INTERNATIONAL JOURNAL OF
AUTOMOTIVE SCIENCE AND TECHNOLOGY

2021, VOL. 5, NO: 4, 398-403 www.ijastech.org e-ISSN: 2587-0963

Design of Piezoelectric Acceleration Sensor for Automobile Applications

Mert Gül[1,2*], Murat Karaer[3], Aydın Doğan[2]

0000-0001-8618-6261[1], 0000-0003-1008-6306[3], 0000-0002-8122-2996[2]

[1] *Nanotech High Tech Ceramics, Eskisehir, 26555, Turkey*
[2] *Materials Science and Engineering Department, Engineering Faculty, Eskisehir Technical University, Eskisehir, 26555, Turkey*
[3] *Product Development Department, Ford Otosan, Eskisehir,26670, Turkey*

Abstract

In this study, piezoelectric based compressive type accelerometer has been designed by using PZT-5A ceramics with bellewasher type spring. FEA analysis were carried out by using COMSOL. According to COMSOL simulation, resonance frequency is nearly 42500 Hz. Sensitivity of the designed sensors were measured and compared each other. Frequency spectrum was between 100Hz-10 kHz. The effects of piezodisk thickness, stiffness of the spring and seismic mass on the sensitivity of the designed sensor were investigated. Voltage output is increasing from 4.1 mV/g to 12.7 mV/g while seismic mass is raised from 3 gr to 10 gr. Linearity depending on the frequency of the designed accelerometer was distorted above 5.5 kHz like commercial accelerometer. In addition, real-time tests were performed using a calibrated accelerometer and a designed accelerometer on the internal combustion engine and drivetrain. Vibration profiles were carried out randomly. According to the results obtained here, it is observed that all the peaks were matched with a coefficient about 1.3.

Keywords: Piezoelectric, Accelerometer, Design, Compressive, FEA

Research Article

https://doi.org/10.30939/ijastech..1006197

Received 17.10.2021
Revised 06.12.2021
Accepted 07.12.2021

* Corresponding author

Mert Gül

mertggg@gmail.com

Address: Materials Science and Engineering Department, Engineering Faculty, Eskisehir Technical University, Eskisehir, Turkey

Tel:+90222313550/6392

1. Introduction

Vehicles produced in last 30 years are equipped with sensors to increase safety and driving comfort. These sensors are used to measure or determine changes in vehicles or external conditions by using parameters in magnetic, electrical or chemical values. In addition to the measurements done on the external conditions, movements such as vibration, collision and shock that occur while the vehicle is in the motion are the parameters must be measured in today's smart vehicles [1]. One of the primary sensors that come to mind for these measurements is accelerometers. Acceleration sensors detects and measures the acceleration that caused by the motion, vibration, impact and shock etc. Acceleration sensors measures acceleration due to Newton's second law of motion [2]. Automotive applications of acceleration sensors are airbag initiation, Anti-lock braking systems (ABS),electronic stability program (ESP), active suspension systems, hill descent control systems (HDC), monitoring noise or harshness etc [3]. These sensors have sensing material based on MEMS, piezoresistive or piezoelectric [4]. Advantages of piezoelectric accelerometers related to MEMS and piezoresistive are wide operating frequency range, small sensitivity to the magnetic fields, linear characteristics in these wide ranges, reliability of a design and long-term stability [5]. Piezoelectric accelerometers are categorized into three commercial subgroups based on working mechanism; 1) Shear mode 2)Bender mode 3) Compression mode [6].

In compression mode design, piezoceramics are deformed by a seismic mass under compression force and obtained voltage or charge is measured. Seismic mass increases the sensitivity and charge output of the piezoelectric ceramics that are most important design criteria for acceleration sensors. However, in compression type accelerometers, affecting too much by base vibrations due to seismic mass and compression is the main disadvantage. Therefore spring effect is important for the basic compression type piezoelectric accelerometers. For this purpose spring element must be both tight enough to transfer acceleration to the piezoceramics and able to compansate the loads to be placed on the system that damage sensitive piezoceramics [7]. Cymbal type accelerometer designed to increase sensitivity of the accelerometer while increasing voltage output [8]. Energy output is the most important parameter of compression mode accelerometer design [9]. Compositions have high g33 values are also used in applications requiring high energy density [10]. PZT-5A is also among these compositions. In the study using the PZT-5A, piezoceramic was processed and used as a 1-3 composite transducer and a 4.8 times voltage sensitivity was obtained [11]. PZT-5A ceramics known to be used in applications such as hydrophone and accelerometer [12].

