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Vibration damping of aircraft propeller blades using shunted piezoelectric transducers

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Vibration damping of aircraft propeller blades using shunted piezoelectric transducers

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Abstract. Gas turbine engine blades experience vibrations due to the flow disturbances, these vibrations are critical to the engine durability and performance. Piezoelectric transducers (sensors and actuators) have been used for engine blade vibrations damping either through a passive or active vibration control. The propeller blades are part of turboprop engine and considered as one of the main source of turboprop engine vibrations. Piezoelectric blade damping ideas have been studied by other researchers for fan blades and compressor blades. In this research a vibration damping procedure using piezoelectric transducers applied to an unmanned aerial vehicle (UAV) composite propeller. Experimental investigation introduces an approach for the propeller vibration damping using piezoelectric transducers in conjunction with appropriate shunt circuit. Three thin piezoelectric transducers macro fiber composite (MFC) type PZT-5A are surface-mounted on the propeller, one at each blade. These transducers are placed at locations of high modal strain areas for the propeller first mode at each blade, where these locations are identified by finite element numerical simulation. Electronic resonance shunt circuit, resistor-inductor-capacitor type, for the piezoelectric transducers is designed and experimentally developed such that effective vibration suppression of the propeller is achieved. The experimental and numerical investigations in this research illustrate that piezoelectric transducers with appropriate shunt circuit reduces the aircraft propeller vibrations.

1. Introduction

Smart materials have been used in vibration damping. The main purpose is to reduce vibrations of a mechanical structure [1]. Piezoelectric transducers have been worked as sensors and actuators to damp vibrations. Piezoelectric transducers are able to change mechanical and electrical energy into each other's [2]. Piezoelectric materials are able to be work as passive or semi active vibration damping with shunt circuit [3]. Piezoelectric transducers with shunt circuit used for damping engineering structures is an identified method. This method depends on the piezoelectric result that changes the mechanical energy to the electrical energy [4]. In a structure using piezoelectric materials with shunt circuit for vibration damping. The shunt circuits may be used for active or passive damping. These circuits consist of capacitors, inductors and resistors [5]. The resistor of the shunt circuit dissipates the electrical energy transformed from mechanical energy due to the effect of piezoelectric transducer [6]. A resistor inductor shunted circuit faces a difficulty of large size of the inductor. Synthetic inductors can be used to decrease the volume and the weight of the circuit [7].

Many authors studied different procedures for blade vibration damping in gas turbine engines utilizing piezoelectric transducers. Duffy et al. [8] studied the result of shunted piezoelectric transducers put on a rectangular plates that loaded centrifugally. They stated that plate vibrations could be damped using shunted piezoelectric transducers. Duffy et al. [9] used flexible macro-fiber-composite piezoelectric patches applied to fan blades, they bonded the piezoelectric transducers on the blades. The piezoelectric transducers placed in a maximum modal strain area for the first mode that identified by finite element. They used spin test rig facility at for testing with magnetic bearing for excitation. The results showed that using active and shunted piezoelectric patches damp vibrations induced to the fan blades at different speeds. Min et al. [7] study experimentally and numerically rotating engine fan blades. The results are the numerical investigation is effective to the rotating engine fan blade. A finite element was studied to identify the best position for the placement of the piezoelectric transducers at the first bending mode high strain area. The results of the tests showed that piezoelectric patches can suppress vibrations of composite engine fan blades. Zhou et al. [10] used a shunt circuit with piezoelectric patches and then applied to a mistuned bladed disk. Piezoelectric patches with shunt circuit were attached to the blade to damp vibrations. Zhou and Zuo [11] used piezoelectric patches applied on cantilever beam to damp vibrations. They used numerical analysis, the numerical results showed that the vibrations are damped. Zakaria et al. [12] Study piezoelectric transducers oscillations to harvest energy. They used experimentally a fluttering composite piezoelectric beam positioned in an air flow at different directions. They show that the best amounts of electric power are got according to the direction of the air flow and its speed. Liu et al. [13] Used experimentally a carbon fiber L-shaped structure that consists of upright and level beams mounted on a shaker. They put two piezoelectric transducers onto each beam to get electrical energy from the beams vibrations. The results show that upright beam gets more electrical power than level one. Marques et al. [14] show experimentally the electrical power getting from vibrations of a an airfoil in wind tunnel. The results show in order to get more electrical power at low speeds the air foil axis moves proportional to the center of gravity. Santos et al. [15] did an experimental and numerical investigations for generating electrical energy using piezoelectric patches bonded to a composite cantilever beam. They used finite element approach for numerical investigations while used experimentally a wind tunnel.

