Kandó Kálmán - Doctoral School

Improvement of the final noise and vibration diagnostic checking system of vehicle powertrain manufacturing systems

Theses of the dissertation

Written by:

Dr. Bánlaki Pál

M. Sc. - Electrical Engineer

Consultant:

Dr. Takács János C. Sc.

Professor

Budapest University of Technology and Economics

Faculty of Transport Engineering and Vehicle Engineering
Department of Vehicles and Vehicle Manufacturing

Budapest
2014

Introduction

In the case of testing components carrying out rotational or reciprocal movement, or being in resonance, vibration diagnostics can be an effective tool. It can successfully be applied in the case of cold tests of engines of internal combustion. Carrying out vibration and noise tests during the warm test of operating engines can be an advantageous solution from several points of view. However, in the case of operating engines the tests are much more difficult to carry out. This is the reason, why it is not applied so often and why it is applied only as a supplementary method. Technical conditions of the traditionally arranged test rigs acted as barriers to the noise and vibration diagnostics of other parts of the drive as well.

It was difficult to insert the noise and vibration diagnostic test equipment into the production line test stations. Some of the reasons: despite of the high technical level of the vibration and noise measuring equipment, they were not elastic enough. On the other hand, these tasks demand some special requirements in the case of vehicle manufacturing which are not common in engineering industry. However, some new electronic and computer techniques, signal and data processing techniques have been developed recently, and they create a possibility to improve the level and the information providing capability of vibration and noise diagnostic tests considerably. The practical use of the method is much more advantageous, and, consequently, more widely used, than before. The manufacturing companies have realized this problem, and launched research projects to solve the actual problem in order to introduce practical applications later on.

The automotive industry is one of the fastest developing industry, and its target is the zero defect level of the products from the quality assurance point of view. That is the reason, why the research and development of the quality assurance methods is so much important.

My job is connected to this research task, and first of all in three topics.

I have been involved in the development of an elastic measurement system designed to test engine of internal combustion, and in elaboration of data evaluation methods, and in testing them under industrial circumstances.

My second topic was the research of the modern noise and vibration test methods of automatic gear boxes. During these tests I only used traditional sensors.

My third research field was the introduction of new microelectronic and optoelectronic sensors, and the conditions of applying wireless data transfer methods in industrial environment.

Survey of the literature

The literature connected to the noise and vibration analysis in automotive industry is huge. In Hungarian there are mostly papers dealing with machine industry. However, among the reports and articles there are numerous of them dealing with automotive industry and of high quality.

In my list of applied literature there are 55 books, 76 articles, 12 standards and 46 application notes and catalogues. This kind of literature typically describes the theoretical results and the practical results of their job.

In another group there are the publications of companies developing tools and methods of tests. The number of publications of automotive manufacturers is not much – e.g. [TOY11].

The topics are concentrated on three areas: failure diagnostics, environment protection, and research connected to the design and construction of various parts. I have concentrated on my own research topics that I mentioned the previous section. However, there is useful knowledge in the literature of other fields as well. For example, the methods of data processing and evaluation are mostly similar to each other, or they are the same in some cases.

I am trying to give summary of my research work in the literature. Substantially I could not find any source dealing with the vibration and noise diagnostics of the manufacturing line, which could be used as starting point, or reference for my own research work.

However, the number of publications, dealing with particular details of both theory and practice, is huge. I have selected the useful information necessary for my job out of these ones.

Unfortunately, for many problems I could not find an answer, and so the topics far away from this field (e.g. data processing and evaluation) had to be collected and processed as well.

Finally, the still open remaining questions had to be answered by my own theoretical and empirical work. These answers were published by me.

