New sensor constructions widen possibilities to use vibration fault diagnosis for vehicles and internal combustion engines

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Abstract: The piezoelectric vibrations sensors which are commonly used presently in the industry are not suitable for some other applications like on-board testing of engines or hot surfaces. New construction principles, e.g. semiconductor devices using MEMS.-based technology, and laser-based optoelectronic equipment may provide revolutionary new possibilities for vibration fault diagnosis of vehicles, gearboxes, and internal combustion engines. The new devices can be used at final test stations of the manufacturing lines and during service, too. We set up some measurement configurations, and made some experiments with a MEMS-based device and optoelectronic equipment. The test results confirmed the expectations and gave information usable practically in later tasks connected to industrial demands. The MEMS vibration sensing devices provide the new possibility to real-time on-board predictive fault diagnosis of heavy vehicles now, and later they can be used for cars, etc., too. The optoelectronic equipment is practical e.g. for service stations, too, where they can be used for very precise, fast and mechanically contactless condition-based predictive maintenance, or fault diagnosis, too, independently from the temperature of the observed part.

1. INTRODUCTION

Vibration sensors are commonly used in the industry and in research labs, e.g. for fault diagnosis, or predictive fault diagnosis *(NI, 2013)*.Vibration sensors are accelerometers to measure dynamic acceleration (but not for static or slowly changing inclination) of a physical device. The most common types measure only along a single axis. The more expensive triaxial accelerometers provide signals by the three axes of the Cartesian coordinate system. There are several physical effects that may be used in a sensor to determine acceleration. The most common is Newton's law. If a mass m is undergoing an acceleration a, then there will be a force acting on the mass. The law can be given by the form $F=m*a$.

Using Newton's law the force must be measured, and by this way acceleration can be determined.

The other basic method based on Hooke's law added to the Newton's law. The system consists of a mass and spring system. If a force F is acting on a spring of spring constant k it will be stretched or extended by Δx distance given by the formula $F=k*\Delta x$. The distance shift can be measured by many ways including inductive, magnetic, capacitive, optical, etc. solutions.

In the first section of this paper the traditionally used vibration sensors will be shown as a reference, and in the main part of the study some new possibilities will be introduced because they can be used later in the vehicle manufacturing industry and some can work on the board of vehicles providing new advantages. Some practical measurement results obtained with representative new devices will be presented, too.

1.1 Piezoelectric vibration sensors (Honeywell, 2010)

Recently the piezoelectric vibration sensors are widely used as a proven and versatile tool for the measurement of various processes and among harsh environmental conditions, too. The principle of operation is the piezoelectric effect of some crystal materials or ceramics, e.g. quartz, - it was discovered by Pierre Curie. If a force is applied on a piezoelectric material a high impedance charge is created on its opposite surfaces which results in a voltage across the device. The voltage is linear as a function of force which can be the result of acceleration of a mass fixed to the piezoelectric bulk. Piezoelectric vibration sensors are manufactured in many forms, with many measuring ranges, by many respectable firms. The subject has a huge literature, - a short overview is summarizing the basic information in the followings.

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The basic inside structure of a single axis (z) vibration sensor is shown in Figure 1.

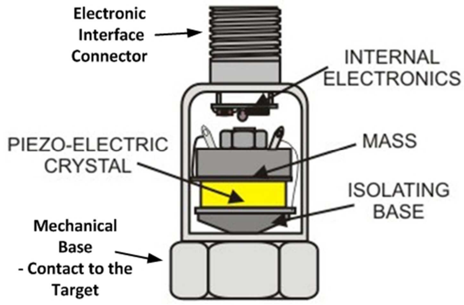


Figure 1. The inside structure of a single axis piezoelectric vibration sensor

Usually the unit includes the signal conditioning electronics, which is compatible with the commonly used IEPE standard, a type of analog signal + power interfaces. However, in some cases, there is no semiconductor circuit in the sensor body, as the metal house and the crystal sensor themselves can work at rather high temperatures, too. In this case, the signal interfaces is near but outside of the sensor.

For example, a commonly used and popular sensor is shown in Figure 2.

Figure 2. Simple axe vibration sensor type AC102 of the firm CTC (USA).

As a reference, the basic parameters of this popular device are the next:

Sensitivity : 100mV/g

Frequency range (±3dB): 0,5 ÷ 15000 Hz

The device is powered by current excitation 2…10mA, at a voltage source 18…30VDC.

A commonly used triaxial vibration sensor is shown in Figure 3. This is the type 993B we commonly use in our observations formerly and now.

The manufacturer is Wilcoxon Research Co. (USA), the basic parameters:

Sensitivity : 25mV/g, each axes

Frequency range (±3dB):

.. Z axe: 2 ÷ 10000 Hz

.. X, Y axes: 2 ÷ 7000 Hz 0,5 ÷ 15000 Hz

The device is powered by current excitation 2…10mA, at a voltage source 18…30VDC, nominally by 4mA by IEPE interface.