In this paper, a finite element model of a composite propeller is introduced to determine the maximum modal strain position of the propeller for the best location of the piezoelectric transducers, and to obtain the propeller natural frequency and mode shape. Then applying piezoelectric transducers experimentally to the propeller blades with shunt circuit to damp vibrations, the results including natural frequencies and vibration damping performance.

2. Finite element modeling

A 3-blade fixed pitch propeller carbon fiber with diameter 24 in and pitch angle 12 in designed for unmanned aerial vehicles (UAV's) is used for numerical and experimental investigations. A finite element analysis of the propeller before bonding piezoelectric transducers is performed, using ANSYS. The propeller is fixed from the hub and the excitations are perpendicular to the propeller blades plane (Z axis direction). The FE model is used first to get the propeller maximum modal strain area that is the best location of the piezoelectric transducers in order to attain best damping. Figure 1 shows the equivalent elastic stain for first mode. In this figure the maximum strain locations are shown. Then modal analysis used to get natural frequencies and mode shapes as shown in figure 2 [16].

3. Theory of using shunt circuit for piezoelectric transducers to damp blade vibration

The illustration of blade damping using piezoelectric transducer with shunt circuit will be demonstrated in this section. Figure 3 explains schematically how the structure of a blade with shunt circuit damp vibrations. The vibration of the blade makes strains. A piezoelectric transducer produces an electric field. then electrical charges are collected piezoelectric patches. The shunt circuit resistor dissipates the electrical energy. The shunt circuit electric resonance ω_e is tuned to the desired resonance frequency ω_m, by shifting the current phase by 90º. The vibrations are damped in the structure [17].

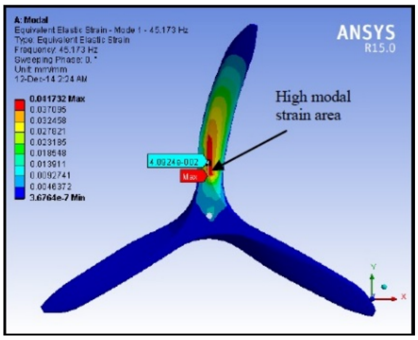
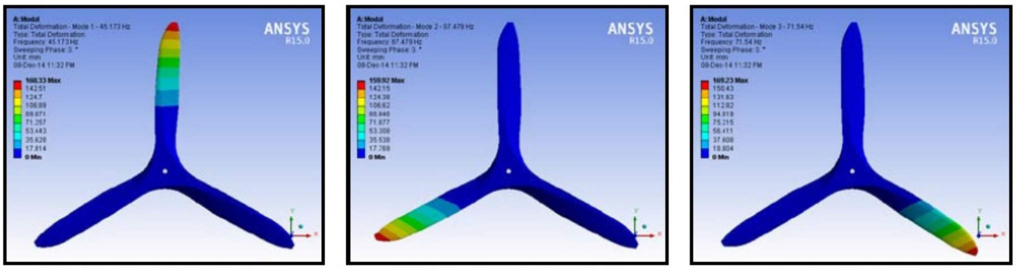


Figure 1. Maximum modal strain area



Mode 1(45.17 Hz) Mode 2 (67.47 Hz) Mode 3 (71.54 Hz)

Figure 2. Propeller modal displacement contours without shunted piezoelectric

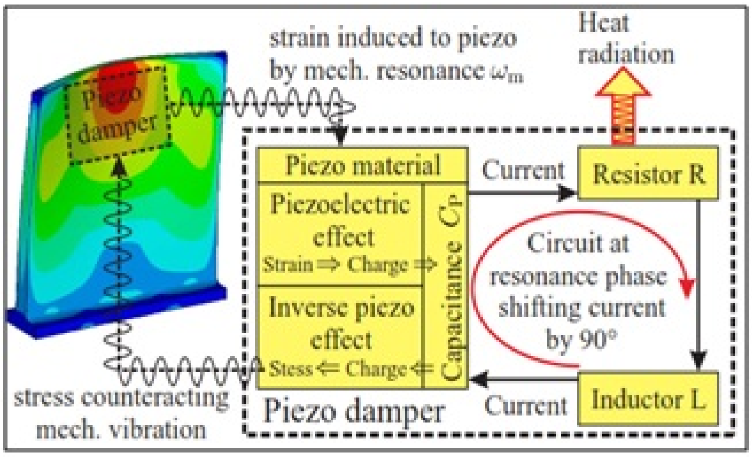


Figure 3. Design of blade vibration damping using shunt circuit [18]

4. Experimental investigation

The goal of this experiment is to design a vibration damping technique for the propeller using shunted piezoelectric transducers, the used transducers are (PZT) Lead Zirconate Titanate macro fiber composite (MFC). The experiments use piezoelectric transducers with shunt circuit to damp vibrations. Electrical resonance circuit is then tuned to the propeller resonance so that piezoelectric transducers act as vibrational absorber device.