Methods and tools used for the research work

Hardware used for the research:

- vibration sensors:

  - AC102 uniaxial vibration sensor – manufactured by CTC, [CTC102]
  - 993B triaxial vibration sensor – manufactured by Wilcoxon, [WIL08]

- microphones:

  - Bruel Kjaer 4189 type Free-Field measurement microphone [BK4189]
  - Bruel Kjaer 4958 type Array measurement microphone [BK4958]

- incremental angle sensor:

  - ROD 426 type optoelectronic incremental angle encoder, manufactured by Heidenhain [HEI10]

- measurement data acquisition system:

  - NI cDAQ- 9172 measurement data acquisition system with USB interface, manufactured by NI [NID9172]
  - NI-9233 4 channel vibration and noise diagnostic analogue input module with 24 bit resolution, manufactured by NI [NID9233]
  - NI-9401 8 channel digital, dual way, fast I/O module, manufactured by NI [NID9401]
  - WLS 9163 WLAN interface, manufactured by NI [NID9163]

Software development environment used for the research:

- LabVIEW software development and application program package, version LV 8.5 … LV 2013, manufactured by NI [NIL13]

Data processing techniques and algorithms used during the research work:

- FFT procedure [BUR08] [NOK07],
- order analysis based on the data re-sampling method (NI patent), which was used during the noise and vibration analysis of internal combustion engines firstly by me in Hungary
- joined time-frequency and time-order based data processing technique (JFTA, etc.), procedures connected to the Gabor transformation, which was used during the noise and vibration analysis of internal combustion engines firstly by me

Test stations used at the drive element measurements:

- Dyno workshop test station (GM Opel Factory), Z18XER and Z16XER engines for the noise and vibration tests
- ENERGOTEST test rig (BME KJK GJT engine workshop), for the test of GM type A14NET engine, and to test the MEMS vibration sensor and optoelectronic distance and velocity sensors
- Allison final test station (GM Allison Factory) at the manufacturing line for high power automatic gearboxes for heavy vehicles. The system has been extended by the new wireless vibration and noise measurement system which was developed in the course of my research work.

Overview of the research work

The results of the research project can be summarized as follows:

- I have created a new, and elastically extendable noise and vibration test system, consisting of high-tech units, which can either be inserted into the final checking system of the production line, or can operate stand-alone.

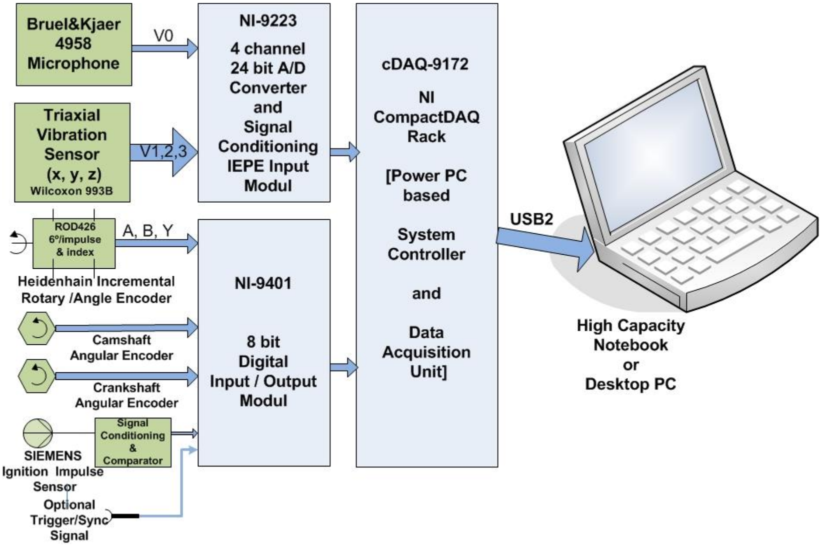

Fig. 1.
The new flexible measuring system developed for the noise and vibration measurements [S4]

The basic configuration of the system is capable to measure the signals from four analog sensors - like e.g. a triaxial acceleration sensor and a noise sensor - with high resolution (24bit) and wide frequency bandwidth, and an 8bit digital I/O interface e. g. for timing, time measuring, and trigger function. The unit is a general purpose unit which can be used a wide range of research tasks. The unit is configurable flexibly and can be enhanced to accept signals from up to e.g. 24 analog and 16 bit digital signal sources. It is very important that all signal samplings occur at the same time exactly.