This is the basic sensor of many DLI instruments, which are commonly used in Hungary, too, and in many other systems.

Figure 3. A triaxial vibration sensor commonly used in condition observing systems – manufactured by Wilcoxson (USA).

The piezoelectric vibration sensors have many advantageous and some disadvantageous properties.

The sensor is a robust device. The sensor element itself can be used up to 500°C. The experts and the industry have a great experience with them. Many measuring systems and many accessories are available for the different types. There are handheld equipment and big computer based systems for each task which can occur in practice in industry or in research labs.

However during usage of piezoelectric vibration sensors some problems can be observed.

There are lightweight types, too, however common single axe type has a mass of about 100g, and triaxial types may have some 100 g mass. It can modify the behavior of the unit under test (UUT). The devices must be in good mechanical contact with UUT. In many cases it is not easy to fix the sensor to the UUT. The electrical signal cable must be moved during changing measuring position and the cable is vulnerable.

The measuring range – frequency bandwidth and acceleration range – is limited, - and sometimes not sufficient.

The price of the device is high, and as a result it is not affordable to use them in many cases when continuous vibration observation would be advantageous, It is true in the industry and e.g. for common on-board vehicle usage, too.

The price of the signal conditioning, data processing and information evaluating system connected to the sensor is high, too.

The piezoelectric vibration sensors have a standard position among the vibration measurement solutions. However the new developments in the field of MEMS/semiconductor sensors and optoelectronic equipment give new vibration sensor solutions for some special and/or new application areas.

2. MEMS BASED DEVICES AND THE ADIS 16227 SENSOR OF ANALOG DEVICES

2.1. MEMS based vibration sensors (Harsanyi, 2013)

Among the first MEMS devices we can find vibration sensors. However the first types were not suitable for machine condition analysis because of their low bandwidth, so they were suitable for tilt sensing, shock sensing, and low frequency vibration measurements up to some hundred Hertz. The basic possibilities to build a vibration sensing element with MEMS technology are capacitive, piezoresistive, piezoelectric, and thermodynamic/moving hot gas bulb detectors. *(Kon, 2007)* First, the firm Analog Devices was able to manufacture a capacitive sensor which has a bandwidth comparable to the conventional piezoelectric sensors, which were suitable for vibration fault analysis, se this too.

Now, there are some new types made by other firms like Bruel Kjaer, or Measurement Specialties Inc.

2.2 Introduction of vibration sensor type ADIS 16227 (ADI, 2013; Scannel,B., 2011)

Analog Devices (ADI) is an industry leader in the field of semiconductor analog and mixed signal integrated circuits, embedded and digital signal processors, and sensors, including MEMS devices. The firm integrated its knowledge into some new products like the type ADIS 16277, which is a triaxial, wide bandwidth vibration sensing system.

The basic physical diagram of capacitive sensing element used for each axes is shown in Figure 4.

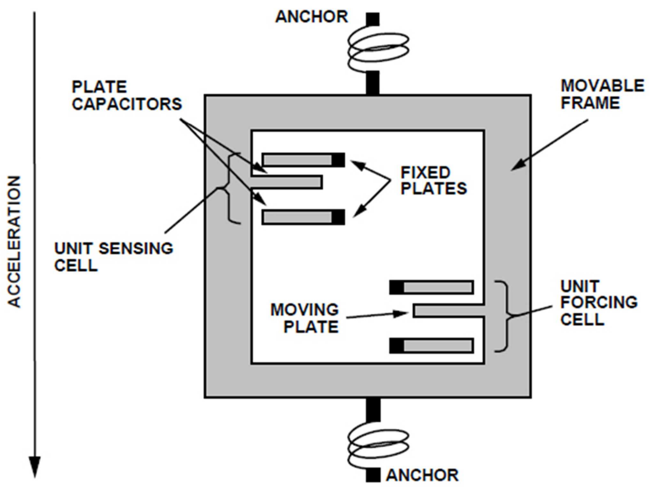


Figure 4. MEMS sensor element diagram

It uses a fixed frame and a moving frame to form a differential capacitance network that responds to linear acceleration. Tiny springs tether the moving frame to the fixed frame and govern the relationship between acceleration and physical displacement. A modulation signal on the moving plate feeds through each capacitive path into the fixed frame plates and into a demodulation circuit, which produces the electrical signal that is proportional to the acceleration acting on the device.

The unit forcing cell is for the self-test function and does apply an electrostatic force (Coulomb force) to the sensor, in order to test it for gross failures. This produce uses SOIMEMs technology.

The simplified signal processing architecture of the unit is shown in Figure 5.