In this study, compression mode piezoelectric based accelerometer is designed by using belleville washer type spring to compensate the base vibration sensitivity. The design is analysed and supported by FEA analysis on the mechanical electrical view. Piezoceramics were machined from PZT-5A ceramics that have higher g33 coefficient and capable of producing high charge under compression. FEM studies were evaluated by using COMSOL. FEM results were compared by the experiments. In addition real time measurements were done on the internal combustion engine and transmissions on Ford Otosan Eskişehir Plant.

2. Experimantal Method

2.1 Piezoelectric Elements

Commercial PZT-5A powders were used to fabricate piezoelectric elements. Powders were compacted by using biaxial pressing and densified with isostatic pressing under 130 MPa. Pressed pellets were sintered at 1250˚C for 2 hours. Table 1 presents the mechanical and electrical properties of PZT ceramics for the functional element.

Table 1. Piezoelectric and electromechanical properties of PZT-5A

	d (g/cm^3)	d_{33} (pC/N)	g_{33} (mV/N)	k_p	Q_m	K^T	N_p
PZT-5A	7,6	450	22.1	0,65	70	2300	2100

d refers to density, d_{33} is the piezoelectric charge constant, g_{33} is the open circuit charge constant, important for the energy related measurements, kp is the coupling coefficient, Qm is the mechanical quality factor generally used for the power transducer applications, K^T is the dielectric permittivity value and Np is the frequency constant.

2.2 Measuring

The sensitivity of the accelerometer was measured and compared by using reference acceleration sensor and the schematic view of the setup is shown in Fig. 1. The instruments of the measurement systems include an Agilent DSO-X3014A osciloscope to measeure mV/g values, a Brüel&Kjær standard reference accelerometer Type 4513-001 (sensitivity =98,73 mV/g for f < 32 kHz) and a vibrator (LDS,model V406) with the control unit (PA500L). The acceleration parameters of the vibrator depends on the Wavefactory WF1944 type signal generator. Acceleration measurements were also checked by using Polytech PSV-500 Scannig vibrometer. Measurements were done at different frequencies between 100 Hz to 10 kHz at 1g (9,81m/s^2).
Besides the laboratory measurements, real time measurements were done on the internal combustion engine by using reference accelerometer in a test room where internal combustion engine and drivetrain development tests were carried out at Ford Otosan Factory. Prototype accelerometer and calibrated Kistler 8766A500BH accelerometer sensor were mounted to the engine and transmissions under same conditions and vibration data were obtained simultaneously by using software.

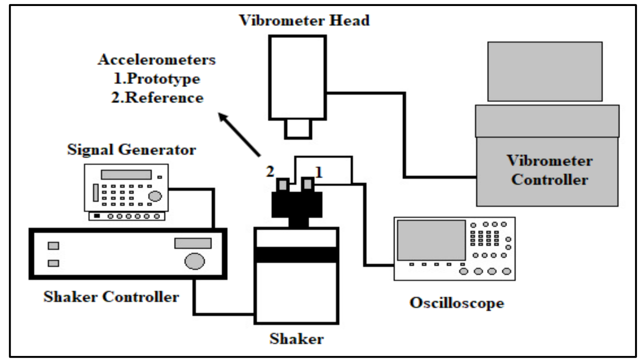

Fig. 1. Schematically view of experimental set up for measuring accelerometer

2.3 Modelling and Prototyping

Figure 2 illustrates the design and FEA simulation inputs of compression type acceleration sensor (Dimension: outer diameter = 12.7mm, inner diameter = 5.1mm and thickness = 1 mm). Accelerometer design consists of bellewasher type spring element, base metal, insulating ceramic parts, piezoceramic discs, conductive sheets for electrodes and bolt. Functional element of piezoceramics were sandwiched at opposite polarization directions with metal electrodes and between 2 isolated ceramic discs (Figure 2).

