VALIDATION OF VIBRATION SIGNALS FOR DIAGNOSTICS OF MINING MACHINERY

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Summary

The paper presents the proposal of vibration signal validation algorithms for monitoring of mining machinery. Since several years vibration based condition monitoring is quickly growing, as there is an increasingly important focus on efficient operation and maintenance of very costly equipment used in mining industry. FAMUR Institute, the leading research and development center for FAMUR's Group – one of the biggest producer of mining machinery and equipment, develops machinery monitoring solutions, according to its e-mine strategy.

One of key issues in the analysis of vibration signals is the validation of acquired signals. It is a key prerequisite, before any further analysis should be performed. In the paper, a survey of a number of existing validation methods is presented. These methods has been successfully applied in industries such as power generation, wind turbines or railway transport. Presented methods are evaluated from the point of view of heavy industry applications especially for underground mining, where the most important thing is to record correct data without sending useless vibration signals for diagnostic inference.

The paper includes a case study, where the real vibration data from high power test stand are analyzed. The object of research was heavy duty gearbox. Proposed methods were also applied for the real data from machines working underground.

Keywords: Vibration, validation, condition monitoring systems, coal mining machines monitoring

WALIDACJA SYGNAŁU DRGANIOWEGO NA POTRZEBY DIAGNOSTYKI MASZYN GÓRNICZYCH

Streszczenie

W artykule przedstawiono propozycje metod walidacji sygnału drganiowego na potrzeby diagnostyki maszyn górniczych. Na przełomie ostatnich lat popularność systemów monitoringu maszyn górniczych opartych o sygnał drganiowy systematycznie rośnie, co jest związane z dążeniem do zwiększania czasu dostępności maszyn minimalizacją nieplanowanych przestojów oraz dążeniem do jak najwcześniejszego wykrycia symptomów zbliżającej się awarii. Zgodnie ze strategią przyjętą przez Grupę FAMUR, FAMUR Institute, Centrum Badawczo-Rozwojowe jest twórcą kompleksowego systemu e-kopalnia. W skład tego systemu wchodzi m.in. FAMAC VIBRO pozwalający na ciągły monitoring drgań oraz temperatur napędów maszyn górniczych.

Jak wynika z dotychczasowych doświadczeń autorów, jednym z najważniejszych zadań w analizie sygnału drganiowego jest przeprowadzenie rzetelnej walidacji zarejestrowanych sygnałów. Opisane w artykule metody zostały zaimplementowane w różnych gałęziach przemysłu (m.in. energetyce, turbinach wiatrowych oraz transporcie kolejowym). Obecnie metody te są rozwijane i dostosowywane do specyficznych wymagań rynku górniczego ze szczególnym uwzględnieniem ograniczenia przesyłania i zapisywania danych nieprzydatnych z punktu widzenia diagnostyki maszyn.

Opisywane w artykule metody walidacji sygnałów zostały przetestowane na danych pochodzących z eksperymentalnych badań przekładni przemysłowych przeprowadzonych na stacji prób napędów dużej mocy. Metody te obecnie są również zaimplementowane w podziemnych systemach monitoringu maszyn górniczych.

Słowa kluczowe: (drgania mechaniczne, walidacja sygnału, systemy monitoringu maszyn, monitoring maszyn górniczych,)

1. INTRODUCTION

In recent years utilizing of systems of monitoring and diagnostics (SM&D) machines with residual parameters such as vibration and temperature are becoming increasingly popular method of maintenance in coal mine industry. These systems allow to detect damage of rotary machinery (e.g. gearboxes, shearer loaders) in its early stage, which is very important with a view to avoiding unplanned machine downtime caused by breakdowns and maintain the continuity of work in coal mines [1, 2, 3, 4].

Very briefly, SM&D based on vibration signals consists of accelerometer, cables, data acquisition unit (with signal conditioning unit and ADC converter), data processing unit and supervisory unit (e.g. with data storage unit). [5, 6]. If system works under extremely difficult, non-stationary conditions and very noisy environment as well as compliance with the explosive atmosphere requirement (ATEX) its structure becomes more complicated. FAMUR Group proposed fully ATEX compliant system for vibration monitoring which was presented in [3]. There is a lot of additional connections between accelerometer and data acquisition unit, some additional equipment and sometimes signal path are very long which can cause numerous disturbances in the signals. According to these facts validation of vibration signals is the first and one of the most important procedure in signal analysis process [6,7].