4.1 Materials and approach

Piezoelectric transducers used in this experiment are DuraAct piezoelectric patch transducers PN: P-876.A15, ceramic type PIC255, (MFC) product of Physik Instrumente (PI) GmbH, their dimensions are 61×35×0.8 mm. Table 1 shows the specifications of the piezoelectric transducers.

Table 1. Specifications of DuraAct piezoelectric patch transducers

Operating voltage (V)	Min. lateral contraction $(\mu m/m)$	Blocking force (N)	Piezo-ceramic thickness (μm)	Electrical capacitance (nF)
- 250 to 1000	800	775	500	45

4.2 Shunt Circuit Design

The shunted piezoelectric transducers used for this study have passive electrical circuits. The components of this RLC shunt circuit: resistor, capacitor, and inductor as shown in figure 4.

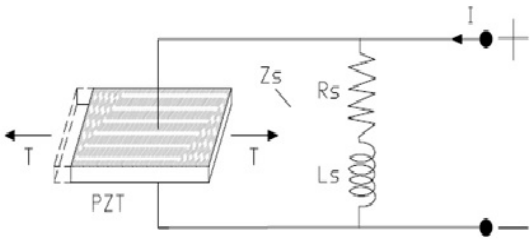


Figure 4. Shunt circuit design

The inductor and capacitor values of the shunt circuit are calculated as in the following equation:

$$\omega_e = \frac{1}{\sqrt{L_s C_P^S}} \tag{8}$$

Where ω_e is the electrical resonant frequency of the circuit, Ls is the inductance for the circuit, the capacitor C_P^S for the circuit is the PZT itself. Electric resonance ω_e is tuned to the propeller first mode ω_m which equal to 46 Hz. The inductor of the RLC circuit, Ls = 10501.99 H, is built electronically as synthetic inductor as shown in Figure 5 [18].

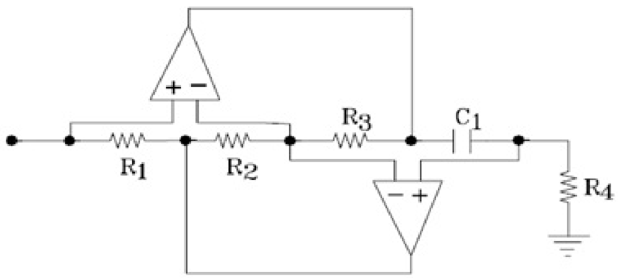


Figure 5. Synthetic inductor for variable inductor [18]

The resistor, R2, is a variable resistor to change the circuit inductance. The resistors R1, R3, and R4 are 10 kΩ. The shunt circuit uses a ±16 Volts, 1 Watt DC power supply.

4.3 PZT placement and application

Three piezoelectric transducers are applied to the propeller blades one at each blade and positioned at high modal strain areas of the first mode identified by finite element simulation as shown in Figure 6. Piezoelectric transducers are glued to the blades using epoxy adhesive.

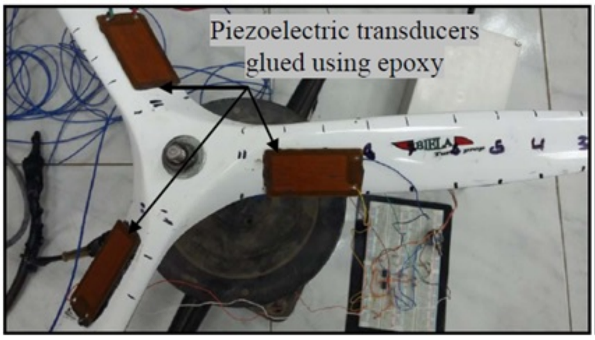


Figure 6. Piezoelectric transducers placement on the propeller

4.4 Experiment procedure
The digital signal processing unit used in the experiment is NI PXle-1085 chassis product of NATIONAL INSTRUMENTS (NI), which includes all system controller modules. The software used is LabView. A NI rack mountable adapter BNC-2144 unit with a NI PXle-4499 module is used to collect the output data through LabView. A NI rack mountable adapter BNC-2121 with a NI PXl-6602 module is used for transfer input signal from LabView to the shaker type 4808 manufactured by Bruel & Kjaer (B&K) through power amplifier type 2712 manufactured by B&K. Three PCB piezoelectric accelerometers attached to propeller blades tip and one accelerometer mounted on the shaker table are used to attain the frequency response functions (FRF) of the propeller. The shaker exited the propeller perpendicular to propeller blades plane. Experiment is performed with the test setup shown in figure 7. In this experiment the propeller is fixed from its hub onto the shaker. The output from the amplifier is connected to the shaker. The shunt circuit is connected to the piezoelectric transducers. The shunt circuit is powered by the power supply. The tests are taken from 40 to 80 Hz that contains the first 3 modes of the propeller.

