A Distributed Active Vibration Control System Based on the Wireless Sensor Network for Automotive Applications

M. Zielinski, F. Mieyeville, D. Navarro and O. Bareille

Abstract This paper presents a new approach of an adaptive vibration control system for automotive applications. We assume that a porting of a centralised system in a distributed system can improve its effectiveness. We present a wireless sensor network (WSN) for vibrations damping. These autonomous sensors are able to measure the vibrations, damp the vibrations and to harvest energy from vibrations by using a single piezoelectric element. We present the simulations and the measurements results. The new approach of distributed active vibration control system based on the wireless sensor network is presented. The designed distributed wireless network node reduces the vibrations of the plate with the efficiency up to 9.4 dB.

1 Introduction

This work is an extended version of paper "A low power Wireless Sensor Node with Vibration Sensing and Energy Harvesting capability" which was presented at iNetSApp, FedCSIS 2014 [1].

The control of vibration and noise is essential in the design process of an automotive industry. From several years, new concept cars equipped with high technology systems used to improve passenger comfort are available. There are several approaches of systems used to reduce the vibrations. The standard passive solutions take into account the application of viscoelastic materials or the modification of the mechanical structures. The second possibility is to use the active vibration control (AVC) systems. These active solutions have some complex

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structures: a central processing unit, sensors, amplifiers and actuators. In the active approach the smart materials are attached directly to mechanical structures to provide the active control of vibration and noise.

The passive methods increase the weight of the cars. They have a major influence on the energy and fuel consumption [2]. The use of the active vibration control can reduce the weight of conventional passive systems, helping to push towards lighter and more fuel efficient vehicles. Over the last years the active vibration control has been widely studied by researchers [3].

The following section provides the short state of the art of the existing AVC systems for the automobile applications. Then our approach of the AVC system based on the WSN is presented and compared to the existing centralized active methods. The results contain: description and measurements of the designed mechanical system, presentation of designed WSN node. The feasibility of the wireless nodes to provide the vibration damping and sensing is proven by the results.

2 Active Vibration Control Systems: State of the Art

In the literature, we can find several solutions applied to reduce vibration and noise in car bodies. An active noise system using the feed-forward methods for tonal engine noise control was proposed in 1988 [2]. This proposed system was composed of microphones and loudspeakers placed in the passenger cabin. The maximum reduction of about 10 dB was recorded at a frequency of 100 Hz. The overall improvement is noted as a reduction of 4 dB.

Shi-Hwan et al. [4] presented an active control system of road booming noise. This system is composed of four reference sensors, two error sensors and two control actuators. In the presented case study, a car is moving at the speed of 60 km/h. The road characteristics are examined and the low frequencies are found as dominant (around 250 Hz). The authors achieved a 5–6 dB reduction of road booming noise at the vicinity of the error microphones. This work showed also the computational power limits of the various algorithms.

Fuller and von Flotow [5] showed the active vibration control system with an active absorber. A test vehicle was equipped with an inertial-mass shaker and a high efficiency calculation unit (dSpace MicroBox). A significant reduction up to 37 dB is achieved only for the very low frequency (up to 50 Hz). However, the disadvantage of the proposed solution is high adaptation time and the tight frequency range due to the usage of the Filtered X Least Mean Squares (FxLMS) algorithm.

The improvement of the smart materials leads to the new, piezoelectric solutions [6]. N. Alt et al. determined the oil pan as the most important source of the vibrations in the car engine and have proposed the active vibration control system based on the piezoelectric elements. In the experimental setup using the collocated control, the reduction of 12 dB is achieved. Respectively for adaptive feedback control, the results are 20 dB and for adaptive feed-forward control, 24 dB. The authors draw attention to the high costs of the system, which prevent the introduction to mass production. Additionally, the results show the generation of noise and vibration, for the higher frequencies (above 50 Hz).

The piezoelectric elements are also used in the active noise control system for the windshield of the car [7]. The authors reported the reduction of 7.45 dB (116 Hz) and 4.36 dB (145 Hz) using the State-Feedback control. The prototype system is composed of: three piezoelectric actuators, six accelerometers, one force sensor and one microphone. As a control unit the PC computer with the dSpice software product is used.

Tom Weyer and Hans Peter Monner are considering the vibrations of the car roof panel [8]. The authors note that the common resonant frequencies for the motor and the car body can cause vibration propagation. Therefore, the authors show the active vibration compensation using the piezoelectric actuators. The FxLMS algorithm is implemented in the dSpace 1005 Power PC computer. The attenuation of 20–30 dB is achieved for the frequency range around 42–62 Hz. The system is composed of six piezoelectric pairs (actuator and sensor).

In summary, the vibrations in the cars are primarily generated by the engine and by the interaction with the road surface. We can identify the disadvantages of the proposed active systems: high power computational units, large amount of cabling, long adaptation time, and lower efficiency for the frequencies above 50 Hz. In some cases, authors disclosed the increase of the noise or vibration in the mechanical systems. It was also noted that the high costs of the proposed systems can disallow mass production. However, the active vibration control system in the automobile application is desired by the market and a great effort has been made to improve the existing methods and solutions.

The aim of this work is to propose the new distributed approach of the active vibration control system, which can reduce the amount of the consumed energy with the vibration damping efficiency comparable to the existing wired solutions.