In this paper authors present a study on vibration signals validation as a prerequisite to evaluate the accuracy of recorded data and their usefulness for future analysis and diagnostic reasoning.

2. SIGNAL VALIDATION

Signals, which in accordance with system configuration are qualified to record (e.g. machine is in acceptable state and time condition is fulfilled), are subjected to data validation process. This process is very important especially when dealing with systems for monitoring multiple machines working in non-stationary conditions. Due to that fact, that there is a lot of signals to analyze (in FAMUR's biggest implementation there are about 120 accelerometers), and no possibility to analyze them without automation. Before making any automation of data analysis one has to know, that analyzed signals are correct. Incorrect signals stored in database could be misleading: process of automation analysis could generate false warning or alert, which may expose condition monitoring service clients to high costs associated with unnecessary reaction of services stuff and unneeded repairs. According to this, through the cooperation of specialists in the field of analysis of vibration signals from the EC Group and FAMUR's Diagnostic Center several rules of vibration signals validation were developed, tested and implemented . These methods could be divided into two groups, which is presented at Fig. 1.

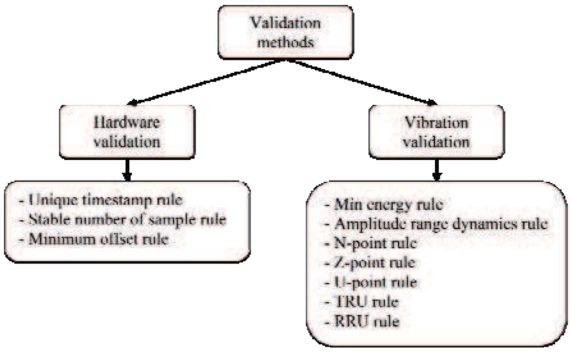

Fig. 1. Classification of validation methods

2.1. Hardware validation

Complete signal validation policy applied in vibration based monitoring system has to be structured in levels enabling to assess signal validity as it follows the path from sensor to the storage database. Such approach leads to implementation of two-steps signals validation, where first process is validation of proper hardware operation. This process consist of three simple rules:

2.1.1. Unique timestamp rule

Task of this procedure is to check if for one channel there is no signals recorded with identical timestamp. This procedure allows the detection of an error in the software for data acquisition, or problems with hardware (e.g. Real Time Clock) which resulted in saving the samples with the same timestamp. Standard visual inspection of the signals does not allow to identify problem as it is possible with automatic validation. As it is shown at Fig.2. this problems sometimes appear in real industry systems. Areas with dotted lines indicate multiple signals recorded with the same timestamp. It is obviously software bug or hardware failure. It is very simple method, but from presented at Fig. 2. Data set it was 50% data rejected due to unique timestamp rule.

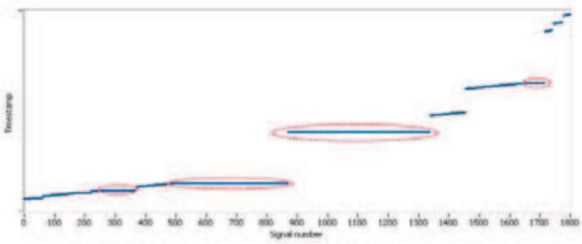

Fig. 2. Data set not valid due to unique timestamp rule

2.1.2. Stable number of samples rule

Stable number of samples rule specifies whether a number of samples in signal is different than that resulting from the system configuration. Wrong number of samples may have several reasons - error during writing to storage space, damaged file, errors in the database or problems with acquisition cards (such as a temporary buffer overflow). When dealing with signal with not valid number of samples, one should always consider problems with the signal continuity. Assuming that the missing bit is the beginning or end of the signal is not acceptable because lack of samples could be low level hardware problem difficult to identify in details.