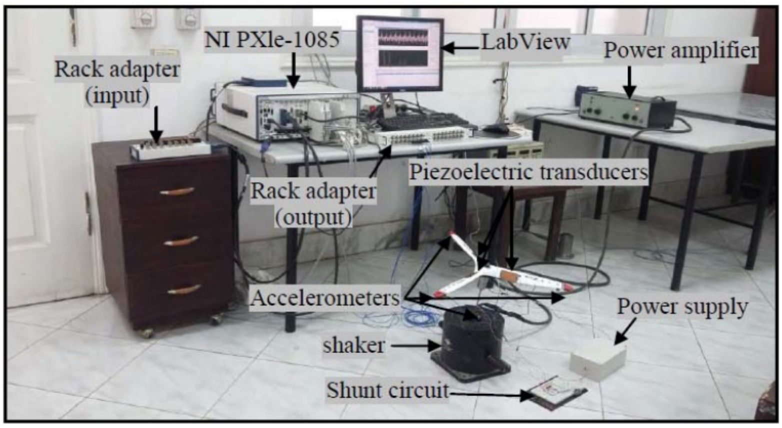


Figure 7. Experimental set up for propeller with shunted piezoelectric

5. Results and discussion

5.1 Propeller modal test and FE model verification
Experimental test is applied first to the propeller before bonding piezoelectric transducers. Figure 8 shows frequency response function (FRF) for the propeller before bonding piezoelectric transducers, this figure shows the first three modes for the propeller that identified by the phase angle change at the peaks appear from the FRF. The comparison of natural frequencies from numerical simulation for the propeller and the natural frequencies obtained from this experiment are shown in Table 2. The comparison results show good agreement with deviation from 0.7% to 2.2%, which validates the numerical simulation.

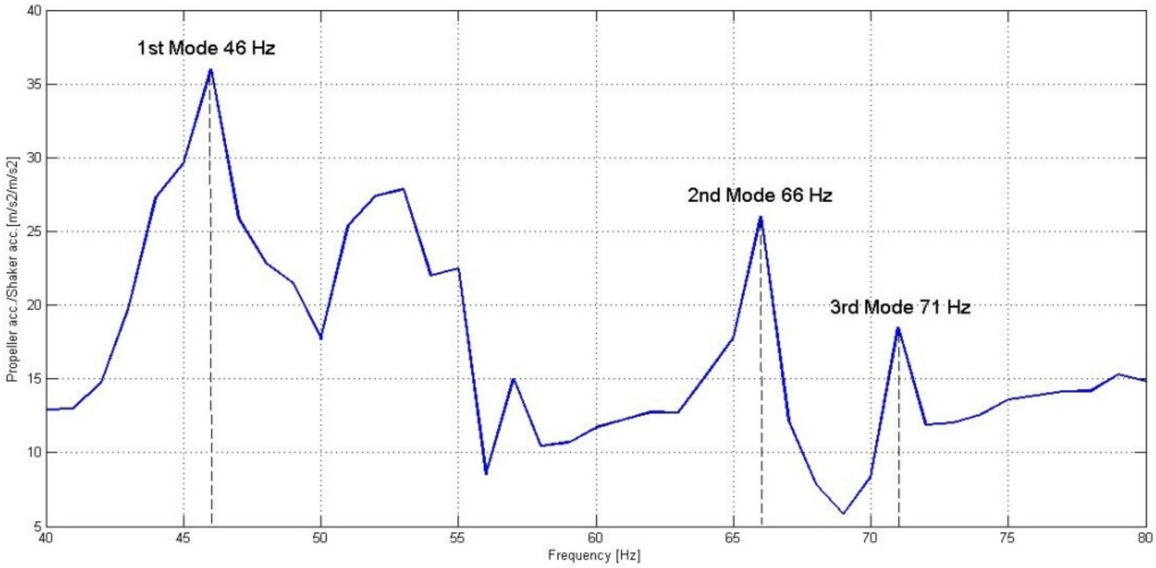


Figure 8. Propeller FRF before applying piezoelectric transducers

Table 2. The **c**omparison between propeller natural frequencies for numerical simulation and experimental investigations