- I have carried out a series of workshop tests with the new measuring system on good engines and on engines having different known faults. During the tests noise measurements and vibration measurements in three directions have been carried out, together with angular displacement and reference position, plus ignition-timing measurements.

- Direct and processed measurement data were shown on diagrams, - namely the high resolution angular and ignition time signals, the noise and vibration time signals, and the related noise and vibration spectra.

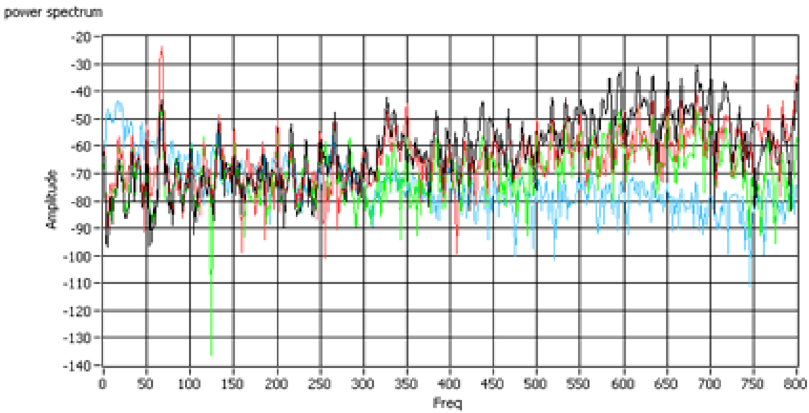

Fig. 2.
Noise and vibration power spectrum of a good internal combustion engine [S4]

In the figure the vertical (red), horizontal (black), main shaft direction (green) and noise (blue) spectra can be seen at 2000 RPM- in the case of a good internal combustion engine.

I have introduced the order analysis in the field of the vehicle diagnostics, based on the re-sampling [NIT372416A], and showed the order spectra:

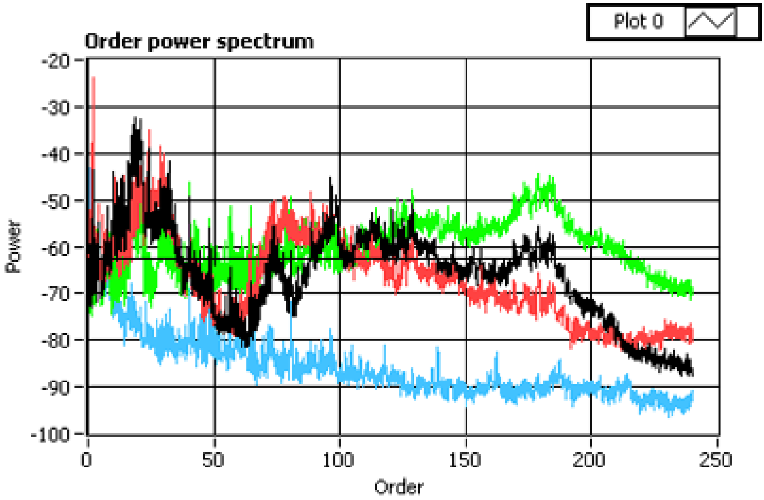

Fig. 3.
Noise and vibration order power spectra of a good internal combustion engine [S4]

In the figure the vertical (red), horizontal (black), main shaft direction (green) and noise (blue) spectra can be seen at 2000 RPM in the case of a good internal combustion engine The vertical axis of power spectra is logarithmic scaled, the horizontal axis is scaled by order frequency.

The resampling-based order spectra is calculated by Fourier transformation of signal data sampled by equidistant angular intervals instead of by time intervals. Consequently order spectra give useful information about vibration and noise phenomena in the case of continuously changing rotational speed, too.

- In the course of my research work I have recognized the high level possibilities of JFTA methods [NI3548] in data evaluation, and introduced some procedures of the Gabor transformation [COH95] [NIE372265B]. Within the framework of this technique the most effective fault diagnostic procedures are the usage of magnitude and power spectograms, and the extraction of the most significant order-component time signals. With the help of the two dimensional analysis even the observation and research of some formerly not known processes, which take place in the engine, can be realized.