3 Integration of the WSN for Active Vibration Control

3.1 Global Structure (New Approach)

Figure 1 presents our new approach of the global system structure for distributed AVC for automotive applications. Wireless nodes are implemented within the body of the car. Nodes are organized in the star topology towards the collecting node.

Each node in the system is powered from the harvested energy from the vibrations and provides mechanical damping. Nodes measure the value of the vibrations and if necessary, send data to the collecting node. If there are no vibrations in the system, the nodes do not have energy to work but there is no need to cancel the vibrations.

When vibrations occur, the WSN nodes are initiated and provide the first level of the mechanical damping. This paper concerns a low power wireless sensor network with vibration sensing, vibration damping and energy harvesting capability.

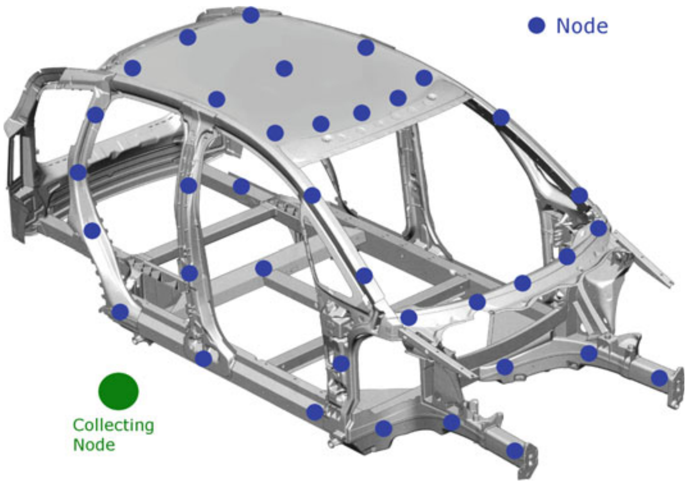


Fig. 1 Global system structure for distributed AVC for automotive application

3.2 Distributed AVC System Versus Existing Centralised AVC Systems

WSNs have rather low transmission rates. Due to delays, an implementation of the efficient real-time system, necessary to provide data processing for centralised AVC, is not possible [9].

In spite of this, WSN could be used to provide active control. A distributed approach used in place of the centralised one can be a solution. In our approach, intelligent nodes provide local action which reduces the amount of the information to transfer, compared to the centralised approach.

The distributed autonomous nodes with sensing feature coupled to semi-active vibration dissipation are the solution proposed in this paper.

Replacing a big centralised (wired) system with low power nodes can improve AVC in the scope of functionality, energy consumption, maintenance, and production costs.

4 WSN Node Design

Figure 2 presents the schema block for proposed WSN node. We distinguish three parallel circuits: energy harvesting, vibration damping, and vibrations sensing. All of them are connected to the one piezoelectric patch transducer. Harvested energy is kept in the storage and used to supply the microprocessor and wireless transmission unit. The following paragraphs describe the design of the proposed WSN node.

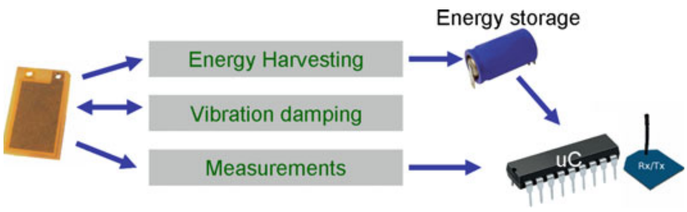


Fig. 2 WSN node schema block

4.1 Impedance Adaptation of the WSN Node

Piezoelectric effect can be considered as a bidirectional energy conversion. A mechanical strain on the piezoelectric element generates the electrical charge and respectively the electrical charge over the piezoelectric element generates the mechanical strain. To understand electrical properties of the piezoelectric patch transducer several measurements have been done. Figure 3 presents achieved results.

The output current and voltage values are measured over the piezoelectric patch transducer in function of the resistive load for constant frequency (Fig. 3). We can notice that the piezoelectric element is a real current source and for the optimal resistive load provides the maximal power. It clearly shows that the energy harvesting circuit must be designed in accordance with the electrical properties of the piezoelectric patch to receive the big electrical current value (optimal resistive load value).

According to Fig. 3 we can observe also that the high value of the resistive load reduces the amount of the energy received from the piezoelectric element. It proves the usage of the piezoelectric element with high resistive load for vibrations sensing (the small value of the leakage current is expected).

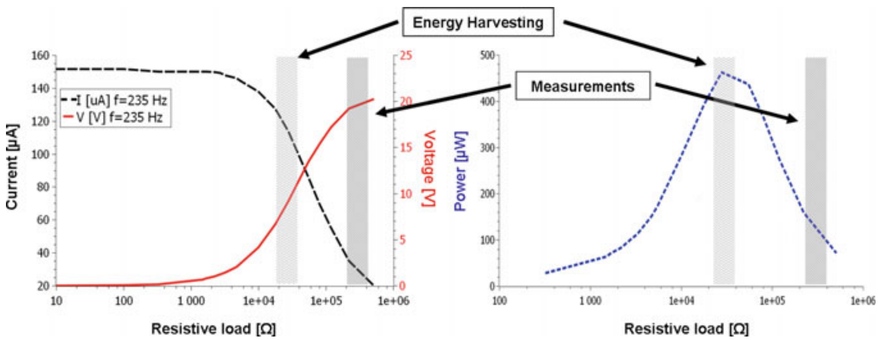


Fig. 3 Measured output electrical characteristics for the piezoelectric patch transducer

As it is presented the dynamic impedance adaptation and dynamic switching with disconnection capability is necessary to connect several parallel circuits with the only one piezoelectric element.

