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USE OF PIEZOELECTRIC FOILS AS TOOLS FOR STRUCTURAL HEALTH MONITORING OF FREIGHT CARS DURING EXPLOITATION

UŻYCIE FOLII PIEZOELEKTRYCZNYCH JAKO NARZĘDZI DO MONITOROWANIA STANU TECHNICZNEGO WAGONU TOWAROWEGO W TRAKCIE EKSPLOATACJI*

Work presents a task of piezoelectric foils application for structural health monitoring of freight cars during their exploitation. Results of laboratory tests conducted on a created in scale laboratory model of the freight car are presented. The possibility of inferred from the dynamic response of the model about the changes in its technical condition was verified. During the first test the model was treated as a half-determined system. In order to excite vibrations a pendulum was used. Measurements were carried out using accelerometers. During the next stage of carried out tests the dynamical response of the model was measured while the object was driving. In order to measure vibrations of the system a Macro Fiber Composite (MFC) piezoelectric foil was used. It was glued on the surface of the model. A series of tests of the model with and without load, as well as with an obstacle on the rail track was carried out. Measured signals were juxtaposed on charts and analysed.

Keywords: *piezoelectric foils, structural health monitoring, non-destructive testing, freight cars.*

W pracy przedstawiono zagadnienia dotyczące zastosowania folii piezoelektrycznych do monitorowania stanu technicznego wagonów towarowych w trakcie ich eksploatacji. Przedstawiono wyniki badań laboratoryjnych prowadzonych na utworzonym w skali modelu węglarki. Określono możliwość wykrycia zmian stanu technicznego wagonu na podstawie analizy jego odpowiedzi dynamicznej. W pierwszym etapie badań obiekt traktowano jako półokreślony, w celu wymuszenia drgań stosowano wahadło. Pomiar odpowiedzi dynamicznej układu w poszczególnych punktach pomiarowych przeprowadzono z użyciem akcelerometrów. Kolejnym etapem badań był pomiar odpowiedzi dynamicznej modelu w trakcie jazdy. W celu pomiaru drgań konstrukcji nośnej modelu zastosowano przetwornik piezoelektryczny typu Macro Fiber Composite (MFC), który naklejono na powierzchni modelu. Przeprowadzono ciąg badań modelu bez obciążenia oraz z obciążeniem, a także z przeszkodami umieszczonymi na jednej bądź obu szynach. Otrzymane przebiegi zestawiono na wykresach oraz omówiono wyniki badań.

Słowa kluczowe: *folie piezoelektryczne, monitorowanie stanu technicznego, badania nieniszczące, wagony towarowe.*

1. Introduction

Rail transport is a very important part of the modern economy, one of the components determining its dynamic development. It is therefore important to conduct research and taking action aimed at the development and refinement of this branch of industry. Such actions directly translate into an increase in its effectiveness, safety, reduction of burden on the environment and society. Nowadays numerous studies are conducted, aimed at introducing new technologies and solutions, both in terms of railway infrastructure and logistics management systems, as well as in traction vehicles themselves [1, 2, 4, 11, 14-17, 20, 22, 29, 32]. Introduction of modern technology helps eliminate or reduce nuisance problems associated with the implementation of any kind of transport or the operation of the used technical means [18, 19].

This paper contains a report on the part of works conducted in the research and development project entitled "Analytical and experimental studies and determination of the structural features of components and assemblies in innovative structure of repaired wagons". This project is realized within the Program of Applied Research by Institute of Engineering Processes Automation and Integrated Manufacturing Systems of Silesian University of Technology together with consortium partners: company DB Schenker and Germaz. The main objective of the project is to develop a technology of modernization of freight wagons for the transport of coal and aggregates, through the use of innovative materials and technologies to repair this type of wagons during periodic repairs. Actions which have been undertaken within the project are to improve the operating conditions considered types of wagons by increasing their resistance to corrosion and freezes transported cargo to the shell of the body in the winter conditions, and thus an easier unloading. An additional objective is also verification of strength of modernized carriages and an estimation of the possibility of reducing their weight, while maintaining or increasing the permissible load. One of elements of the project is also to develop a system for diagnosing the technical condition of the modernized shell of wagon body during operation. For this purpose the use of non-destructive testing methods of technical state of constructions will be used, including methods that use the analysis of dynamic response of the object. Therefore research is conducted which examines the possibility of use of the foils with piezoelectric properties as sensors used in the system of vibration measurement of tested items. These research efforts are a continuation of previous work related to the analysis of possibilities to use of composite materials as a part of the wagons boxes shell [1, 2]. The authors in their works also take is-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** sues related to the analysis and synthesis of vibrating mechanical and mechatronic systems including those in which the classical or non-classical piezoelectric transducers are used as actuators or vibration dampers [3, 5, 7-9, 26, 27, 31]. In the Gliwice Research Centre they are also conducted extensive research in the field of analysis and synthesis of mechanical systems and mechatronics [6, 12, 13, 21, 33].