Mode number	Frequency (Hz) Simulation	Frequency (Hz) Experimental	Deviation percent
1	45.173	46	1.7 %
2	67.479	66	2.2 %
3	71.54	71	0.7 %

5.2 Propeller with shunted piezoelectric test and FE model verification

Similar test is applied to the propeller after bonding shunted piezoelectric transducers. Figure 9 shows frequency response function (FRF) for the propeller after applying shunted piezoelectric transducers, in this figure the first 3 natural frequencies for the propeller are shifted up after applying shunted piezoelectric transducers due to increased stiffness of the propeller as a result of applying shunted piezoelectric transducers. Table 3 shows the comparison between the first 3 natural frequencies of the propeller before and after applying shunted piezoelectric transducers, this table shows that the increase in natural frequencies are from 4.2 % to 10.8 %.

A finite element simulation using ANSYS for the propeller with shunted piezoelectric transducers (sensors and actuators) is developed and analyzed as shown in figure 10, a perfect adhesive bonding between the transducers and blades is assumed.

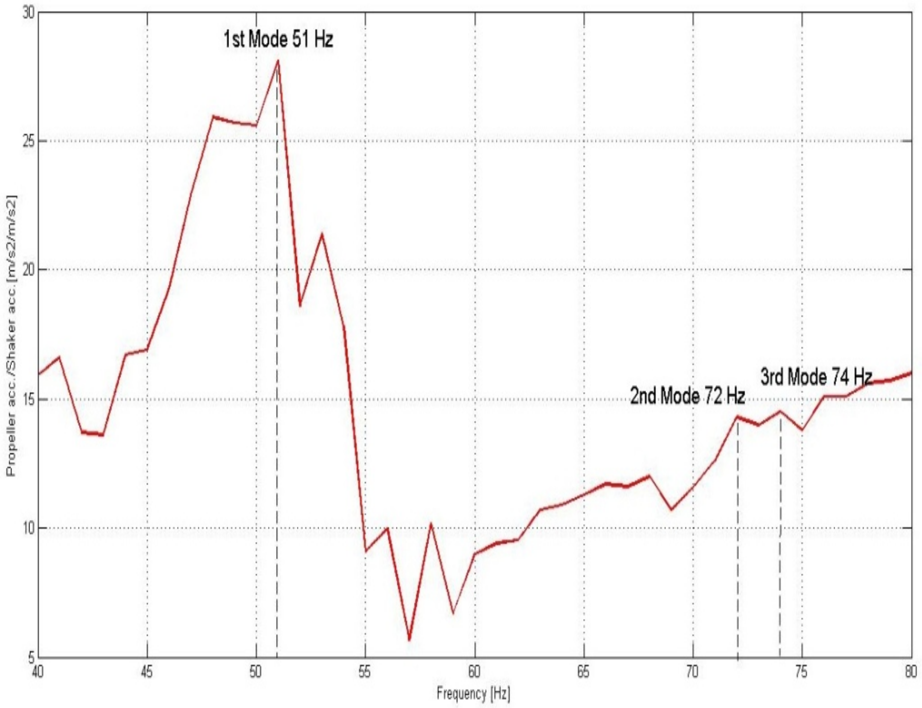
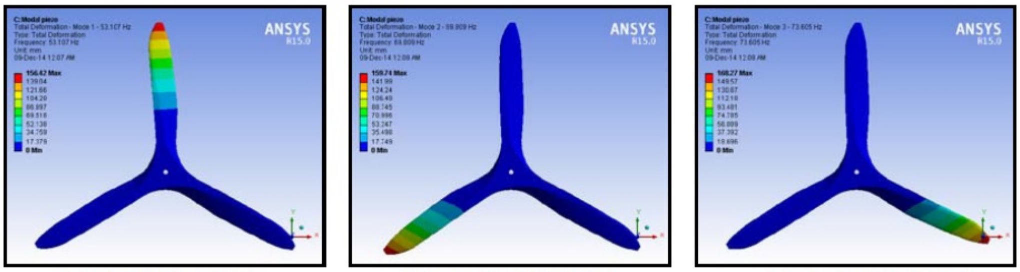


Figure 9. FRF for the propeller with shunted piezoelectric transducers

Table 3. Comparison between natural frequencies before and after applying shunted piezoelectric transducers to the propeller

Mode Number	Frequency (Hz) before applying piezoelectric	Frequency (Hz) with shunted piezoelectric transducers	Percent increase
1	46	51	10.8%
2	66	72	9.1 %
	71	74	4.2 %



Mode 1(53.1 Hz) Mode 2 (69.8 Hz) Mode 3 (73.6 Hz)

Figure 10. Propeller modal displacement contours with shunted piezoelectric

Table 4 shows the comparison of the natural frequencies for the propeller with applying shunted piezoelectric transducers between experimental results and finite element (FE) simulation. The comparison results are in good agreement with deviation between 0.53% to 4.13%. These results validate the FE simulation.