2.1.3. Minimum offset rule

Generally, in correctly recorded acceleration signal offset should be close to zero [6]. Very simple way of describing offset is calculate mean of analyzed signals. When calculated offset is significantly different from 0, it is possible that the errors occurred in acquisition hardware. When this situation persists, there may be a need to replace the data acquisition module or sensor.

Thanks to above mentioned methods, we could react really fast against hardware fault and replace wrong sensor or module. It is really important especially in large industry monitoring systems, where there is no possibility to supervise system continuously, and service should be informed about any problems with the hardware.

2.2. Vibration validation

If recorded signals are correct due to above methods of hardware validation, automatic validation starts to validate data in terms of its suitability for data analysis and diagnostic information content about technical condition of monitored object. This process consist of following rules[6,7]:

2.2.1. Minimum energy rule

Minimum energy rule is a procedure based on calculating the root-mean-square (RMS) of the analyzed signal and comparing it with the specified limit [6,7]. It allows for the rejection of the samples recorded during downtime of machines - unimportant from the standpoint of diagnosis. These simple method is also useful for detection of total sensor failure or cutoff of cable which is quite frequent in large system of monitoring based on vibration for underground coal mines.

2.2.2. Amplitude range dynamics rule

Characteristic for large SM&D installed in underground coal mines is, that in one system different machines are monitored. There are gearboxes, where vibration levels are quite big because of excitation, but on the other hand we are monitored drums which rotation speed is small and external excitation are small. There is no economical reason to use another sensors or acquisition modules for each machine. In situation, when 16-bits ADC are used, it is very important to set correct measurement range. If range is e.g. +- 60g, and typically vibrations is about 2g (P-P), there may be a problem of low level of signal quantization, which problem is shown at Fig. 3. Following the Jabłoński [6,7] channel range should be set so that nominal data covers about 15-20% of total channel range.

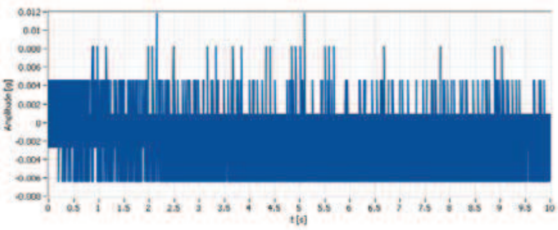

Fig. 3. Signal not valid due to amplitude range dynamics rule

2.2.3. N-point rule

This rule describes maximum number of consecutive samples in signals with the same amplitude value [6,7]. Proper setup threshold for this rule is very important and if it is set proper N-point good describes e.g. signal saturation as it is shown at Fig.4. Consecutive samples with the same amplitude are marked. High rate of N-point could also appear when channel range is too small and real vibration are much bigger than maximum channel range. In this case, N-point does not inform about invalid signal but about wrong system configuration. This threshold depends on resolution of ADC and sampling rate. N-point rule may be described as follow dependency Eq.1[6,7]:

$$(\forall_x \in X)(\neg\exists_x \in \exists)(\forall_{i=i,+1,\ldots,i+N-1}(x_i = x_i + 1)) \qquad (1)$$

Where:
X – set of signal values
x – single signal values
N – the N-point rule coefficient (threshold)

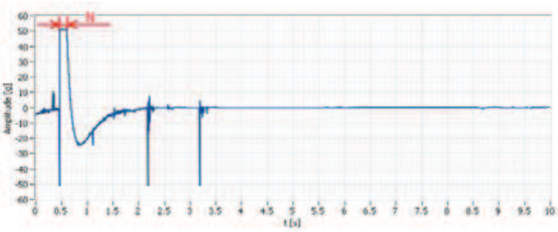

Fig. 4. Signal not valid due to N-point rule

2.2.4. Z-point rule

The results of the Z-point rule procedure is the maximum number of consecutive samples in signals with the same sign which can be an indicator of sensor saturation [7]. Signal with high z-point indicator is shown at Fig. 5. With red lines there is marked the area where the signal has a constant sign. This situation often occurs in vibration monitoring systems for underground machines (e.g. belt conveyors, shearer loaders).