4.2 Vibration Sensing

Designed circuit for vibration sensing is presented on Fig. 4. It can be divided into several parts: impedance adaptation, gain and offset control, filter, and measurement.

Presented circuit is composed of the voltage divider and impedance adaptation circuit (R1 and R2) and the AD8138 low distortion differential analog-to-digital (ADC) driver from Analog Devices. The low pass filter is used to cut-off high frequencies over the output of the ADC driver (R7 with C1 and R8 with C2). The differential ADC driver provides also offset voltage (Pin 2 connected to the 1.65 V). Hence, the negative and positive values are measured. The low-power differential amplifier is supplied from single 3.3 V, which simplifies the supply circuit. An internal ADC of the microcontroller is used. This solution provides low energy consumption since there is no additional ADC to supply.

The voltage over the piezoelectric element corresponds in phase to the acceleration of the mechanical vibrations.

4.3 Vibration Damping and Energy Harvesting (Series SSHI Method)

The vibration damping and energy harvesting in the designed WSN node is based on the Series Synchronous Switching Harvesting with Inductor (SSHI) method [10]. The Series SSHI circuit is presented on the Fig. 5. It is a so-called

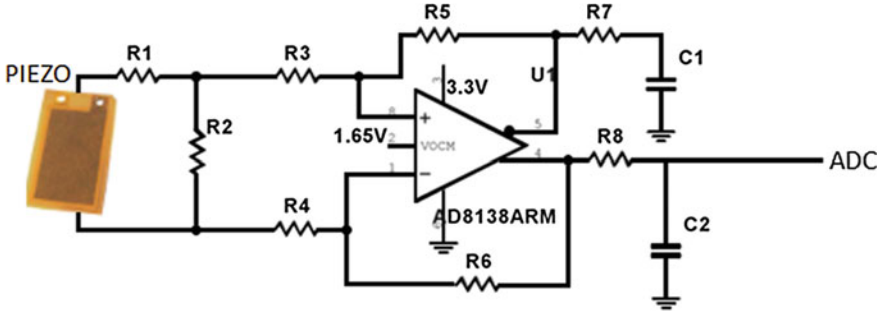


Fig. 4 Vibration measurement circuit

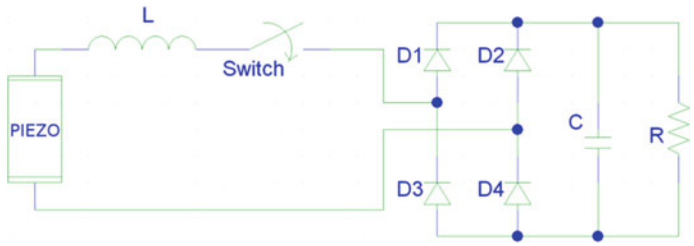


Fig. 5 The general "Series SSHI" circuit schema

"synchronised switch damping" (SSD) semi-passive method developed to address the problem of vibration damping. However, techniques based on SSD method provide efficient energy harvesting by increasing the energy flow between the piezoelectric element and the electrical load. Hence to it, the designed WSN node can provide the vibration damping and energy harvesting using the only one piezoelectric element.

The Series SSHI technique consists in a non-linear processing of the voltage delivered by the piezoelectric. In the series SSHI method, the inbuilt piezoelectric capacitance (PIEZO) and external inductance L creates the series resonant circuit. The switch keeps the circuit in the open-circuit. While the extrema of the mechanical displacement is detected (the maximal value of the electrical charge is generated in the piezoelectric element), the switch is closed for half of the electrical resonant period. It causes inversion of the piezoelectric element voltage because of the resonant circuit. In the same time, the electrical charge is stored in the storage capacitor C. Additionally we are using the bridge rectifier to provide full-wave rectification.

The designed series SSHI circuit contains two IRL630 NMOS transistors driven by the microcontroller (full-wave switch circuit with low current leakage and low short-circuit resistance). The usage of the logic-level transistor simplifies the circuit; the output of the microcontroller can be used to drive the electronic switch. The circuit works with the short switching times so we are using the Schottky diodes to increase their switching time.

4.4 Integration of a WSN Node (Simulations)

Designed analog circuits are simulated using the SPICE models in the NI Multisim software [11]. Figure 6 presents the general schema of the simulated WSN node.