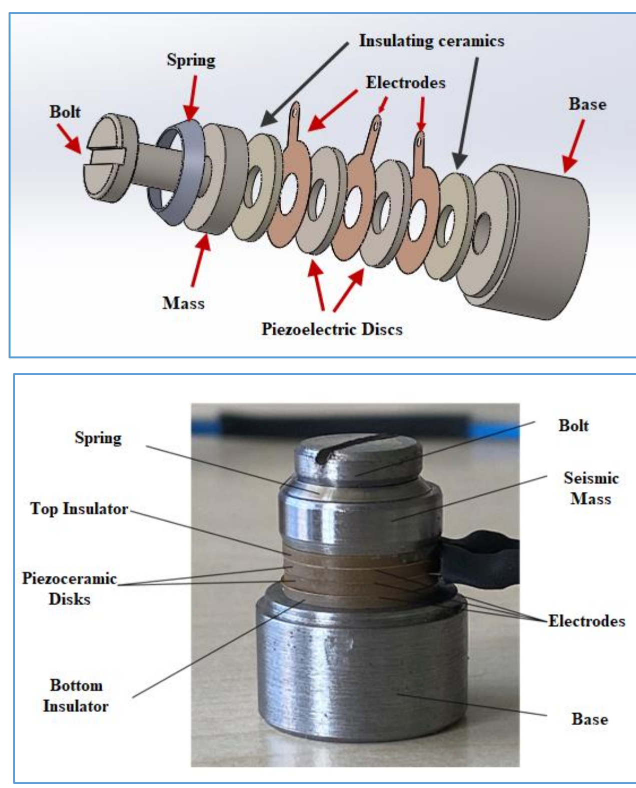

Fig. 2. a) Exploded view of the acceleration sensor b) protoype accelerometer

2D dimensional view, design variables, mesh models and FEA results of stress points at 1 g (9,81 m/s^2) were given at Figure 3. FEA simulations were done by using COMSOL 5.4.

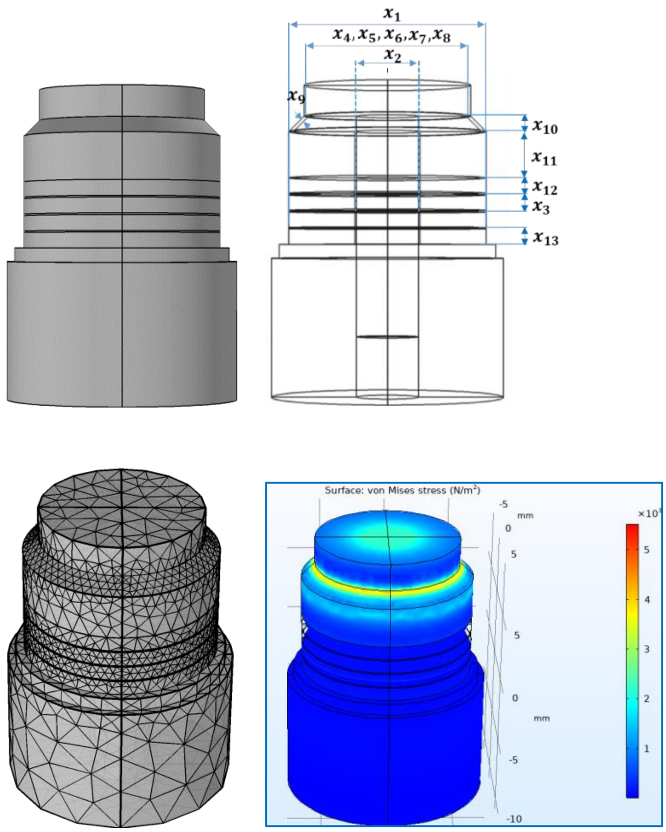

Fig. 3. (a) 3D wiev and components of designed accelerometer, (b) Design parameters of accelerometer (x1 to x13) (c) Finite element modelling and meshing of designed accelerometer d) Stress analysis of the designed accelerometer at 1 g.