2.2.5. U-point rule

Procedure for determining the number of unique samples in the vibration signals [6,7]. This type of signals by nature is highly volatile so this parameter is expected to be very high. In industrial systems of vibration monitoring 16-bits ADCs are quite common which means, that there is only 65536 possible unique samples (in case of full coverage channel range) so U-point is much more reduced than in 24-bits ADC, where 16777216 unique sample values are possible. In addition U-point is highly dependent on signal length (number of samples in signal) and total channel range coverage and it is relatively difficult to identify correctly the limit for that indicator. However, linking it with number of sample and total channel range shows the accuracy that can facilitate automatic selection of thresholds. This is especially important in the case of 24-bit ADC, where the acceptance threshold for u-point is much higher than for 16-bit ADC. Currently the authors are working on modification of this method into two others: TRU (time relative u-point) and RRU (range relative u-point). Problem of the u-point is illustrated at Fig. 6 and Fig. 7, where two signals are compared – valid and invalid due to U-point rule.

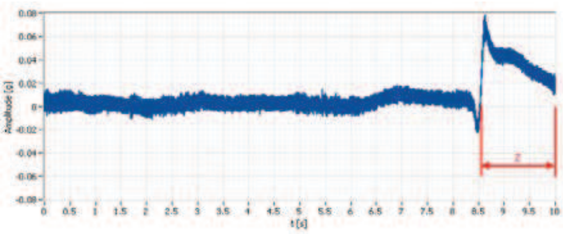

Fig. 5. Signal not valid due to Z-point rule

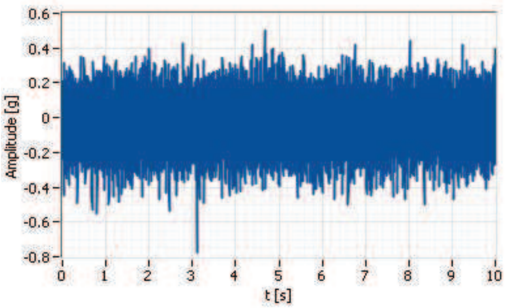

Fig. 6. Signal valid due to U-point rule

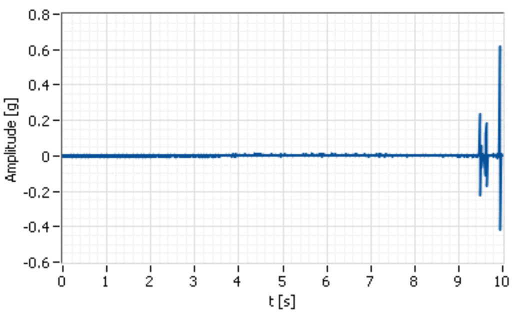

Fig. 7. Signal not valid due to U-point rule

3. CASE STUDY

Methods discussed in previous chapters were applied to vibration data recorded during simultaneous testing of two heavy duty gearboxes (about 300kW) on FAMUR's large scale high power drives test lab. Six channels where recorded (three per each gearbox) with 24-bits ADC resolution. System was configured to record signals with length of 10 seconds with sampling rate of 51,200Hz. During this test, rotation speed was constant (direction was changing) but load was variable.

As it shown at Fig. 7 signal recorded at nominal operating condition of monitored object has amplitude range 21,93 g. According to total channel range 100 g it is shown, that signal is valid due to amplitude range dynamics rule. Ratio of signal amplitude range to total channel range is about 20% for signals recorded at nominal operating parameters. These meets previously mentioned amplitude range dynamics rule criteria described in [6, 7].

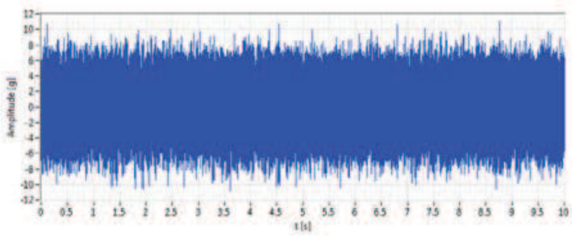

Fig. 8. Signal recorded at nominal operating parameters for observed gearbox

Table 1 illustrates results of validation procedure performed on data set of 4326 signals - 721 signals per each of six channels. To better illustrate functioning of individual rules for each signal complete calculation procedure was carried out. With this approach it is possible to illustrate which of rules exclude the signal from the data set.