Table 4. Comparison between natural frequencies of the experimental investigations and FE simulation for the propeller with applying piezoelectric transducers

Mode Number	Frequency (Hz) Experimental	Frequency (Hz) FE simulation transducers	Deviation percent
1	51	53.107	4.13 %
2	72	69.809	3.04 %
3	74	73.605	0.53 %

5.3 Comparison between the propeller for un-shunted and shunted piezoelectric

Tests are applied to the propeller after the piezoelectric transducers are bonded to the propeller with shunt circuit (shunted piezoelectric) and without shunt circuit (un-shunted piezoelectric) to study the effect of shunt circuit. The shunt circuit is then tuned to the first three modes of interest for the propeller to achieve best damping. Figure 11 demonstrates the effect of the shunt circuit on the propeller vibration response after applying shunted piezoelectric transducers. The first three modes accelerations are significantly reduced for the shunted piezoelectric propeller while the natural frequencies are the same values because the structure stiffness does not change.

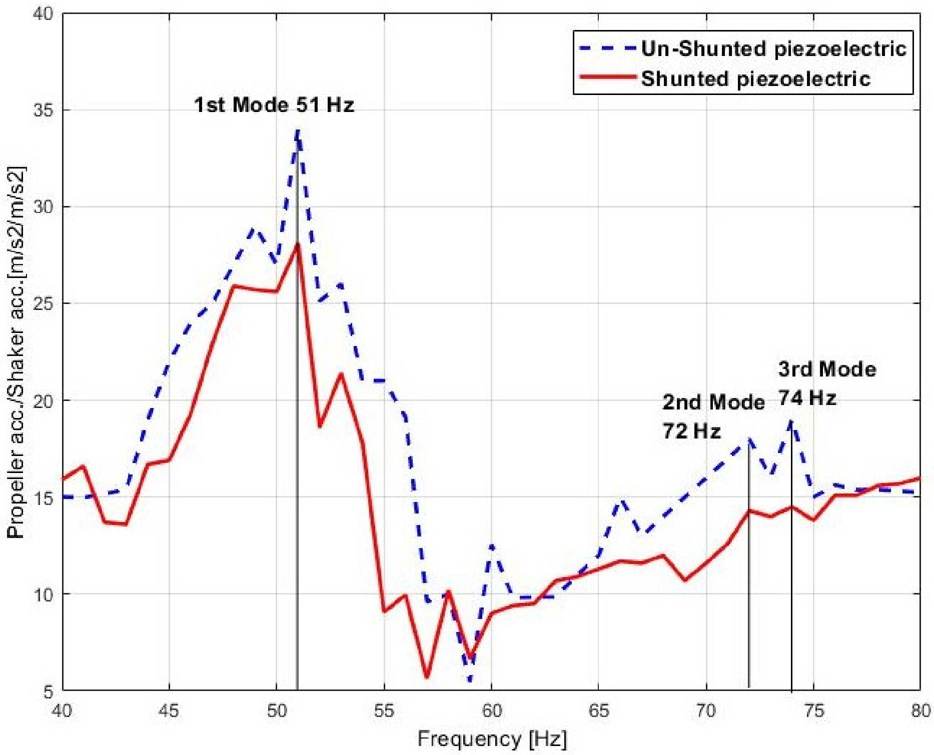


Figure 11. FRF for un-shunted and shunted piezoelectric propeller

Table 5 presents the decreases in the first three modes accelerations that were obtained using the tuned shunted piezoelectric transducers by comparing the values of peak accelerations results of propeller open loop (un-shunted) and closed loop (shunted). The results indicate that the shunted circuit significantly reduce the propeller vibrations by reducing acceleration peaks for the first three modes up to 20.99 %.

Table 5. Effect of shunt circuit on resonance acceleration peaks of the propeller

Mode Number	Un-Shunted PZT's $\left({}^{m/s^2}/_{m/s^2}\right)$	Shunted PZT's $\left({}^{m/s^2}/_{m/s^2}\right)$	Reduction percent
1	34.1	28.1	17.60%
2	18.1	14.3	20.99%
3	18.2	14.5	20.33%

5.4 Comparison between the propeller before and after applying shunted piezoelectric

Figure 12 illustrates the effect of the piezoelectric transducers with tuned shunt circuit on the propeller vibration response compared to the FRF of the propeller before bonding piezoelectric transducers (without piezoelectric). This figure shows reduction in the accelerations of first three modes for the shunted piezoelectric propeller and the increase in the first three natural frequencies indicated by (1), (2) and (3) for results without piezoelectric and with shunted piezoelectric.