The figure above contains the simple model of the microcontroller output pin used to control the Series SSHI switch. It is modelled as an ideal voltage source (V1). Then we can find the T1 transformer used as a galvanic isolation between the

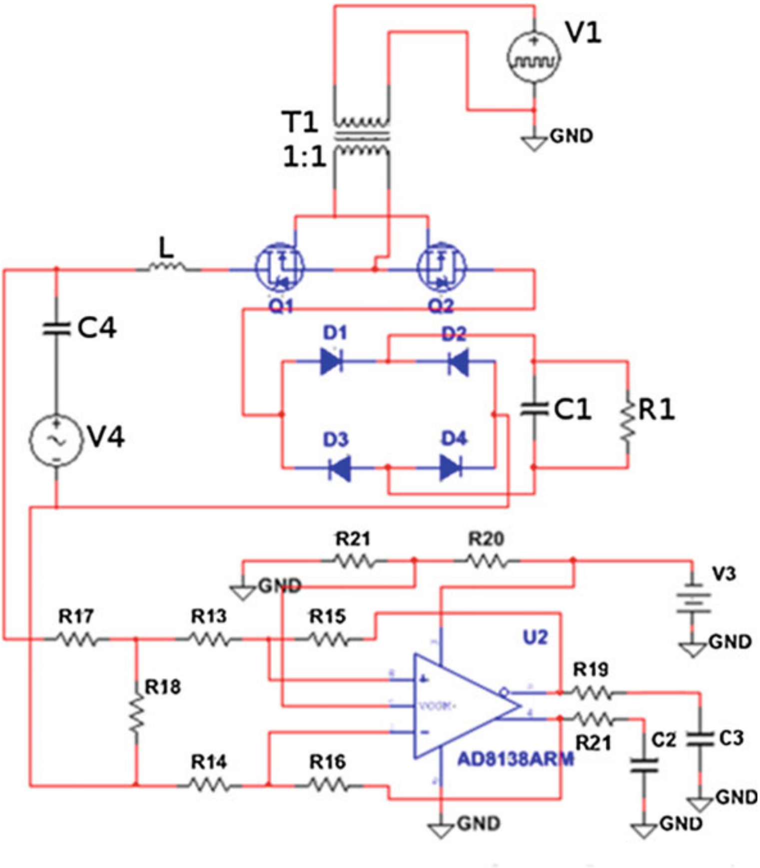


Fig. 6 Simulated analog part of the WSN node

microcontroller and the electronic switch to provide the switch circuit non-referenced to the ground.

A pulse transformer is, in principle, a simple, reliable and highly noise-immune method of providing isolated gate drive. It can be advised for applications were duty cycle is small [12]. The Series SSHI method is a system with low duty cycle because the period of the mechanical displacement is much longer than period of the electrical circuit. It makes the pulse transformer a promising solution for our design.

The piezoelectric element is simulated by the simplified electrical model composed of the voltage source and the capacity (V4 and C4). Then the vibration sensing circuit and the Series SSHI circuit are connected in parallel with the model of the piezoelectric element.

The series SSHI circuit contains two transistors and the inductor L. Additionally, the bridge (diodes: D1, D2, D3 and D4) is used to transform voltage from AC to

DC. Finally, the load and the storage capacitor are modelled by the resistor R1 and the capacitor C1.

4.5 Integration of a WSN Node (Prototyping)

According to the presented system approach and the specifications, the WSN node for the AVC system has been designed. The node is composed of the Microchip products: PIC16LF88 microcontroller and MRF24J40 radio transmitter. Moreover, the designed and already presented circuits (vibration sensing and series SSHI method for energy harvesting and vibration damping) are implemented according to the simulated schemas.

Figure 7 shows the photo of the prototyped device used in the experiment. The device dimensions (50.8 mm × 68.6 mm) are almost the same as the dimensions of the piezoelectric patch.

The microcontroller has been chosen because of its low energy consumption. The 8-bits microcontroller with the internal 10-bits analog-to-digital converter (ADC) is sufficient for our application. Moreover, the usage of the internal ADC reduces the energy consumption in comparison to the external devices. The MRF24J40 radio transmitter supports the IEEE 802.15.4 communication standard. The WSN node measures the amplitude and the frequency of the vibrations and transfer data using the non-beacon transmission mode. The wireless communication applied in the node needs a very low amount of the energy to provide the data transfer [9].

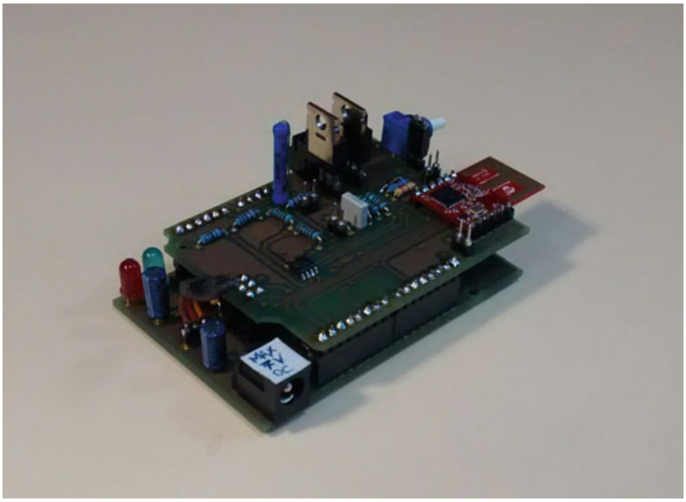


Fig. 7 Picture of the designed WSN node for AVC system

4.6 Validation of the WSN Node Design (Simulations Versus Measurements)

The WSN node is now designed, simulated and prototyped. The next step is to compare the results of the simulations and the measurements to verify the design and the choice of the used methods and components.

Figure 8 presents a block diagram of the designed WSN node and the three measurement points.