Mesh element was selected as triangular can be seen in figure 3c. When the acceleration force due to vibration is applied to sensor at z direction, bellewasher type spring counteracts the stress as can be seen in figure 3d.

Table 2 presents the mechanical properties of all the components used for theoretical modelling in FEA analysis.

Table 2. Mechanical Properties of Components of Prototype Acceleration Sensor

Component	Material	Density (kg/m^3)	Young's Modulus (Gpa)	Compressive Strength (MPa)
Spring Element	Copper	8960	130	45
Mass	Steel	7767	193	300
Base	Steel	7767	193	300
Electrodes	Copper	8960	130	45
Insulating Parts	Alumina	3950	393	2400

3. Results and Discussion

According to simulations, resonance frequency of the accelerometer was 43,5 kHz while seismic mass was 3 grams. If seismic mass of the sensor was increasing to 15 gr, resonance frequency was decreased to 37,5 kHz. Resonance frequency depends on the design parameters include piezoceramic element, base, seismic mass [13]. In addition, effect of seismic mass 3 gr to 10 gr to the voltage output is shown in figure 4.

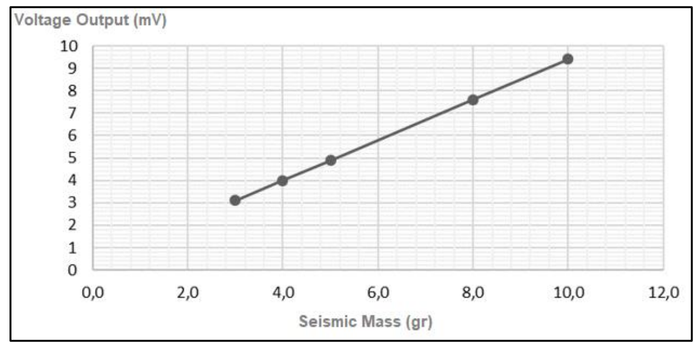

Fig.4. Voltage Output depending on Seismic Mass (Theoretical)

COMSOL simulations showed that voltage output level increased as linear from 3,11 mV to 9,41 mV when seismic mass has been increased. Voltage and charge sensitivity was propotional to the electrical output of the piezoceramics as expected. Kwon exhibits the relationship between voltage and charge sensitivity of compression type accelerometer depending on the d_{33} and g_{33} values related to composition of PZT discs [14].

In experimental studies, it was observed that voltage values increased when the seismic mass was increased by looking at the voltage sensitivity graphs in the range of 0.1 kHz-10 kHz. In addition, it was observed that the accelerometer prototypes showed linearity in the 0.1-5 kHz range and showed a useful frequency range in this frequency range [7].

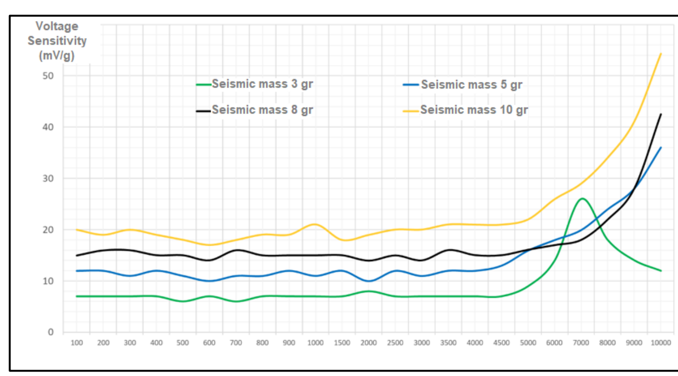

Fig. 5. Voltage outputs of the prototype acceleration sensors at 0.1-10 kHz frequency depending on seismic mass

In Figure 5, measurements were done at 1 g acceleration value depending on the frequency. It was obtained an average voltage output of 7.12 mV when 3g mass was used in the measurements. It was observed that the voltage value increases as the mass increases, and the highest voltage output was obtained when using

10 gr mass. However, when 10 gr mass was used, the sensitivity value increases up to 19.88 mV/g, oscillations on the voltage output at some frequencies were also observed. Voltage output level denotes the sensitivity increased almost linearly [15]. Piezoelectric materials produce more voltage output when mass is added to them under oscillating conditions. [16,17]. This situation can also be explained by Newton's principles. [18]. The designed system provides more consistent outputs in the 0-5kHz frequency range.