The main goal of the experiments is to determine the vibration reduction by the application of piezoelectric transducers with shunt circuit to the propeller as shown in Figure 12. Table 6 shows the reductions in the resonance frequencies accelerations that are obtained using the shunted piezoelectric transducers by comparing the values of these acceleration of propeller before bonding piezoelectric transducers (without PZT's) and after applying piezoelectric transducers with shunt circuit (shunted PZT's). The results indicate that the shunted piezoelectric transducers significantly reduce the propeller vibrations by reducing acceleration peaks for the first three modes up to 45.04 %.

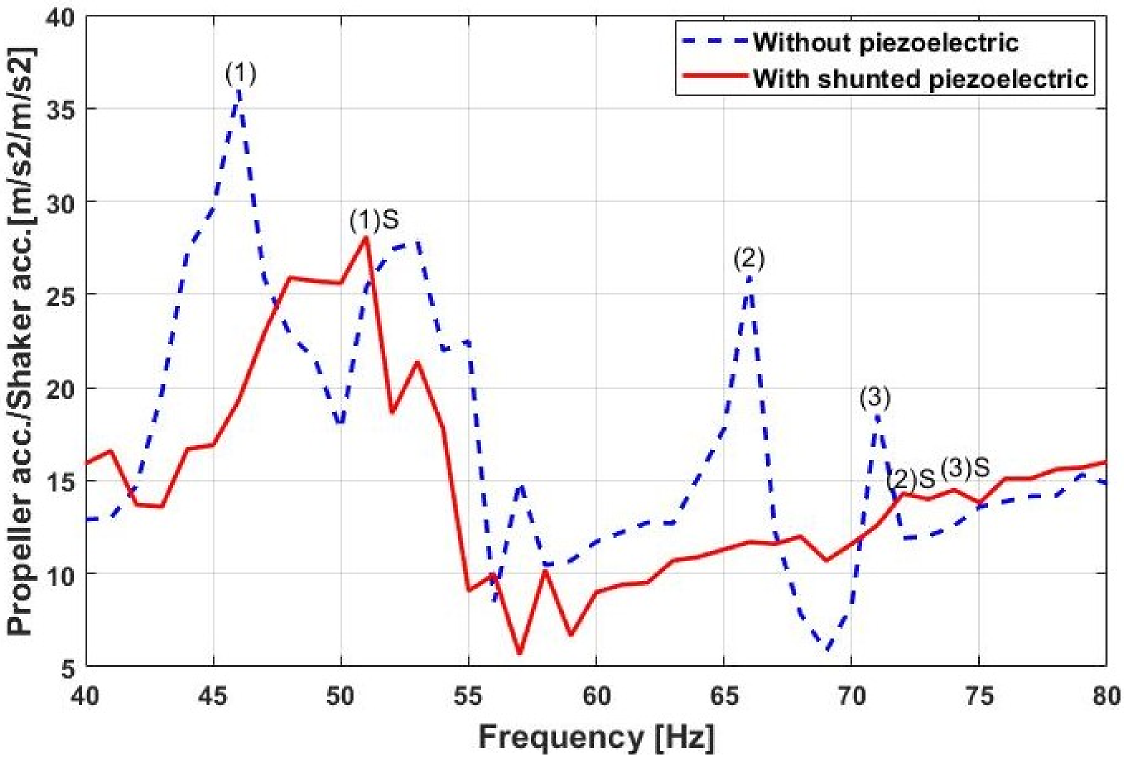


Figure 12. Effect of applying shunted piezoelectric transducers to the propeller

Table 6. Effect of shunted piezoelectric on vibration reduction

Mode Number	Without PZT's $\left(\frac{m/s^2}{m/s^2}\right)$	With shunted PZT's $\left(\frac{m/s^2}{m/s^2}\right)$	Reduction percent
1	35.97	28.1	21.87 %
2	26.02	14.3	45.04 %
3	18.51	14.5	21.66 %

6. Conclusions

This research used a numerical and experimental investigations to develop piezoelectric transducers with shunt circuit to damp vibrations for a real composite aircraft propeller blades.