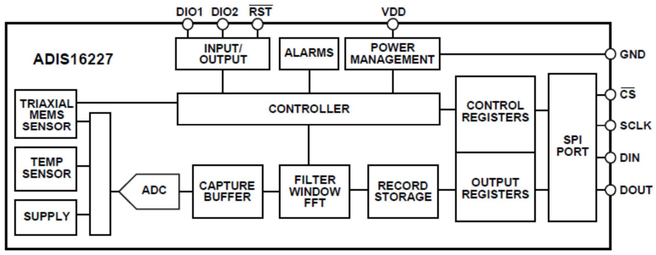


Figure 5. The simplified signal processing architecture of ADIS 16227

Very briefly, the unit is a member of the AD’s iSensor (intelligent sensor) family, a tri-axial, digital vibration monitor which combines the iMEMS® sensor technology with ADI's data conversion and sensor signal processing technologies. The system consists of the vibration and temperature sensors, data acquisition system, and data processing system, which based on a 16 bit digital signal processor. It includes convenient data capture capability and an SPI (serial peripheral interface), which is a simple, reliable and fast serial interface. The SPI and data buffer structure provide easy access to sensor data. The ADIS16227 samples, processes and stores ***x***, ***y*** and ***z*** directions acceleration data with FFT (fast Fourier transform) processing including time stamp. The programmable digital filter offers low-pass configuration options, and an internal clock drives the data sampling system during a data capture event. The data capture function has three different modes (externally triggered, or internally programmed modes), that will accommodate the needs of many different applications. The device also offers an integrated digital temperature sensor and digital power-supply measurements, as well as a digital self-test feature that enables reliable embedded operation within the targeted applications. The extended operating temperature range for the device is −40°C to +125°C.

The mechanical design of the device is shown in Figure 6.

Figure 6. The mechanical form of ADIS16227 vibration sensor system.

The introduction of fully integrated and reliable vibration sensors, with the ability for autonomous and configurable operation, provide predictive maintenance program developers the ability to significantly improve the quality and integrity of the data collection process, without the limitations and compromises posed by past vibration analysis approaches. With the high level of integration and a simplified programmable interface, these new sensors enable easier adoption of vibration sensing, previously limited to a handful of highly skilled technologists with decades of analytical experience in machine vibration. The device can be built in embedded supervisor equipment which can substitute even extended PC based vibration analyzing systems with expensive additional hardware and software tools.

The device has some very remarkable technical features and parameters. It can collect and provide vibration data in time domain, or can give data in frequency domain. The full measurement range is ±70g max., the smallest selectable range is ±1g. The maximum sample rate is 100,2kHz. The measurement can be triggered by external SW command, external HW signal, or by the own timer of the system. Before calculating FFT there are three windowing options: Hanning, flat top, and rectangular. There is a possibility to store some spectrums, as “good” reference data, and the actual measurement results can be compared with them. Compared the actual and reference data we can get warning or alarm notice using windowed limit method in six programmable spectral bands. The manufacturer provides application kits to support the work with the unit including PC software with USB interface, and some other solutions, too.

3. VIBRATION MEASUREMENTS USING OPTOELECTRICAL EQUIPMENTS

3.1 Vibration measurement and optical possibilities

Formerly there dedicated sensor types were used to measure distance, speed, and acceleration, based on different physical principles. Naturally, each quantity can be calculated from any other one by derivation or integration operation(s) in theory. However the early analog or digital signal processing techniques were not adequately precise, fast, and practical to solve the task. Now the presently available digital signal processing HW and SW solutions give the possibility to perform the operations - data acquisition, processing and storage – satisfactorily. The new methods can work in real time and give precise results in the case of common vibration measurement tasks.

The optical measuring methods can determine distance basically, or velocity of the target using Doppler effect. They have some very beneficial properties, e.g. they can work without mechanical contact with the unit under test and the temperature of the unit can be very high. If the sensor uses blue light the target cen be even at red-hot temperature.

The optical measurements need no mass loading on the measured objects. As a result lightweight, small, delicate structures, and soft or flexible materials can be observed.

The optoelectronic measuring devices have a long developments history. The optoelectronic microphones can be very sensitive and/or small. The optoelectronic distance meters can be very precise but usually they operate slow. Presently there are new equipment on the market which are very precise and fast, too, and as a result they can be used for vibration analysis in common practice, too.

3.2 Introduction of Bruel Kjaer Vibrometer Type 8329 (Bruel Kjaer, 2003)

The firm Bruel Kjaer is a worldwide market leader in the field of sound, noise and vibration measurements, including sensors, microphones, measuring equipment and related information processing and evaluation. The firm recognized the possibilities of the optoelectronic solutions and developed a very sophisticated measuring system named Laser Doppler Vibrometer, which is shown during operation in the Figure 7.