2. Measuring and testing the dynamic response of railway infrastructure

Issues related to the study of the dynamic response of both railway rolling stock and railway infrastructure are the subject undertaken by a number of research centres. Dynamic loads generated during the passage of railway trains are deleterious to the infrastructure, such as bridges or buildings located near tracks, as well as people staying in them. There is however the possibility of their use in systems for condition monitoring of infrastructure components [10, 14, 16, 25, 30]. Due to the dynamic loads generated by moving with higher and higher speed of trains, in the face of aging and worn out infrastructure, these issues are now becoming extremely important. In recent years it can be noticed that significantly increase interest in this subject, as well as the increase in the number of performed acceptance tests of objects under dynamic loading [28]. This is the result of activities related to the implementation of the program of modernization of railway lines in Poland and the introduction of high-speed rail, so passenger transport at speeds above 200 km/h. These issues are discussed among others in the works [14, 16, 25, 28], regarding the dynamic impact of high-speed trains on railway bridges and viaducts, as well as acceptance testing of such facilities under dynamic loading test. Also important are issues of protection of building against vibration generated by the ground and underground rail communication as well as protection and minimize the impact of vibrations on both the passengers and persons in the buildings surrounding the railway line [30].

The aim of these authors' research is to determine the possibility of identifying the technical state of the modernized freight wagon based on continuous measurement of the dynamic response during operation. The idea is to create a system integrated with elements of the modernized wagon body shell and for generating alarm signals that will be able to be read periodically by the service, or sent directly after the occurrence, using a wireless system. As sensors piezoelectric transducers in the form of films will be used. They will be integrated with elements of the modernized wagon shell.

Also in the paper [29] the principles and operation of a system for monitoring loads or state truss railway bridges are presented. Piezoelectric transducers are used as sensors. In this case, the system is based on an analysis of the signals generated by the piezoelectric transducers mounted on railroad tracks before entering the bridge and on the truss bridge elements. The wireless transmission of measured signals to a data center is possible. The system is thus characterized by low cost of installation and lack of significant restrictions on the traffic of railway rolling stock during installation and operation. The amplified and filtered measuring signal can be interpreted in order to identify the load, so weighing the passing train and monitoring the technical condition of the truss bridge. According to the authors, research work aims to create an integrated system for monitoring the technical condition of structures and detect of overloaded rail depots. The theoretical assumptions of the authors are supported by the presentation of the results of measurements on a waveform signals recorded by piezoelectric sensors when the train is passing and the reference signal level to the mass of the wagon, determined by a static weight. The values obtained allow clear identification of the type of wagon after previous calibration of the measurement system.

The results of the simulation and modelling of the impact of static and dynamic load on strength of the railway platform, used in railroad transport systems while horizontal handling are presented in paper [10]. The process for modelling and analysis of wagon chassis platform using finite element method is presented. Model verification based on static analysis and comparing its results with the results of the experiment on a real object was presented. Next, the modal analysis was carried out as well as the results of a simulation of moving of the loaded frame over an obstacle with a height of 5 mm were presented. The response of the structure in the form of vertical displacement changes of the central model node in a half of the length of the wagon and the accompanying stress changes reduced was calculated.

The measurement of the dynamic response of the ground floor of the building located in the vicinity of the Warsaw subway tunnel it became the foundation of the system of monitoring, whereby it is possible to identify trains that generate excessive vibration due to the deformation of worn wheel [30]. The authors present a comparison of horizontal vibration acceleration waveforms on ground floor of the building during the passage of two trains of the same type with different values of radial run out wheels. It has been shown that in the case of rolling stock with deformed wheels is possible dozen times increase in the level of generated vibrations. It has been proven so that there is a possibility to inference about technical condition railway rolling stock based on the analysis of dynamic response of infrastructure forced by its passing. The authors of this study adopted the assumption that such a system can be successfully integrated with the modernized freight wagon and allow monitoring of its technical condition during operation. Attempt to estimate the forces acting on the wheel sets of rail vehicles based on the measured dynamic response is also shown in paper [23]. Using a developed model of wagon and a finite element method, forces acting on the object of study as a result of deformation of the railway track were determined.