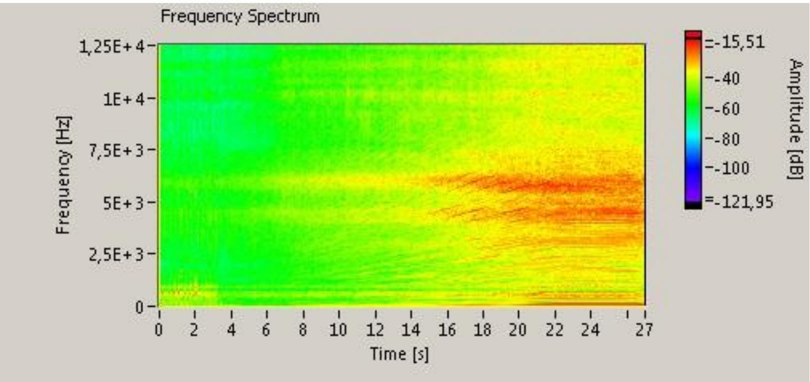

Fig. 4.
The time - frequency Gabor spectrogram of the vertical direction of a faulty engine, where one cylinder is not working [S11]

There are considerable vibrations observable at idel till 3s in time. Later the engine much higher vibration levels than a good one.

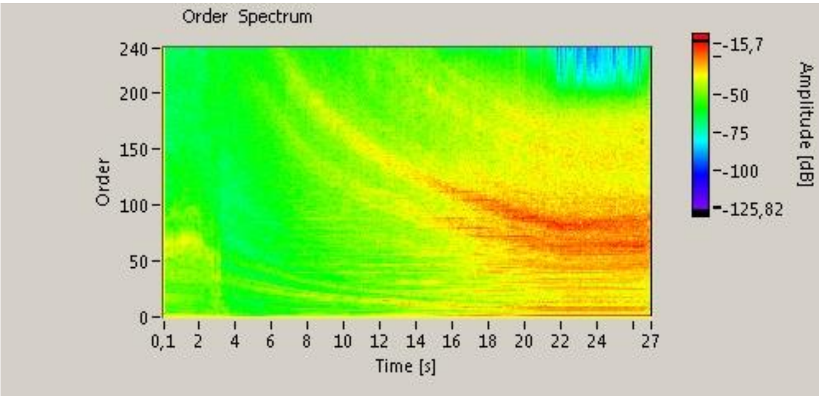

Fig. 5.
The time – order frequency Gabor spectrogram of the vertical direction of a faulty engine, where one cylinder is not working [S11]

The information in this figure is equivalent to the information in the figure above however the reference base is order frequency here and (time-based) frequency above. It depends of the physical phenomena observed which method is usable basically or more advantageous to study the behavior of the unit under test.

The above figures show and prove, that using JFTA methods even the so complicated noise and vibration problems, that occur in an operating engine, can be tested. Moreover, they provide a more reliable and extensive information, necessary for diagnostic evaluation, than the one dimensional frequency and re-sampling order analysis. Naturally, these methods require a higher level measuring equipment, and it costs more of course, too.

This method provides a proper solution to find the typical faults occurring in practice most frequently. The most simple method of diagnostics is the comparison of actual results with reference measurements, which is evaluated manually.

In practice the analysis and classification of stochastical data collected through the measurements by statistic and probability methods can bring good results. These methods can be used for properly separated bands or ranges extracted from the time- frequency or time – order frequency spectrograms.

The real solution can be the use of neural computers and artificial intelligence. There are practical solutions existing today. The continuation of my job can be the elaboration of such at method.

- For the re-sampling order analysis a sensor providing signal of angular displacement is also necessary. I showed with the help of a detailed analysis, that the internal sensor of angular displacement, fixed to the main shaft inside the engine is not suitable for this purpose, because of the non-equidistant signal samples. I have elaborated various solutions in order to solve this kind of problems [S09] [S10].