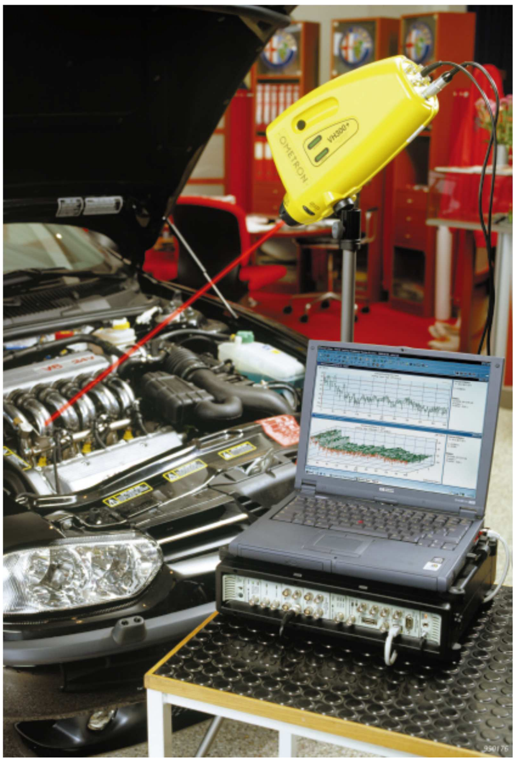


Figure 7. The Laser Doppler Vibrometer in usage

The optical unit of the system is an industrially engineered interferometer manufactured by the firm Ometron (UK). It is basically a Michelson interferometer in which a laser beam is divided into a reference beam and a signal beam. The signal beam is directed onto a vibrating test structure, and the back-reflected light is recombined with the internal reference beam. When the test structure moves, the frequency of the signal beam is shifted, resulting in intensity modulation of the recombined beam due to interference between the reference and signal beams.

One complete cycle of the intensity modulation corresponds to a surface movement of l/2 = 0.316 mm, half the wavelength of the helium neon laser source (where l is the wavelength of the source, 0.633 mm). The whole system is very complex, precise, reliable, - and expensive.

The principle of operation basically determines the capabilities of the system, which are considerable. The measurement velocity range is up to 425 mm/s, the frequency range is about from 0,1 Hz to 25 kHz. The distance of the target must be between 0,4 m and 25 m.

The laser optical unit is integrated into the BK vibration analyzing system "PULSE". The equipment is useable in both laboratory and industrial environments. One application area is modal analysis. At University of Miskolc it is used for observation of vibration of different industrial machines and household machines, too.

Keeping the laser interferometer based vibration measuring architecture other firms developed new equipment which can measure vibration of 3D surfaces, too. (*Polytec, 2010*)

3.3 Introduction of KEYENCE type series LK-G5000 Laser Displacement Sensor (KEYENCE a, b, 2013)

The firm KEYENCE is a worldwide market leader in the field of optical measurements including 1D displacement sensors , 2D/ 3D surface scanners, super high resolution digital cameras with ultra-high depth-of- field observation possibility. The firm offer top quality image processing solutions. They deal with some other sensor and security devices, too.

Recently KEYENCE introduced the LK-G5000 series ultra-high speed and high accuracy laser displacement sensor family. Very briefly, the highest capacity member of the family has 0.005 µm repeatability parameter, 0.02% accuracy in the measuring range, and max. 392 kHz measuring frequency. The whole measuring system consist of the displacement sensor, a fast digital controller for data acquisition, signal processing and data storage, together with several interfaces and additional functions, and e.g. a PC acting as human machine interface to set measurement parameters, and evaluate measurement information in details if necessary.

The operation of the system and its building parts based on well-known principles in most cases however almost every detail of the equipment is redesigned an improved by some way.
Basically, the principle of distance measurement is simple. There is a light source in the measuring head. The light is reflected from the target in different angle directions depending from the position – the distance from the head – and will arrive through a lens system to different points of the light position detection elements. This is a practical realization of the well-known triangulation method, shown in Figure 8. Depending on the sensor head design and/or setup, the measurement can be implemented in the case of diffuse reflective surfaces or specular reflective surfaces because of the very attractive and new lens system designs.

The quality of reflected light differs depending on material and surface conditions of the target object, and a regular reflection is dominant for a specular body while a diffuse reflection is dominant for objects with a normal surface.

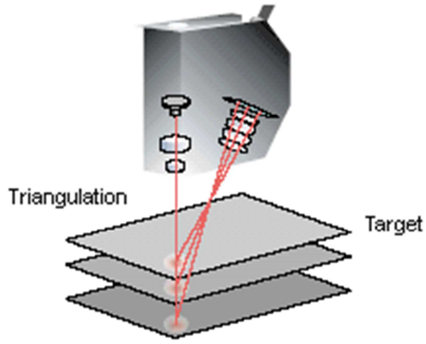


Figure 8. 1D distance sensor using triangulation method

The inside structure of the sensor head is shown in Figure 9.