In this study, besides from seismic mass effect, piezo-disc thickness effect was also investigated parametrically. According to the COMSOL simulation studies 3 gr seismic mass was used constant, while the piezodisc thickness increases from 0.5 mm to 2.5 mm, the obtained voltage level increases from 1.47 mV to 8.12 mV (Figure 6).

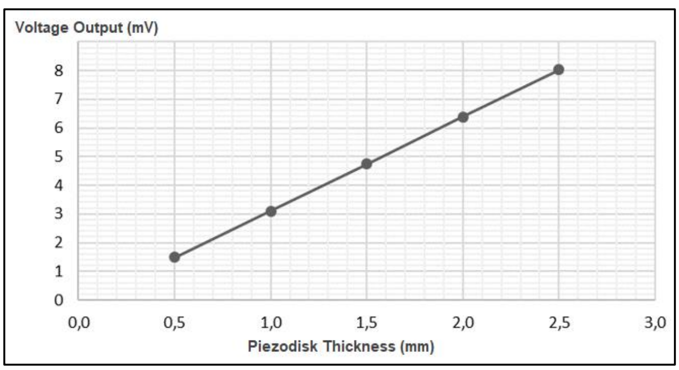

Fig. 6. Voltage Output depending on piezodisk thickness (Theoretical)

In experimental studies of piezodisk effect, seismic mass was used as 10 gr as constant. It was observed that voltage values increased from 11.61 mV to 24.38 mV when the piezodisk thickness changed from 1 mm to 2 mm in the range of 0.1 kHz-10 kHz. As the thickness of the piezodisc increases, the energy density of the piezoceramics increases due to the volume of atomic charges [19]. Although the voltage level and accordingly the sensitivity value increases when the piezodisc thickness was increased to 2 mm, maximum useful frequency decreases from 5 kHz to 3 kHz due to nonlinearity effect [20].

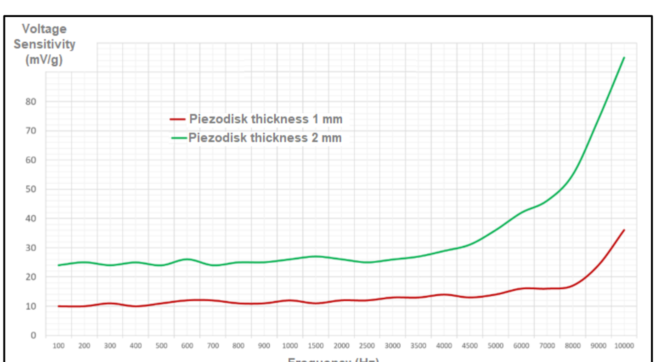

Fig. 7. Voltage sensitivity depending on thickness of piezoelectric ceramic at 1 g while seismic mass was 10 gr

Real time measurements were done on the Ford internal combustion engine and gearbox to compare with the reference accelerometer that shown in figure 8.