- The signal transfer of noise and vibration sensors using cables can face several problems at test stations in case of final check of manufacturing lines. As a result of my research work, I have solved the problem of full band, multichannel noise and vibration signal transfer by using wireless components of computer technology, available on the market. Additionally, after studiing the standards and set-up possibilities I have used very special software configuration for measurement data transfer which is different from the common solutions [DROT14] [S7].

- In the field of traditional vibration diagnostics piezoelectric sensors [HON10], or equipment based on interferometric distance measuring equipment [BK8329] are used to determine vibration acceleration by direct or indirect ways. For the noise analysis measuring microphones are applied.

  Typically, signals and data are processed and evaluated by complicated computer systems recently. During my research work I have searched solutions which are simpler, more modern and have better technical parameters at lower price level.

Studying the literature of new sensor developments I found very new microelectro-mechanical systems [SCA11] - and optoelectronic [KEY13] devices, which seem to be applicable to realize my goals. I have purchased samples of these sensors from the manufacturers.

I have carried out measurements on the engine test rig of the department in order to research the applicability of the sensors in the field of vibration diagnostics of automotive industry. The results met the expectations. On the basis of this the continuation of the research project and the wide use of these sensors can be expected.

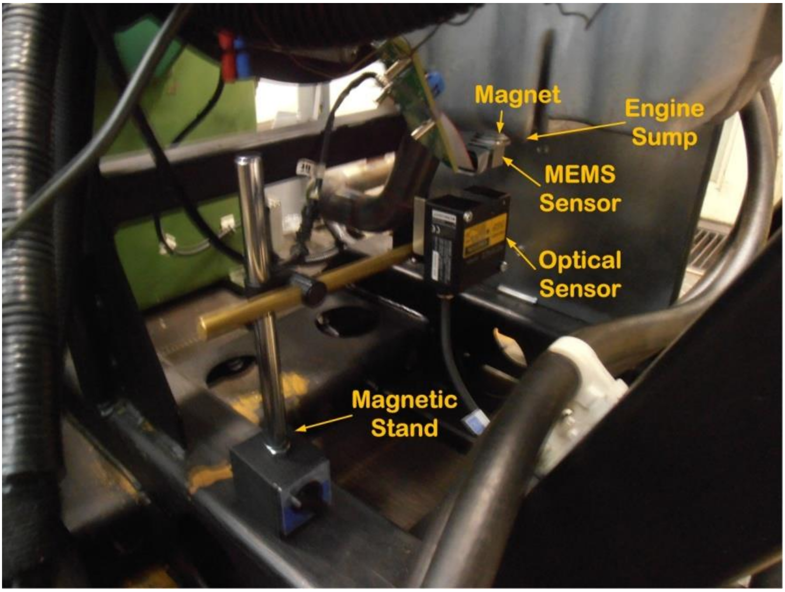

Fig. 6.
Installation of the MEMS intelligent vibrodiagnostic sensor fusion and the super-fast optoelectronic distance sensor working on the basis of triangular measurement during the test of operation on the test rig [S8].

The manufacturing technology of the new microelectro-mechanical systems (MEMS) is compatible with the analog, digital, and microcomputer semiconductor technologies. The unit - which l found and tested thoroughly - can carry out the data processing, FFT evaluation and decision making by reference info as well.

The optoelectronic sensor can measure the distance by 400 kHz sampling frequency and 6 nm resolutions. The new devices provide a new horizon to the application in vibration diagnostics.

Summary of new scientific results in theses

T-1 Thesis: I have elaborated a noise and vibration diagnostic method based on order analysis for the warm-test check of internal combustion engines using petrol [S1, S2, S3, S4, S5, S6].

I have converted sampled data taken at equal time differences into signals of angular installments. For this I have used the signals coming from the outside sensor of angular displacement joined to the crankshaft.

For the vibration measurements I have used triaxial piezoelectric sensors, and for the noise measurements I have used microphone prepared a measuring system. Also, I have developed a measuring and data processing system using LabVIEW software solutions.

During my experimental measurements of some good engines and some engines having known faults, I have proved that the order spectra are sensitive to the faults, and consequently can provide a better localization of faults related to the conventional methods.