In table 2 impact of each discussed validation rule on sample rejection is presented. A slightly different point of view is illustrated in Table 3 It shows the percentage of invalid signals according to various rules relative to all the rejections for the channel. This approach illustrates exactly which of the rules has the highest impact on the rejection.

From Table 1, according to Table 2 and Table 3 it may be concluded, that, some rules have almost no impact on rejection signal from data set, but on the other hand some rules (especially U-point) have nearly 100% affected the removal of the signals from the set. If some signals were found as invalid, it was almost always because of u-point rule. This may indicate that approach used for U-point for 16-bits ADC may be too sensitive for samples recorded with 24-bits ADC.

Table 1. Number of invalid signals due to discussed rules

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	57	66	63	71	71	71
Maximum offset	1	0	1	0	0	0
N-point	1	0	1	0	0	0
Z-point	61	41	64	62	54	64
U-point	84	86	84	164	164	140
Total signals	**721**	**721**	**721**	**721**	**721**	**721**
Total invalid	**87**	**86**	**85**	**165**	**164**	**141**
Total valid	**634**	**635**	**636**	**556**	**557**	**580**

High amount of invalid signals due to minimum energy rule could be explained in fact, that there were few downtimes during this research. Removal of that signals is beneficent, because they will not be taken into account during the automated analysis, and even if they are properly registered, they do not bring anything in terms of diagnostic machines.

Small share of rejection according to offset and N-point rule should not be surprising. Minimum offset rule is closely connected to the operation of hardware and on the test stand there is high quality hardware dedicated to data acquisition. On the other hand N-point violation often occurs with signal saturation, and there were only few such signals associated with a strong impact near the sensor.

Significant part of rejected signals are signals invalid due to Z-point rule. Reason for this may be for example impacts near the sensor or the need for swapping cables during tests.

Table 2. Number of invalid signals due to discussed rules

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	7,91	9,15	8,74	9,85	9,85	9,85
Maximum offset	0,14	0,00	0,14	0,00	0,00	0,00
N-point	0,14	0,00	0,14	0,00	0,00	0,00
Z-point	8,47	5,69	8,88	8,60	7,49	8,88
U-point	11,65	11,93	11,65	22,75	22,75	19,42
Total invalid	**12,07**	**11,93**	**11,79**	**22,88**	**22,75**	**19,56**
Total valid	**87,93**	**88,07**	**88,21**	**77,12**	**77,25**	**80,44**

Table 3. signals according to various rules relative to all the rejections for the channel [%]

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	65,52	76,74	74,12	43,03	43,29	50,35
Maximum offset	1,15	0,00	1,18	0,00	0,00	0,00
N-point	1,15	0,00	1,18	0,00	0,00	0,00
Z-point	70,11	47,67	75,29	37,58	32,93	45,39
U-point	96,55	100,00	98,82	99,39	100,00	99,29

4. CONCLUSIONS

Paper dealt with validation of vibration signals. Despite the fact that data set analyzed in case study was obtained during laboratory testing, 10% to 20% of data for each channel was rejected due to validation rules. This fact indicates that the validation of vibration signals is very important especially if the signals are further dedicated to automatic analysis. Very often it happens that the vibration signal is disturbed by external factors, such as work carried out near the observed object. This was also true in this case, in part of the invalid signals were visible impact hitting most likely caused during the works near the gearbox. It often happens that in the case of experimental research are required minor modifications during the test and if not carried out the validation of vibration signals, the invalid signals can significantly disrupt the results of analyzes carried out in the future.

Additionally, the authors state that in the case of 24-bit ADC, some of the methods given in the paper should be modified to better mapping really false signals. The largest area for future research, the authors saw at dependence of U-point to the time of registration (number of samples) and the dynamic range of the signal. Given in [6,7] the method performs very well in the case of 16-bit ADC, but 24-bit ADC introduce additional complications, and methods described above should be modified.

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