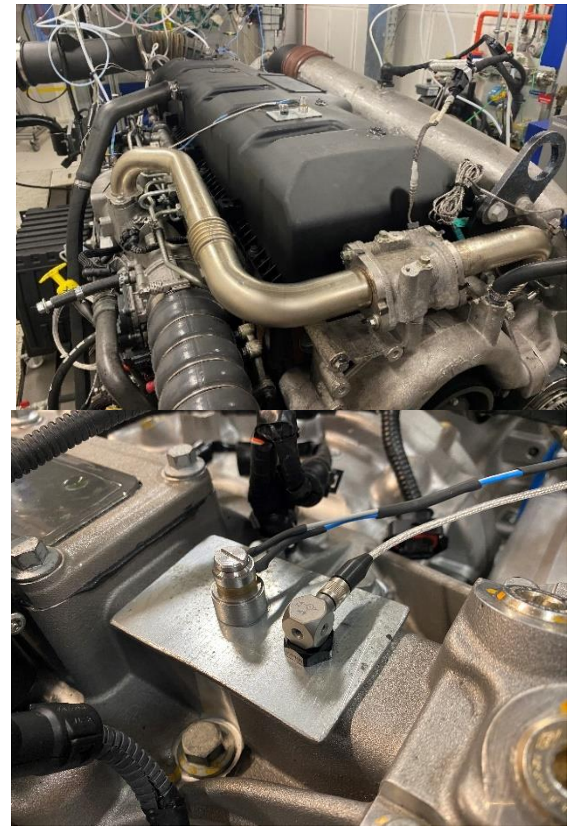

Fig. 8. Positioning the accelerometers on to internal combustion engine and transmissions a) general positioning b) mounting to engine

The acceleration magnitude was measured simultaneously by two sensors in 172 randomly generated artificial vibration movements.

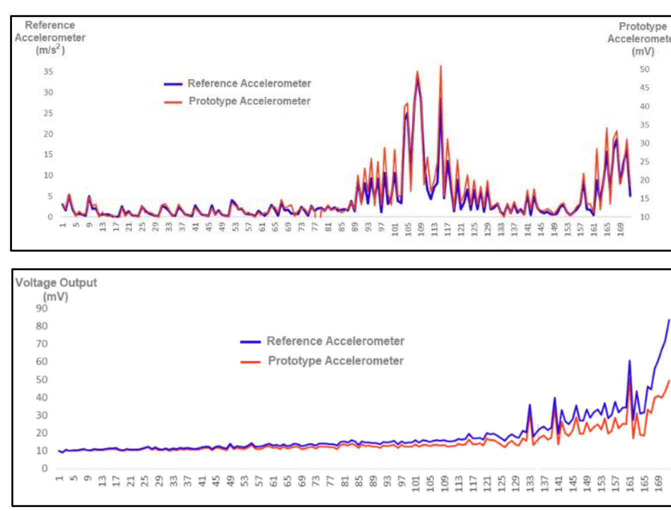

Fig.9. Comparison of the random vibration data that measured with prototype and common accelerometer

According to the results in Figure 9 a, the prototype accelerometer and reference accelerometer peaks were completely matched in the measurement points between 13-65. Measurement deviation was observed at points 69, 77 and 161. Except for these points, all the peaks appeared simultaneously. In the measuring range 89-129, the reference accelerometer indicated an acceleration value of 3 g. The proto-type accelerometer showed a value of 52 mV. When the data were cleared from noise measurement, it was observed that the data curves obtained from the two sensors followed each other at a rate of 97% as in figure 9. The curves formed by ordering these data from smallest to largest are given in figure 9.b.

In the study, voltage output up to 50 mV was taken from the prototype accelerometer at 3g (30m/s2) acceleration value in random vibration. The graph shows that the acceleration measurement curves of the two sensors follow each other with an A coefficient (A ~ 1.3).

In the acceleration measurements made for performance research, the prototype accelerometer with the base design was also exposed to real vibration cycles besides random vibrations.