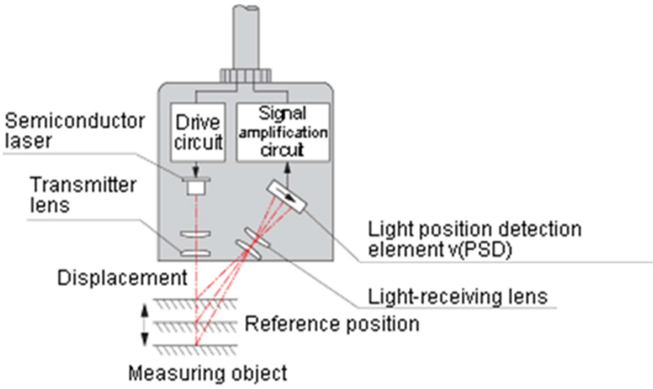


Figure 9. The sensor head configuration inside

The light source is a semiconductor red laser diode. The laser light intensity is adjusted to achieve the best measurement accuracy by sensing the reflected light intensity from the target. This is a complex solution, the so-called ABLE (Active Balanced Laser control Engine) intelligently controls the three elements of laser power, emission time, and the light sensor CCD gain.

In the case of the highest precision type LK-H008 the radiated beam diameter is 20 µm. However the reflected beam arriving to the light sensor is ellipse shaped with 20 µm and 550 µm diameters by the advanced lens system. This is one secret of the excellent accuracy of the measurement.

Another newly developed device is the CCD light sensor which contents oblong shaped pixels which fit to the ellipse shaped beam. The CCD is very high speed, high resolution, and its characteristic is very linear. The device's photo is shown in Figure 10.

The device is manufactured by the so-called RS-CMOS technology but electrically it is a CCD based circuit.

Figure 10. The Li-CCD light sensor of KEYENCE

A member of the 1D distance sensor family is shown in Figure 11.

Figure 11. LK-G5000 series displacement sensor – with the way of light shown

The displacement sensor system includes a special controller, too.

The compact measurement controller can work with two measuring heads together. It is really a task oriented computer with PLC like properties, too. The controller has USB2 and Ethernet interface to communicate with a PC, EIA-232 interface for industrial networks, and analog signal output e.g. for recorders and oscilloscopes. It can store 1.200.000 data, distance, velocity or acceleration. The unit is capable calculate velocity and acceleration real-time, and can execute other tasks like filtering, etc. The measured or calculated data is readable in two numeric displays. With a simple keyboard it is programmable directly, too, but this is not a convenient method.

Keyence is providing a Windows based PC software named LK Navigator 2 acting as human machine interface. With the software the working modes and parameters can be set, then the measurements can be controlled, and the results can be observed, storaged, and sent to other equipment.

Figure 12. The compact measurement controller of KEYENCE

4. VIBRATION MEASUREMENTS RESULTS OF AN ENGINE WORKING ON TEST RIG

There are measurement samples available in the related documentation of the new sensor types ADIS16227 and the KEYENCE products. We made some experiments formerly with electrical motors, loudspeakers, etc. using these devices among laboratory conditions. However the basic research goal is to study and prove the usability of the devices in the case of internal combustion engines, and other power train items. These sensors were not developed for the automotive applications directly and there is little information available in the subject. However formerly our research group took part in vibration and noise based quality control and fault diagnosis projects in the frame of cooperation with GM Opel (internal combustion engines cold and warm measurements) and Allison (final quality control of ready-assembled heavy duty vehicle gearboxes) *(Banlaki, 2011).*

We had a possibility to measure an engine type GM-A14NET on a test rig in the measuring lab of are Department of Automobiles and Vehicle Manufacturing (Faculty of Transportation Engineering and Vehicle Engineering, TU Budapest).

The test rig with the engine is shown in Figure 13.

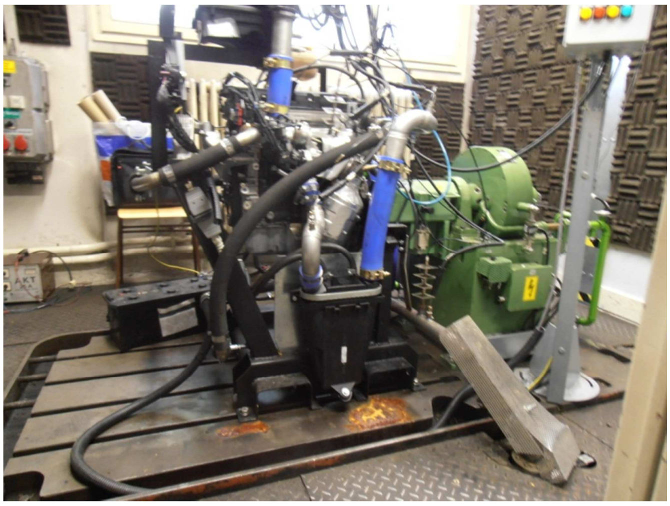


Figure13. The test rig with the GM engine under test

Our purpose was to use the ADI and the KEYENCE sensors at the same time. As a test point we chose a hole with steel spacer at the bottom of the engine in the sump. The MEMS sensor was fixed by a steel substrate and magnet. The optoelectronic sensor has bigger dimensions and must be fixed independently to a vibrationless basement. The steel base of the rig with a magnetic stand was used for this purpose. The experimental assembly is shown in Figure 14.

We measured the engine several speeds of 750, 100, 200, 300, 400 and 5000 RPM.

