed.

Reduced TVAS weight: The precise frequency tuning and the adjustable quality factor of the Piezo-TVA allow designing TVAs with minimal inertial mass, thus reducing the overall weight.

High reliability: The proposed design is based on mass production piezoceramic stack elements developed for automotive piezo-injection. In automotive series application, the piezoceramics are tested to 10^9 duty cycles under extremely harsh conditions. The proposed Piezo-TVA technology will thus have a high degree of operational reliability.

Easy upgrade to active system: The proposed Piezo-TVA system can be easily upgraded to an active system operation, e.g. active control of structural response.

Multi-mode operation: The Piezo-TVA technology allows integrating the fundamental BPF and its higher harmonics (2BPF, 3BPF) into a single multi-mode TVA device. This leads to a considerable lower number of devices.

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