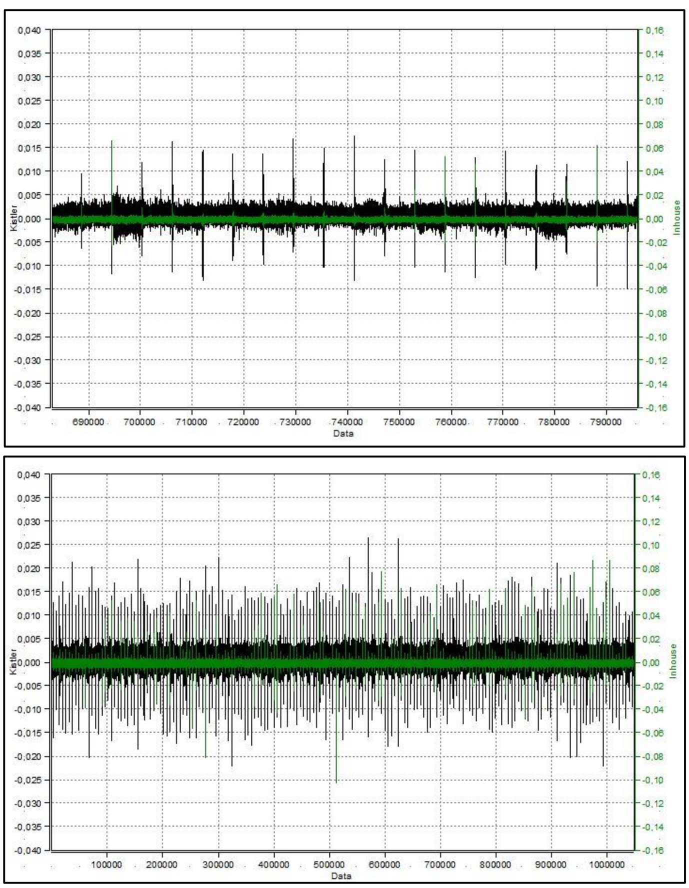

Fig. 10. Engine and Transmissions vibration data of the reference and prototype accelerometers received simultaneously a) Whole spectrum b) Detailed spectrum (between 700000-800000)

In a test room where internal combustion engine and drivetrain development tests were carried out, prototype accelerometer and calibrated acceleration sensor were connected to the engine and transmissions under the same conditions, as can be seen in Figure 8a, and simultaneous vibration data were obtained from the sensors. Figure 10a shows vibration data taken simultaneously with two sensors at 1 kHz data recording frequency.

The data collected for 30 minutes was analyzed and it was determined that a total of 214 vibration peaks that should be recorded every 6 seconds depending on the gear change due to the test cycle could be detected by both sensors and the data peaks were coincident at 214 points. Green lines belongs to prototype accelerometer. In the time-domain data, a vibration data wass generated when each gear in the gearbox engages[21] and also peaks originating from rotational, axial and radial vibrations in the gearbox [22] So, At every gear change, unusual vibration peak occurs.

It can be more easily understood on a detailed spectrum in a randomly selected data section, as in Figure 10b, where these peaks are coincident.

4. Conclusions

In this paper compressive type acceleration sensor has been designed with bellewasher type spring element. Design parameters has been investigated in systematic approach. Models were analyzed by using COMSOL finite element analysis simulations.

In compression type design, as the seismic mass increases from 3 gr to 10 gr, voltage output increases from 7.12 mV to 19.88 mV. However, seismic mass must be limited due to design depending on the resonance and reliability criteria. As piezodisk thickness was increased from 1 mm to 2 mm, obtained voltage outputs increased from 11.61 mV to 24.38 mV. The increase trends of the COMSOL analysis are largely consistent with experimental results. The number of experiments can be reduced by using the COMSOL software in piezosensor design and similar studies. Useful frequency range was detected as 0-5 kHz.

Measurements done simultaneously with the calibrated acceleration sensor in real environments show that the data obtained from the prototype acceleration sensor is consistent about 97% and verifiable.

This research will be the first study on design and product development of acceleration sensor based on piezoelectric technology for automobile applications in Turkey. It can be predicted that more sensors will be used in vehicle technology to solve mobility solutions and have better safety and comfort.

Acknowledgment

This study was supported by TUBITAK/TURKEY in frame of the project code of 3189196 as researchers, we thank the TUBITAK and also Ford Otosan Test Department for experimental supports. Also thanks to Nebahat Bıyıklı, Ali Bıyıklı and Çağdaş M. Ünal for experimental, to İrem Panta for administrative supports.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Mert Gül: Conceptualization, methodology, writing-original draft, investigation, visualization, validation,
Murat Karaer: Conceptualization, investigation, data curation, visualization, software, validation,
Aydın Doğan: Supervision, project administration, resources.

References

[1] Fleming WJ. New Automotive Sensors—A Review. IEEE Sensors Journal, 2008; 8 (11):1900-1921.

[2] Ghemari Z, Salah S, Bourenane R. Resonance Effect Decrease and Accuracy Increase of Piezoelectric Accelerometer Measurement by Appropriate Choice of Frequency Range. Hindawi Shock and Vibration 2018, 5370438, 8 pages.