As reference measurements, we used SKF measurement equipment with its own sensor with magnetic fixing method.

The MEMS sensor system includes a temperature measuring unit, too. During our tests the temperature of the measuring point stayed below 100°C.

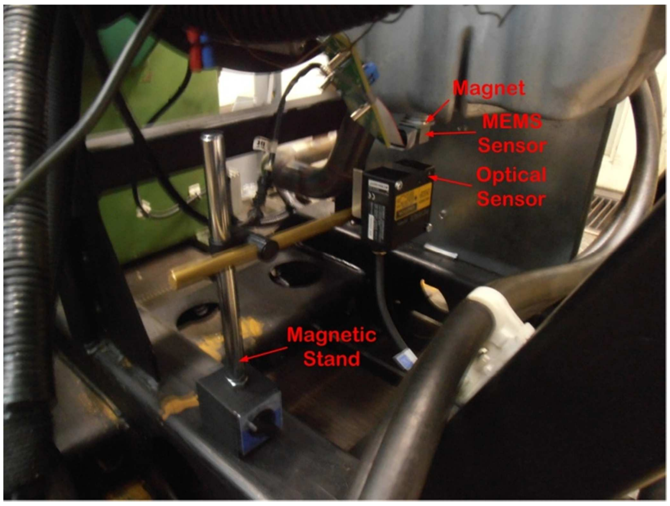


Figure 14. The experimental sensor assembly

4.1 Results of the measurements made by the ADI type ADIS16227 MEMS vibration sensing system

To get experience in practice the ADISUSBZ evaluation system was used which is a good solution to use ADI MEMS products. However as the members of the sensor and evaluation system were not designed directly for automotive applications some additional mechanical, electronics, and SW supplement were necessary to execute our task.

At idle speed the engine was running very quiet.

The spectra – drawn by Excel from csv format file of ADISUSB is shown as a whole result, and magnified details, are shown in Figure 14a and 14b.

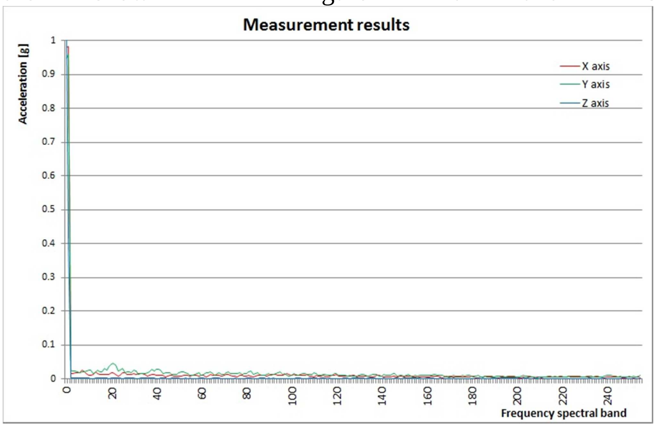


Figure 14a. Full vibration spectra measured at 750 RPM. A frequency band is 195 Hz wide.

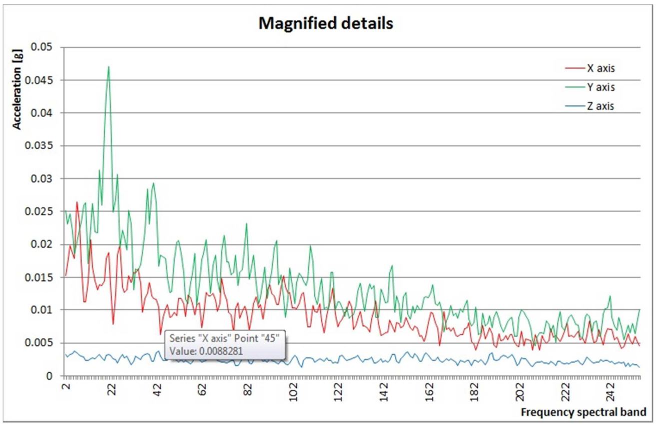


Figure 14b. Vertically magnified vibration spectra of the former diagram without the base order band - at 750 RPM. A frequency band is 195 Hz wide.

The vibration spectra is more complex and takes more information at higher engine speed. It is demonstrated in the next figures as some examples of the measurement results.

In Figure 15. the vibration spectra of the engine running at 4000 RPM is shown.

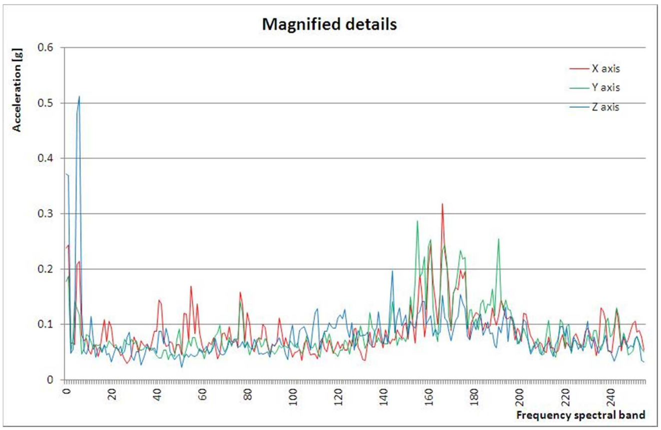


Figure 15. Vibration spectra of the engine running at 4000 RPM. The figure is vertically magnified, and a frequency band is 24,5 Hz wide horizontally.