In the point 1 we look at the simulated and measured value of the signal conditioned in the vibrations sensing circuit. In the point 2 we track the value of the signal used to control the electronic switch of the series SSHI method (generated by the microcontroller on the basis of the measurements). In the point 3 we look at the output characteristic of the piezoelectric element (voltage and current). Figure 9 presents the comparison of the achieved, simulated and measured, results for the presented measurement points.

The simulated and measured signals in the point 1 are firstly the sinusoidal waves. During this period of the time, the Series SSHI method is inactive; the signal received by the microcontroller corresponds to the mechanical deformations.

The single vibration period is needed to measure the frequency and the amplitude of the vibrations by the WSN node. Then, extrema of the mechanical strain is detected. In this moment the microcontroller activates the Series SSHI method by generating the control signal (see measurements in point 2). This signal is used to control the electronic switch of the Series SSHI method.

In the point 3, we observe the current and the voltage values over the piezoelectric element. We can notice that the current flows only when the electronic switch is closed. We can also notice the voltage inversion caused by the resonance circuit created by the internal capacity of the piezoelectric element and the external inductance L.

The simulated and measured results are in good correlation. However, the ideal voltage source used in the simulations does not take into account the inductive and

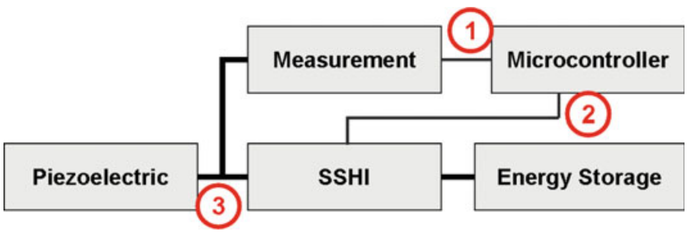


Fig. 8 Block diagram of the designed WSN node with the marked measurements points

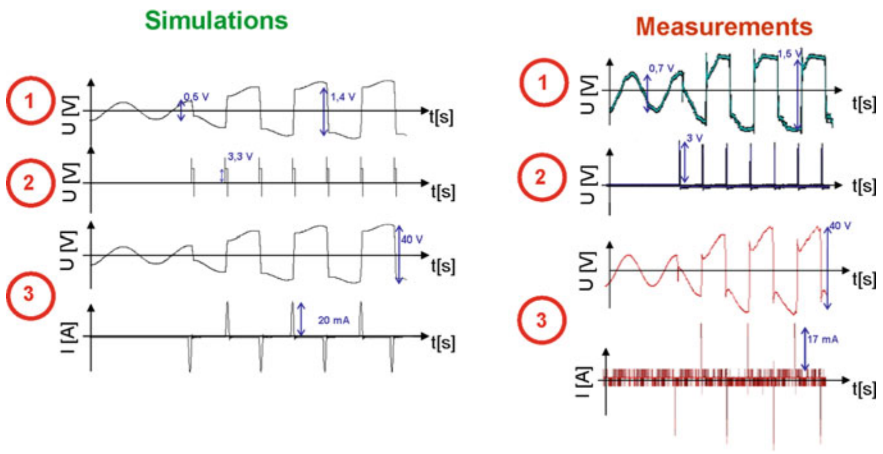


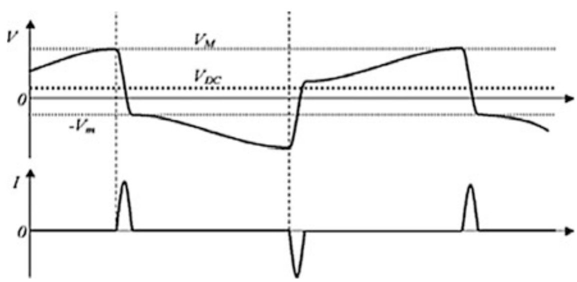
Fig. 9 The comparison of the simulated and measured signals

capacitive characteristics of the real piezoelectric element. Due to it, the differences are visible; they are mainly caused by the simplified model of the piezoelectric element or by the measurement noise.

Figure 10 presents the theoretical voltage and current values over the piezoelectric element for the Series SSHI method. We can compare it with the results from the simulations and measurements. It proves the design of the WSN node.

The designed WSN node provides the vibration sensing, mechanical damping and energy harvesting using the only one piezoelectric element. The node is independent and autonomous; it does not use any additional control signal. Moreover, using the wireless communication the node is able to send the measured values (frequency and amplitude of the vibrations). Since the WSN node for the AVC system is realised we can evaluate its feasibility using the mechanical structure as an experimental setup.

Fig. 10 Theoretical signals for the Series SSHI method (voltage and current) [10]



5 Experimental Setup

5.1 Specification for the AVC System in the Automobile Application

According to the state of the art, the vibrations in the body of car are the low frequency signals (up to 300 Hz) [13]. They are generated, among others, by the engine or by the interaction between the wheels and the road surface.

It is possible to identify the common vibration modes for different parts of the car body. It affects the propagation of vibrations. Therefore, the AVC system distributed on the surface of the car can be an interesting solution.

Nowadays, the car bodies are mostly made of the steel elements. Engineers are looking for lighter replacements [14, 15]. The most interesting material is aluminium. Despite the disadvantages related to its weld-ability and form-ability, aluminium is more popular than magnesium or polymer composites. Therefore, aluminium elements are used for our experiments.