[3] Fleming WJ. Overview of Automotive Sensors. IEEE Sensors Journal, 2001; 1(4):296-308.

[4] Nemirovsky Y., Nemirovsky A, Muralt P, Setter N. Design of a novel thin-film piezoelectric accelerometer. Sensors and Actuators A, 1996; 56: 239-249.

[5] Korobiichuka I, Bezvesilna O, Kachniarz M, Koshovyj M, Kvasnikov V. Methods and Ways of Piezoelectric Accelerometers Fastening on the Objects of Research. Acta Physica Polonica A, 2018; 133(4):1112-1115.

[6] Metra Mess- und Frequenztechnik. Piezoelectric Accelerometers Theory and Application. © 2001.

[7] Serridge M, Licht TR. Piezoelectric Accelerometers and Vibration Preamplifiers Theory and Application Handbook. 1987 Denmark, K. Larsen &Son A/S.

[8] Koc B, Dogan A, Fernandez JF, Newnham RE, Uchino K. Accelerometer Application of the Modified Moonie (Cymbal) Transducer. Jpn. J. Appl. Phys. 1996;35(1): 4547-4549.

[9] Denghua L, Daining F, Lina W,Weijun J, Meijian J. Cymbal Piezocomposites for Vibration Accelerometer Applications. Integr. Ferroelectrics, 2006; 78: 165–171.

[10] Islam R A, Priya S. High-Energy Density Ceramic Composition in the System Pb(Zr,Ti)O3–Pb[(Zn,Ni)1/3Nb2/3] O3. J. Am. Ceram. Soc., 2006;89 (10): 3147–3156.

[11] Li D, Duan K.1-3 Piezocomposite for Vibration Accelerometer Applications, Ferroelectrics, 2014; 466(1): 86-91.

[12] Bilgen O, AminKarami M, Inman D J, Friswell M.I. The actuation characterization of cantilevered unimorph beams with single crystal piezoelectric materials. Smart Mater. Struct. 2011;20:055024 (9pp).

[13] Lee MK, Han SH, Park KH, Park JJ, Kim WW, Hwang WJ, Lee GJ. Design Optimization of Bulk Piezoelectric Acceleration Sensor for Enhanced Performance. Sensors 2019; 19: 3360.

[14] Kwon, J.R. Influence of effective piezoelectric properties on performance of piezoelectric accelerometer for vibration measurements. J. Korean Ceram. Soc. 1995, 32(8), 945-49.

[15] Karaer M., Design of Piezoelectric Based Accelerometer. Ms Thesis, Eskisehir Technical University, Eskisehir, Turkey, July 2020.

[16] Kim HW, Priya S, Uchino K, Newnham R E. Piezoelectric Energy Harvesting under High Pre-Stressed Cyclic Vibrations. J Electroceram 2005:15, 27–34.

[17] Xie XD, Wu N, Yuen KV, Wang Q. Energy harvesting from high-rise buildings by a piezoelectric coupled cantilever with a proof mass. International J Eng Sci, 2013; 72: 98-106.

[18] Chua HG, Kok BC, Goh HH. Modelling and design analyses of a piezoelectric cymbal transducer (PCT) structure for energy harvesting application WIT Transactions on Ecology and the Environment, 2015:103-114.

[19] Moulson A.J., Herbert J.M. (2003). Electroceramics, John Wiley & Sons Ltd, 2. edition West Sussex, Great Britain.

[20] Sun CL, Lam KH, Choy SH, Chan HLW, Zhao XZ, Choy CL. High sensitivity cymbal-based accelerometer. Review of Scientific Instruments 2006; 77: 036109.

[21] Praveenkumar T, Sabhrish B, Saimurugan M, Ramachandran K I. Pattern recognition based on-line vibration monitoring system for fault diagnosis of automobile gearbox. Measurement, 2018;114: 233–242.

[22] Park CI, Lee JM. The Load Transmission and Vibration Characteristics of Automobile Gear. 932917, SAE Technical Paper Series, Worldwide Passenger Car Conference and Exposition, Dearborn, Michigan, October 25-27,1993.