In Figure 16. the vibration spectra of the engine running at 5000 RPM is shown.

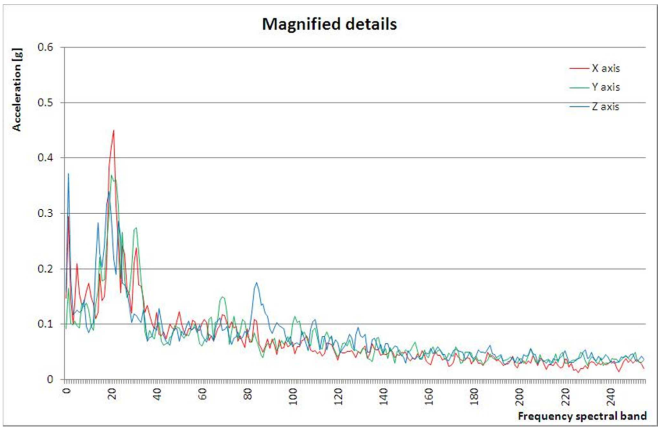


Figure 16. Vibration spectra of the engine running at 5000 RPM. The figure is vertically magnified, and a frequency band is 195 Hz horizontally (with the lowest band by frequency ignored).

A copy of the ADI Evaluation measuring window is shown in Appendix A.

The results taken with the ADI MEMS sensor system are considerably straightforward. However, many more measurements and a long-time experience is desirable before its real use in the industry/on manufacturing lines or on the board of powertrain items.

4.2 Results of the measurements made by the KEYENCE LK-H022 laser displacement sensor

We got a laser displacement sensor type LK-H022 to execute our experiments by courtesy of Keyence Hungary Ltd. The basic parameters of the device are the followings:

Nominal measuring distance : 20 mm

Measuring range: ± 3 mm

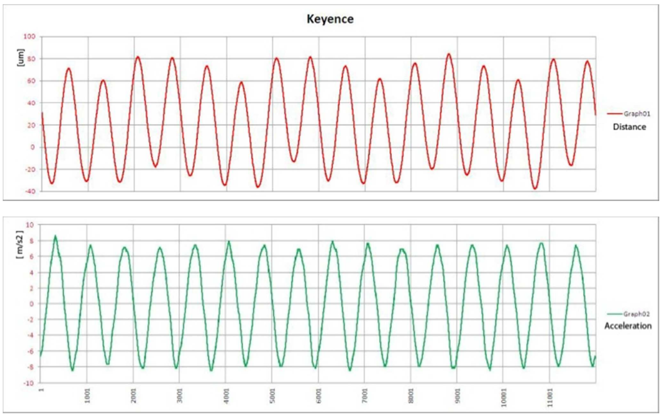
Repeatability: 20 nm

Beam spot diameter: 25 μm

Mode: diffuse reflection measurement

Max. sampling frequency: 392 kHz

From the measurement results a detail is shown in Figure k. The engine speed was 2000 RPM, the sampling frequency was set to 100 kHz. It is practical as sample distances on the time axe will be 10μs. The measured data was stored by the Navigator SW in csv file format. The information was processed and presented by an Excel program.



Figure

The upper red diagram is the distance between the engine and the sensor, the lower diagram is the acceleration of the engine. It is easy to observe that we can follow the work of each piston, as the time difference between two peaks is 750 samples, which corresponding to 7,5 ms.

A copy of the Navigator measuring window is shown in Appendix B.

5. CONCLUSIONS

There are new vibration sensor types on the market. However the new devices are not introduced for quality control or fault diagnostics of vehicles power train – neither during manufacturing nor for on-board vibration sensing. Their operating principles are different from the old piezoelectric devices and open possibilities for new application areas and/or have beneficial properties for conventional measuring practice. In some cases they can substitute the presently used devices. MEMS based devices are cheap and even the digital information processing system may be integrated into the unit. The solution open the way of condition-based maintenance on the board of heavy vehicles now and later in middle class cars, too. The other new line, the fast laser-based electro-optical equipment make possible e.g. fast measurements, (observing hot parts, too), without the need of mechanical assembly at test stations of manufacturing lines or service workshops. Our test measurement results show the way to new developments for the vehicle industry, maintenance, and vehicle on-board applications.