The piezoelectric elements offer advantages such as: the high actuator force, the fast answer regarding changes, the bi-directionality of the piezoelectric phenomenon. It makes them more interesting than other damping solutions (viscoelastic, electrostatic, electromagnetic etc.). The inorganic piezoelectric elements are commonly used in the sensors and energy harvesting systems [16]. Hence, the P-876.A15 PICeramic actuator has been chosen. It is an elastic transducer which can also be applied to curved surfaces (dimensions: 61 mm $\times$ 35 mm $\times$ 0.8 mm). It is made of a modified lead zirconium titanate (PZT) material, optimised for actuator applications [17].

5.2 Mechanical System Used in the Experiments

Figure 11a presents the mechanical system designed and implemented in accordance with the established specifications. It is composed of the aluminium frame (profiles side length 0.045 m). The electrical vibrator attached to the frame using four nylon strings (diameter 0.01 m). The aluminium square panel (side length 0.332 m, thickness 0.001 m) attached to the frame by two nylon strings (diameter 0.001 m).

The square panel is considered as a simplified model of the body of the car. The electrical vibrator and panel are connected using the thin steel rod. The mechanical system has the following global dimensions: height 1.64 m, width 0.58 m and depth 0.49 m.

The dimensions and position of aluminium panel, piezoelectric elements and the excitation point are presented on Fig. 11b. The chosen piezoelectric elements are positioned on the panel surface in order to verify local, as well as, global influence of the designed AVC system. The excitation force is measured using the quartz

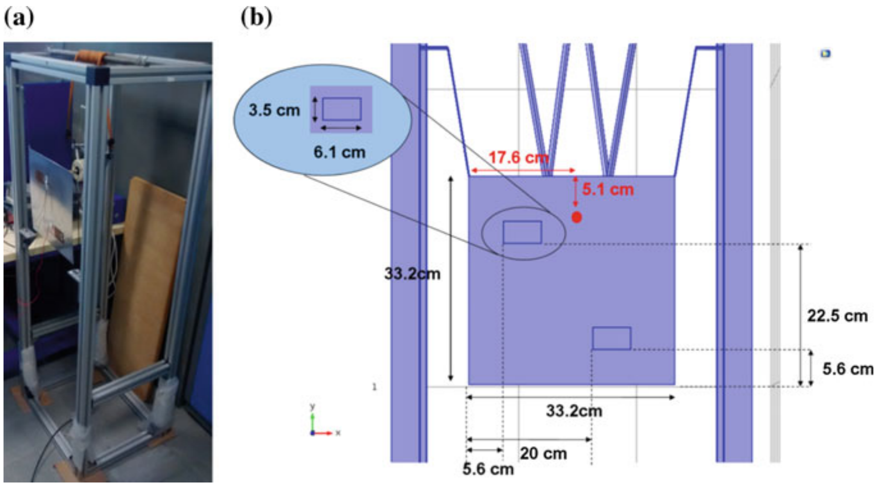


Fig. 11 **a** The mechanical system used in the experiments (photo). **b** Position and dimensions of the aluminium plate, excitation point and piezoelectric elements

force sensor manufactured by the PCB company (PCB 208C02). The force sensor is located between the electrical vibrator and the thin rod. The vibration velocity of the aluminium panel is measured using the laser doppler vibrometer: CLV-3D Compact 3D Laser Vibrometer produced by Polytec. Both measurements are realised in the z-axis according to the coordinate system presented on Fig. 11b. Designed system is excited with the signal generated by a function generator.

Figure 12 presents the point of the velocity measurements for the aluminium plate and its measured frequency response. We have also marked on this figure the frequencies: 65, 113, 130, 165 and 235 Hz, which correspond to the mechanical structure vibration modes.

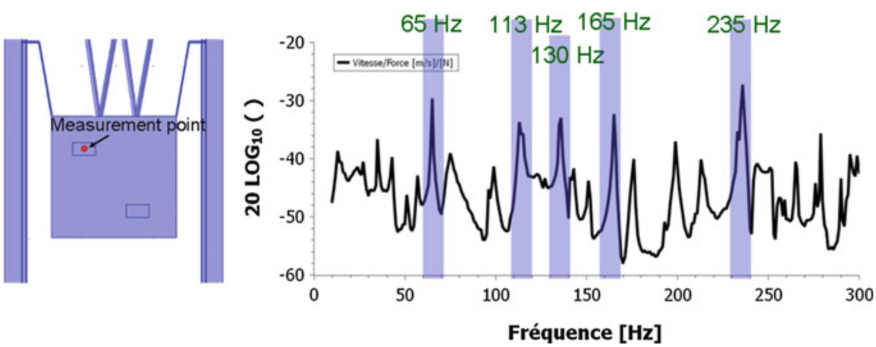


Fig. 12 Frequency response of the mechanical system

Since the mechanical system is presented and described, we can validate the feasibility of the designed WSN node. We will validate the vibrations damping capability for the marked vibration mode frequencies.

6 Validation of the WSN for the AVC

Firstly, we validate the single WSN node. In this case the only one WSN node connected to the one piezoelectric element is used to verify the local vibration damping capability. Then, the network of the two autonomous WSN nodes is used to verify the global vibration damping capability of the designed system.