T-2 Thesis: I have shown, that the signal of the internal angular signal source cannot be applied directly during the order analysis, because the reference of the angular position causes a considerably high basis noise apart from the useful signal to be measured [S9, S10].

I have tested the application of the internal sensor. In order to find equidistant angular position samples, I have also tested the problems and possible solutions. I compiled suggestions in order to solve the problems.

T-3 Thesis: The Gabor procedure has been inserted into the measurement data processing system. By the evaluation of the above method used on former measurements data sets has been proved the increase of the capabilities of the detecting failures [S11].

Researching the possibilities of order analysis I have found the discrete Gabor transformation and expansion as a related new method, which enables the evaluation of the signals in both time and frequency domain, and there is no need for angular displacement information. According to the theory and practice, this method requires high level computing resources and long time. However, as the technique is developing, it is expected that the difficulties will be overcome.

T-4 Thesis: I have checked and analyzed the noise and vibration diagnostic measurements of some good and some faulty engines according to the aspects of constant revolution of speed and during acceleration process. I have found that from the point of view of the efficiency and economy of the tests the noise and vibration tests have to be carried out at 2000 RPM, and during the acceleration from idle to 4200 RPM [S11].

In the case of idle or changing ECU control procedure some transient phenomena can happen during the noise and vibration measurements. In the case of measurements at 2000 RPM almost all the typical problems are observable that can occur at constant rotation speeds. The resonance phenomena can be located during the process of acceleration. At higher speeds the probability of disturbances independent of the operation of the engine may increase. These causes can be hardly separated from other sources, e.g. fixing the engine under test, test rig build-up, etc.

.T-5 Thesis: Using high- speed optoelectronic distance measurement system based contactless triangular principle and MEMS based vibration analytic system I have elaborated new testing methods for vibration diagnostic inspection of internal combustion engines [S8].

The two systems have been tested together simultaneously in the course of engine measurements at the test rig. The results proved the applicability of new the testing methods both mutually and independently. The new methods enable the application of vibration diagnostics in new fields, in case of simple tasks even without a computer background as well.

T-6 Thesis: I have developed a new, wireless data transmission system to submit data of collected and unprocessed information acquired from noise and vibration signals using standard (both commercial and industrial type) WLAN tools and special software configuration [S7].

The system is not conventional, but unique and is capable to provide real time high reliability data transfer with point to point connection setup. The system is independent of the local computer network. There is no need to use expensive, non-standard solutions, and it is not fixed to some special manufacturer of sensors or RF networks.

The signal side unit is powered by a battery, and its lifetime exceeds 24 hours by the design.

The solution enables the wireless measurements in the case of separated and protected measurement stations. As a result, there is no need to use expensive, difficult installation procedures and solutions.

The speed of data transfer enables the real time transfer of 24 bit data at a maximum sampling speed of 50 kS/s for all the four channels of the analog input module.

Author's publications related to the theses

[S1] dr. Pál Bánlaki, Szilveszter Kulcsár: „Monitoring the Operation of Internal Combustion Engines Using Order Analysis of Noise and Vibration Measurements Data", Journal of Machine Manufacturing, Volume XLIX. 2009, Issue E3-E5, (HU ISSN 016-8580), page 142-144

[S2] dr. Pál Bánlaki, dr. Ferenc Dömötör: „Vibration Acceptance Test of Vehicle Gearboxes used in Agriculture", International Journal of APPLIED MECHANICS AND ENGINEERING, Special Issue – 2010 Volume 15 Number 2, ISSN 1425-1655, University Press Zielena Gora, Poland

[S3] dr. Pál Bánlaki, Szilveszter Kulcsár: „ENGINE DIAGNOSIS APPLYING ORDER ANALYSIS ON VIBRATION AND NOISE INFORMATION", FISITA 2010 World Automotive Congress- Proceedings, CD, ISBN 978-863-8058-29-3, Budapest, 2010,
- FISITA 2010 World Automotive Congress – Book of Abstracts, ISBN 978-963-9058-28-6, Budapest, 2010.