Electronic resonance shunt circuit attached to piezoelectric transducers type PZT-5A is designed and experimentally examined such that vibration damping of the propeller is achieved. The shunt circuit used is resistor-inductor-capacitor type. The piezoelectric transducers are surface mounted on the propeller that attached to a shaker. The experimental vibration test and numerical simulations are conducted from 40 to 80 Hz, were the following results are concluded:

1- Applying shunted piezoelectric transducers cause the first 3 natural frequencies for the propeller to shift up from 4.2 % to 10.8 %. The cause of this increase is referred to the propeller increase structure stiffness.
2- The comparison of the propeller first 3 natural frequencies with applying shunted piezoelectric transducers between experimental results and finite element are in good agreement with deviation between 0.53% to 4.1%. These results validate the FE simulation.
3- Shunt piezoelectric transducers can effectively reduce the propeller vibrations throw reducing acceleration peaks of the first three modes up to 45.04 %.

The obtained results show that piezoelectric transducers with appropriate shunt circuit can be used to damp vibrations induced in aircraft propeller blades by applying these patches at propeller blades first mode maximum modal strain locations. However, for industrial application, piezoelectric transducers can be embedded to the propeller blades to avoid a strong air flow disturbances during operation.

References

[1] D'Assuncao D and Junior C 2014 Applied self-powered semi-passive control for a 2-degree-of-freedom aeroelastic typical section using shunted piezoelectric materials *J. Intelligent Material Systems and Structures* **26** pp 373-385.

[2] Zhou B *et al.* 2013 An adaptive control strategy based on passive piezoelectric shunt techniques applied to mistuned bladed disks *J. Computational and Applied Mathematics* **246** pp 289-300.

[3] Mayer D, Heuss H, Thiel O, Abele J and Melz T 2014 A*dditive manufacturing of active struts for piezoelectric shunt damping 25nd International Conference on Adaptive Structures and Technologies* (The Hague, The Netherlands)

[4] Neubauer M and Wallaschek J 2013 Vibration damping with shunted piezoceramics: fundamentals and technical applications *J. Mechanical Systems and Signal Processing* **36** pp 36-52.

[5] Pohl M and Rose M 2015 Piezoelectric shunt damping of a circular saw blade with autonomous power supply for noise and vibration reduction *J. Sound and Vibration* **361** pp 20-31.

[6] Hogsberg J and Krenk S 2015 Balanced calibration of resonant piezoelectric RL shunts with quasi-static background flexibility correction *J. Sound and Vibration* **341 pp** 16-30.

[7] Min J, Duffy K, Choi B, Provenza A and Kray N 2013 Numerical modeling methodology and experimental study for piezoelectric vibration damping control of rotating composite fan blades *J. Computers & Structures* **128** pp 230-42.

[8] Duffy K, Provenza A ,Trudell J and Min J 2009 *Passively shunted piezoelectric damping of centrifugally loaded plates Proc. of the 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (Palm Springs, CA) p 2524.

[9] Duffy K, Choi B, Provenza J, Min B and Kray N 2012 *Active piezoelectric vibration control of subscale composite fan blades Proc. ASME Turbo Expo* (Copenhagen, Denmark) p 028.
[10] Zhou B, Thouverez F and Lenoir D 2014 Essentially nonlinear piezoelectric shunt circuits applied to mistuned bladed disks *J. Sound and Vibration,* **333** pp 2520-42.
[11] Zhou W and Zuo L 2015 A self-powered piezoelectric vibration control system with switch precharged inductor (SPCI) method J. *IEEE/ASME transactions on mechatronics* **20** pp 773-81.
[12] Zakaria M, Al-Haik M, and Hajj M 2015 Experimental analysis of energy harvesting from self-induced flutter of a composite beam *Applied Physics Letters* **107** (2) 023901.
[13] Liu D, Al-Haik M, Zakaria M and Hajj M 2017 Piezoelectric energy harvesting using L-shaped structures *Journal of Intelligent Material Systems and Structures* **29** (6) pp 1206-15
[14] Marques F, Pereira D, Zakaria M and Hajj M 2017 Power extraction from stall-induced oscillations of an airfoil *Journal of Intelligent Material Systems and Structures* **29** (7) pp 1407-17.
[15] Santos C, Pacheco D, Taha H, Zakaria M 2021 Nonlinear modeling of electro-aeroelastic dynamics of composite beams with piezoelectric coupling *Composite Structures* **255** 112968
[16] Morad A M, Elzahaby A, Abdallah S, Kamel M and Khalil M 2015 Application of piezoelectric materials for aircraft propeller blades vibration damping *Int. J. Scientific & Engineering Research* **6** pp 513-20.
[17] Sebastian M, Szwedowicz J, and Neubauer M 2012 *On blade damping technology using passive piezoelectric dampers Proc. ASME Turbo Expo* (Copenhagen, Denmark) p 68600.
[18] Horowitz P and Hill W 1994 *The art of electronics* (Cambridge: Cambridge University Press).