6.1 Local Vibration Damping

The WSN node is connected to the left piezoelectric element mounted on the experimental aluminium plate (Fig. 13).

The panel is excited with a harmonic force with a constant magnitude. The amplitude of the vibration velocity is measured for two cases: when the designed WSN node is not active and when it is active. Afterwards, the velocity ratio is calculated (the results are presented in the decibel scale). Table 1 presents the results for the local vibration damping for different vibration frequencies.

According to the results presented in the Table 1, we notice the different efficiency of the vibration damping. Moreover, for the frequencies: 65 and 130 Hz, the vibration damping is not achieved.

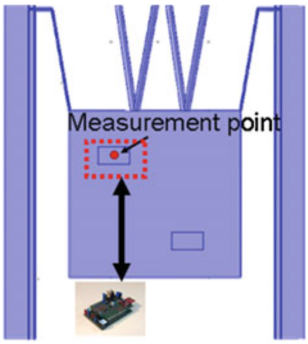


Fig. 13 The local vibration damping experimental configuration

Table 1 The local vibration damping efficiency for the different vibration frequencies

Frequency	65 Hz	113 Hz	130 Hz	165 Hz	235 Hz
Damping	0 dB	0.77 dB	0 dB	8.00 dB	9.34 dB

The FEM simulations are used to explain these differences. The experimental structure is simulated using the COMSOL 5.1 software. The deformations of the mechanical structure for the frequency of 65 Hz are presented on the Fig. 14.

The Fig. 14 shows the element piezoelectric which is not deformed. It explains why the designed WSN node is not able to damp the mechanical vibrations of 65 Hz. The same conclusions have been achieved for the frequency of 130 Hz.

The maximal vibration damping efficiency is achieved for the frequency of 235 Hz. The Fig. 15 presents the simulated deformations of the mechanical structure for this frequency.

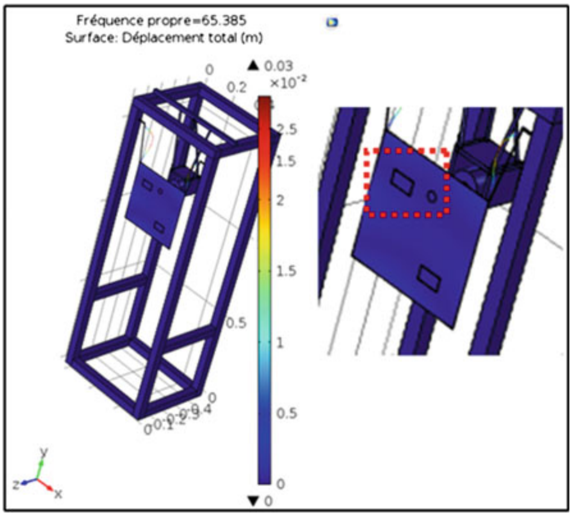


Fig. 14 Simulated deformations of the experimental setup for the frequency of 65 Hz

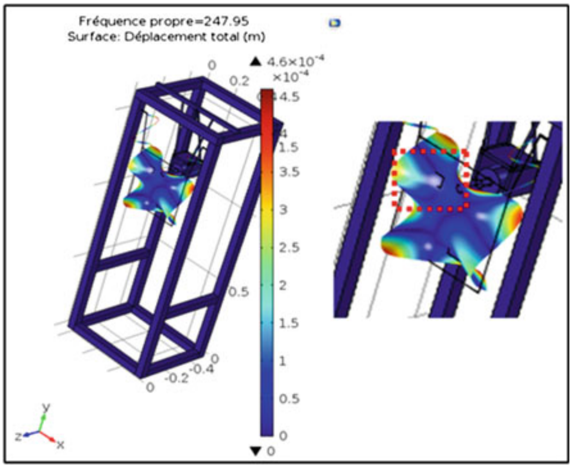


Fig. 15 Simulated deformations of the experimental setup for the frequency of 235 Hz

The Fig. 15 proves the deformation of the left piezoelectric element used to damp the mechanical vibrations. Moreover, for this frequency, the left piezoelectric element is placed next to the vibrations wave anti-node; thus, the maximum efficiency of damping is achieved.

The Fig. 16 presents the efficiency of the passive resistive method (the resistive load which is connected directly to the piezoelectric element) in comparison with the designed WSN node. The vibration efficiency is presented in decibel scale in function of load value. The mechanical excitations have the frequency of 235 Hz and are constant in the amplitude.

Figure 16 shows the difference in efficiency for the two considered methods. The passive method achieved the maximal efficiency of 4.31 dB for the load of 28 kΩ. For this load the WSN node is more efficient and has achieved the efficiency of 5.81 dB. The WSN node achieved the maximal efficiency of 9.34 dB for the load of 100 Ω. While, the passive method has achieved the efficiency of 3 dB for this load value. The presented results prove the local vibration damping capability of the designed WSN node.

6.2 Global Vibration Damping

The next step is to validate the global vibration damping with the designed distributed AVC system based on the WSN. In this case the two piezoelectric elements mounted on the aluminium plate are used. Both are connected to the designed WSN nodes.