[S4] dr. Bánlaki Pál, dr. Dömötör Ferenc, Mesics József: „Belsőégésű motorok minőségének javítása rezgés- és zajanalízis felhasználásával", Magyar Mérnök Akadémia, „Innováció és fenntartható felszíni közlekedés", IFFK2010 - Proceedings of Conference, edited by Peter Tamas,
- CD version, ISBN 978-963-88875 -1-1, Budapest, 2010,
- Internet version, ISBN 978-963-88875-0-4, Budapest, 2010

[S5] dr. Pál Bánlaki, Zoltán Magosi: „PART FAILURE DIAGNOSIS FOR INTERNAL COMBUSTION ENGINE USING NOISE AND VIBRATION ANALYSIS", Periodica Polytechnika – Transportation Engineering, 38/1 – 2010,BME-OMIKK Budapest, Printed version: HU ISSN 0303-7800, Internet version:HU ISSN 1587-3811

[S6] dr. Bánlaki Pál: Belsőégésű motorok működésének elemzése a mért rezgés és zaj adatokon végzett order analízis alkalmazásával, - Chapter 25.2, edited by dr. Dömötör Ferenc, in Volume II of book: Rezgésdiagnosztika, [DOF10], Dunaújváros, 2011

[S7] dr. Bánlaki Pál, dr. Dömötör Ferenc, Stipkovits András, Devecseri Szabolcs: Noise and Vibration Measurement of a Gearbox during the Acceptance Test in the Manufacturer's Workshop, Perner's Contacts, Vol. VI,Spec Issue 2, 2011, University of Pardubice, Pardubice (Czech Republic)

[S8] dr Bánlaki Pál, dr Dömötör Ferenc, Vass Sándor: New sensor constructions widen possibilities to use vibration fault analysis for vehicles and internal combustion engines", Magyar Mérnök Akadémia, „Innováció és fenntartható felszíni közlekedés" IFFK2013 - Proceedings of Conference, Edited by Peter Tamas, Paper 28,
- CD, ISBN 978-963-88875-2-8, Budapest, 2013,
- Internet version ISBN 978-963-88875-3-5, Budapest, 2013

[S9] Bánlaki Pál, Dömötör Ferenc: A MÉRÉSI ADATGYŰJTÉS NÉHÁNY AKTUÁLIS KÉRDÉSE REZGÉSDIAGNOSZTIKAI FELADATOK ESETÉBEN, The Publications Of Microscience – XXVIII. microCAD International Mlultidisciplanary Scientific Conference, Innovative Mechanical Design and Technology Symposium, Session D3, Paper 24, - University of Miskolc, April 2014, ISBN 978-963-358-051-6

[S10] Pál Bánlaki, Ferenc Dömötör: SOME ACTUAL PROBLEMS OF DATA ACQUISITION IN THE CASE OF VIBRATION ANALYSIS, Chapter4, (Pages 38-47), - önálló fejezet a Stanislaw Borkowski . Marek Krynke: MACHINES OPERATING CONDITIONS, Ministry of Science and Higher Edocation – Officina Wydawnicza SMIJP, Czestoshowa, 2014 kiadványban, ISBN 978-93-63978-13-5

[S11] dr. Bánlaki Pál: „Belsőégésű motorok rezgés-és zajdiagnosztikai állapotvizsgálata Gábor eljárások felhasználásával", Magyar Mérnök Akadémia, „Innováció és fenntartható felszíni közlekedés" IFFK2014 - Proceedings of Conference, edited by Peter Tamas, Paper 21,
- CD version, ISBN 978-963-88875-2-8, Budapest, 2014,
- Internet version, ISBN 978-963-88875-3-5, Budapest, 2014

References

[BK4189] Bruel Kjaer: Falcon Range ½" Microphones Type 4189 Product Data, bp1380.pdf, Bruel Kjaer: Deltatron Microphone Preamplifier Type 2671 Product Data, bp1446.pdf http://www.bksv.com/Products/transducers/acoustic/microphones/microphone-preamplifier-combinations/4189-A-21?tab=specifications