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NI Corrporation, USA - National Instruments Hungary Kft.
OPEL Szengotthárd Kft., Hungary

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REFERENCES

ADI: ADIS16227 Data Sheet, rev. 2013, ww.analog.com/static/ imported-files/data_sheets/ADIS16227.pdf

Banlaki P., Domotor F., Stipkovits A., Devecseri Sz. (2011): Noise and vibration measurement of a gearbox during the acceptance test in the manufacturer's workshop, *Perner's Contacts*, Volume VI, ISSN 1801-674K, PERNER, Pardubice

Bruel Kjaer: OMETRON Laser Doppler Vibrometer — Type 8329, 2003, *Bruel Kjaer*, www.bksv.com/library/10929184118329.pdf

Harsanyi G. et al.: MEMSEDU, 2013, Budapest, *E-learning material*, www.ett.bme.hu/memsedu

Honeywell: How does a piezoelectric accelerometer work? 2010, *Honeywell*, content.honeywell.com/sensing/sensotec/ accelerometer_faq.asp

NI: The Engineers Toolbox for Measuring Vibration, 2013, NI, www.ni.com/white-paper/14339/en

Keyence (a): Measurement Guide for Vibration Eccentricity Measurement, 2013, *Keyence*, www.keyence.com/rss/vision/lkg/vib.php

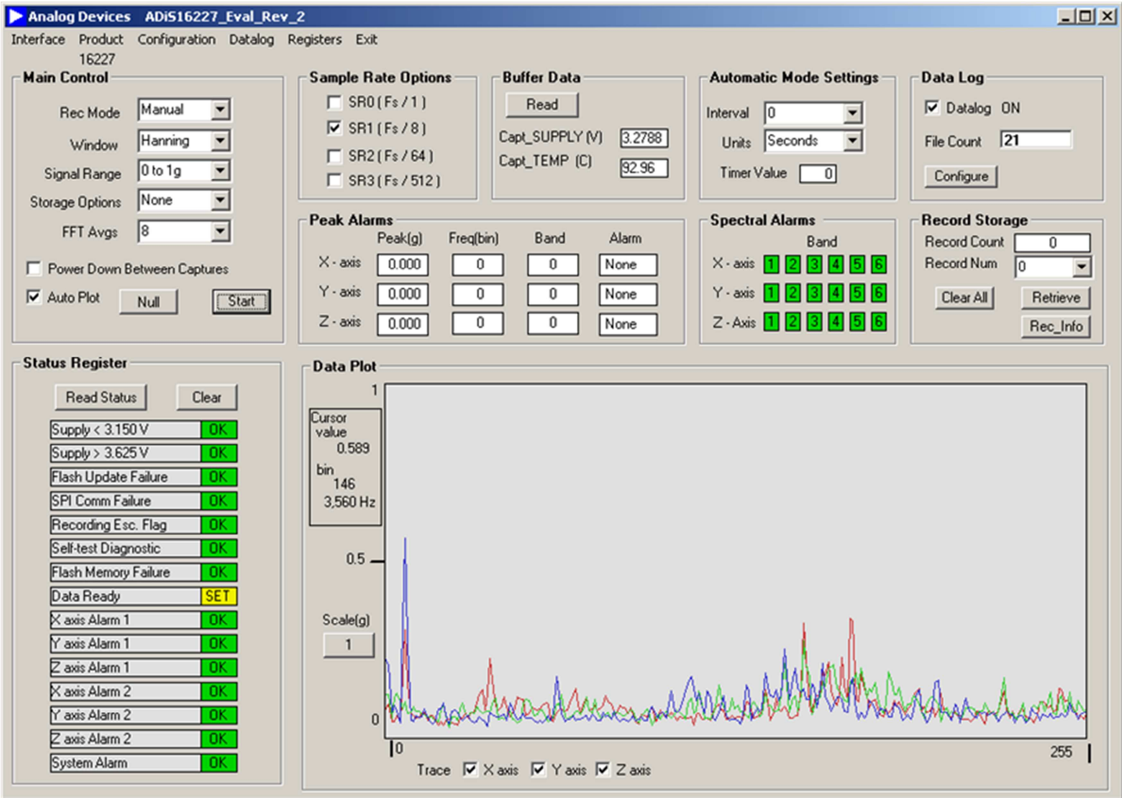
Keyence (b): Ultra High-Speed/High-AccuracyLaser Displacement Sensor, 2013, *Keyence*, www.keyence.eu/dwn/lkg5000_kb.pdf

Kon, S., Oldham, K., Horowitz, R.: Piezoresistive and Piezoelectric MEMS Strain Sensors for Vibration Detection, 2007, *Proc. of SPIE*, Vol. 6529, Berkely

Polytec: HSV-2000 High Speed Vibrometer, 2010, *Polytec Gmbh.*, www.polytec.com/en/products/vibration-sensors/single-point-vibrometers/

Scannell, B.: The Pursuit of Accurate, Reliable Vibration Sensing for Condition-Based Predictive Maintenance, 2011, *ADI* Technical Article M-2115, www.analog.com/static/imported-files/.../MS-2115.pdf

Appendix A: ADI Evaluation SW Window – a screenshot for demonstration



Appendix B: KEYENCE SW - Storage Window – a screenshot for demonstration