Since two piezoelectric elements are used, both of them have to be deformed to provide the mechanical damping. Analysis of the experimental structure has shown the vibration frequency of 113 Hz as the most suitable for this experimental

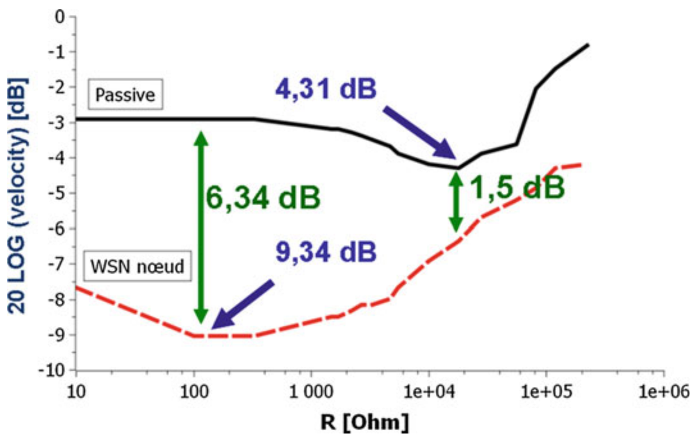


Fig. 16 The vibration damping efficiency: the comparison between the passive method and proposed WSN node

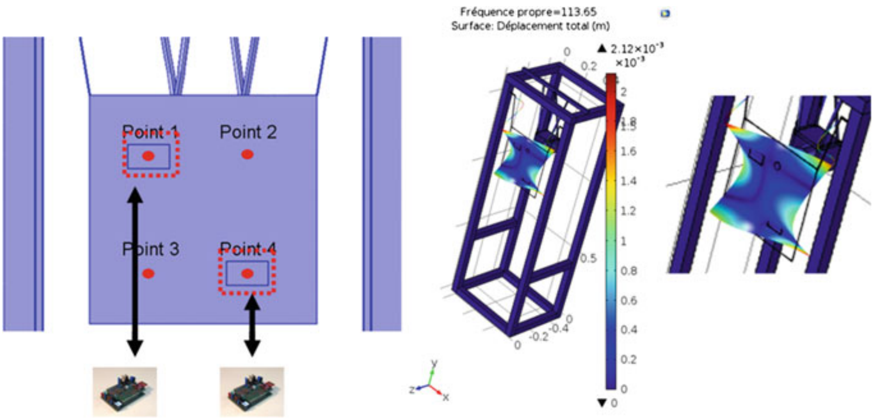


Fig. 17 The experimental setup for the global vibration damping and the simulated deformation

Table 2 The global vibration damping efficiency for the frequency of 113 Hz

	Point 1 (dB)	Point 2 (dB)	Point 3 (dB)	Point 4 (dB)
Left WSN node is active	0.77	0.75	0.89	1.53
Right WSN node is active	0.77	0.39	0.89	0.99
Both WSN nodes are active	1.62	1.52	2.41	2.10

setup. The Fig. 17 presents the experimental configuration and simulated mechanical deformation of the mechanical system for the chosen vibration frequency.

In this case, the vibration velocity is measured in the four points marked on the Fig. 17. Firstly, we measure the efficiency for two WSN nodes separately (local vibration damping). Then, the efficiency of the distributed system composed of two nodes is measured. The results are presented in Table 2.

The results prove the efficiency of the proposed distributed active vibration control. The designed WSN provides the additional damping action. We can notice the increase of the mechanical damping efficiency with the number of the nodes.

7 Conclusion

Centralised and wired systems for active vibration control are costly and use a large quantity of energy. A distributed solution based on an energy aware wireless sensor network has been proposed as a replacement for the centralised system. The autonomous WSN node needs to be designed to provide efficient wireless network for distributed active vibration control. In this paper the global approach and the system assumptions are established and used as input data for the design. The proposed design of the WSN node is in accord with the prescribed requirements.

Designed node provides: vibration sensing, shunting the piezoelectric element and wireless communication. Furthermore, the series SSHI technique, chosen for the design, provides damping of the mechanical vibrations and the energy harvesting capability.

Designed circuits for sensing vibrations and shunting the piezoelectric element are presented and described in details. The WSN node is modelled using the SPICE models. Achieved simulation results are consistent with the expected ones and validate the design. The WSN node prototype has been constructed. The simulation results are compared with the measurements. The measurement results correspond to the simulation results.

The distributed wireless AVC system is presented. The vibration damping is verified using the proposed experimental mechanical system. We have created two test scenarios. The first one is used to validate the local vibration damping capability. The measurements show the importance of the piezoelectric element position. The efficient vibration damping can be achieved only by using the actives elements placed next to the nodes of the vibration waves. The results prove also the necessity of the impedance adaptation. The second scenario is used to validate the global aspect of the designed distributed system. The two piezoelectric patches are used to damp the mechanical vibrations. The measurements prove the distributed approach. We have achieved the additional action provided by the network of the nodes.

The results confirm the application of the low power wireless nodes in the distributed AVC system. The achieved efficiency of 9.4 dB is comparable with the existing systems. Moreover, the scalability of the system is proved. The increase of the network will improve the global mechanical damping efficiency. Finally, results prove the usage of the autonomous wireless sensor network nodes in the vibration damping application.

The following step is the validation of the energy harvesting capability in the designed WSN in order to confirm the auto supply possibility. The designed and described mechanical system and the proposed distributed AVC system will be used to measure the value of the energy harvested from the vibrations by the implemented Series SSHI method. Then, the distributed vibration control algorithm will be proposed.

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