[BK4958] Bruel Kjaer Type 4958 - 20 kHz precision array microphone, http://www.bksv.com/Products/transducers/acoustic/microphones/microphone-preamplifier-combinations/4958

[BK8329] Bruel Kjaer: OMETRON Laser Doppler Vibrometer — Type 8329, 2003, Bruel Kjaer, www.bksv.com/library/10929184118329.pdf

[BUR08] Burrus, C. Sydney: Fast Fourier Transforms, CONNEXIONS, Rice University, Houston, Texas, 2008, e-Book CC-BY 2.0

[COH95] Cohen, Leon: TIME-FREQUENCYANALYSIS, Prentice Hall PTR, Upper Saddle River, 1995, ISBN: 0-13-594532-1

[CTC12] CTC: AC102 series Multi-purpose Accelerometer, Connection Technology Center Inc, 2012. https://www.ctconline.com/fileup/3DNEWPDF/AC102series_datasheet_3D.pdf

[DROT14] Drotár István, Kovács Ákos: Kommunikációs Rendszerek Programozása, Textbook, Széchenyi István Egyetem Távközlési Tanszék, Győr, 2013, http://www.tilb.sze.hu/tilb/targyak/NGB_TA024_1/WiFi_jegyzet_2013.pdf

[GAB46] D. Gabor. Theory of communications. *Journal of the Institute of Electric Enginers*,Vol 93:No III., pp. 429–457, IET, London, November 1946.http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=5298517&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5298517

[HEI10] HEIDENHAIN GMBH: Angle Encoders with Integral Bearing, 2010, pdf file, http://www.heidenhain.hu/de_EN/php/documentation-information/documentation/brochures/popup/media/media/file/view/file-0023/file.pdf

[HON10] Honeywell: How does a piezoelectric accelerometer work? 2010, Honeywell, content.honeywell.com/sensing/sensotec/accelerometer_faq.asp

[KEY13] Keyence : Ultra High-Speed/High-AccuracyLaser Displacement Sensor, 2013, Keyence, www.keyence.eu/dwn/lkg5000_kb.pdf

[NI3548] NI Joint Time-Frequency Analysis (JTFA) Overview, 2013, http://www.ni.com/white-paper/3548/en/

[NID9163] NI: WLS9163, NI, 2010, http://www.ni.com/pdf/manuals/372488c.pdf

[NID9172] NI: cDAQ 9172, NI, 2008, http://www.ni.com/pdf/manuals/371747f.pdf

[NID9233] NI 9233, NI, 2008, http://www.ni.com/pdf/manuals/373784f.pdf

[NID9401] NI 9401, NI, 2012, http://digital.ni.com/manuals.nsf/websearch/EFE31C64622F92DE86257C6A0063F353,http://www.ni.com/pdf/manuals/374068f.pdf

[NIE372268B] NI: Gabor Transform and Expansion VI: labview\examples\Time Frequency Analysis\TFAFunctions, 2013, http://zone.ni.com/reference/en-XX/help/372656B-01/lvtimefreqtk/tfa_discrete_gabor_expansion/

[NIL13] NI: LabVIEW System Design Software, 2013, http://www.ni.com/labview

[NIT372416A] NI: Order Analysis Fundamentals, http://zone.ni.com/reference/en-XX/help/372416A-01/svtconcepts/intro_ord_ana/, (2014)

[NOK07] Norton, M., Karczub, D.: Fundamentals of Noise and Vibration Analysis for Engineers, Cambridge University Press, 2007, Cambridge, ISBN 978-0-521-49561-5

[TOY11] TOYOTA: Vibration from Engine after Cold Soak, Toyota Service Bulletin, T-SB-0204-11, 2011, Torrance (USA), http://priuschat.com/attachments/t-sb-0204-11-engine-vibration-pdf.33917

[WIL08] Wilcoxon Research model 993B series General purpose, hermetic triaxial accelerometer, 2008, http://www.wilcoxon.com/prodpdf/993B%20Series%20spec%20(98872D.2).pdf