3. The object of research, its model and the test stand

The object of research is the four axial freight wagon of ordinary type Eaos 1415-A3 production BREC Belgium. The considered freight wagon after periodic refurbishment and its model created using CAx-class program are presented in Fig. 1. CAD model was created on the basis of documentation provided by the consortium member – company DB Schenker, which includes eleven construction drawings and technical documentation, technical conditions execution of repairs and acceptance after repair, air brake calculations, the program and report on the operational tests. Missing data for the object in question was obtained during the inspection and measurement of real objects and consultation with technical staff responsible for carrying out repairs and technical tests.

During the consultations it was established that the typical problems during the operation of a freight wagon of this type are:

- corrosion of car body shell and the floor,
- freezes of transported cargo to the shell boxes in winter conditions,
- mechanical damage shell boxes, damaged during use improper methods of unloading (of the wagon is designed for unloading with the use of tippers).

Verification of the correctness of the CAD model of the freight wagon was made by comparing the actual mass of the object and the model after assigning material properties. The resulting inaccuracy is 5.34% and it is the result of not taken into account the braking system in the model. Developed CAD model was then used to carry out a series of analysis with use of the class of CAx software such as modal analysis, strength analysis or setting a speed limit while passing wagon loaded or deprived of cargo along the arc of a specified radius of curvature.

In order to conduct research on the dynamic response analysis of freight wagon on extortion and estimate the possibility of inference on its basis of the technical condition of the object the laboratory stand that is shown in Fig. 2 was created. The simplified model of the supera)

b)

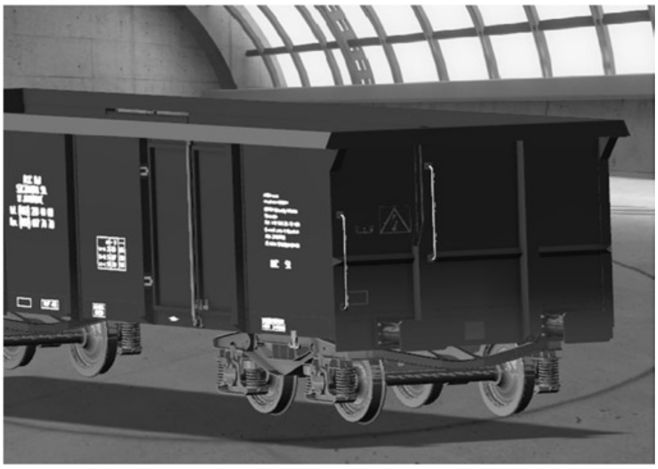


Fig. 1. The freight car type EAOS 1415-A3 (a) and its CAD model (b)

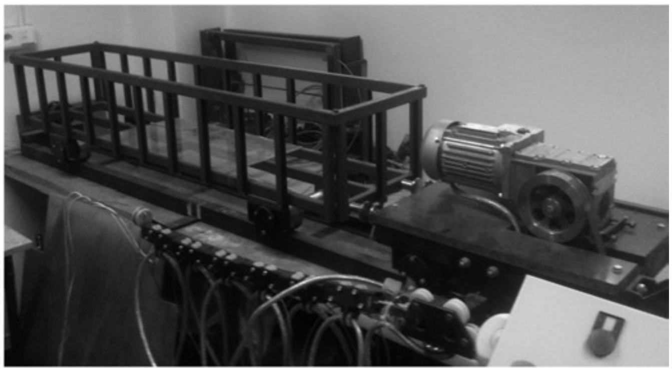


Fig. 2. The laboratory stand for testing the dynamic response of freight car model

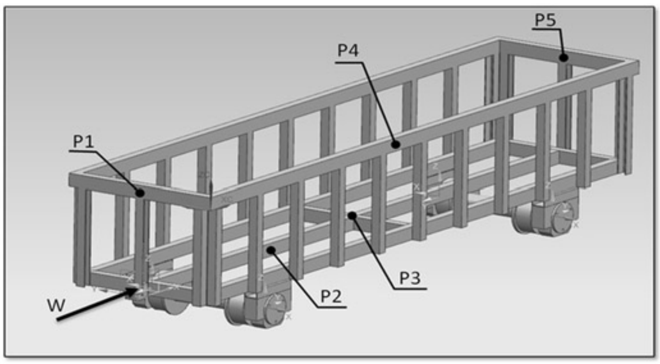


Fig. 3. The CAD model of the laboratory stand with marked positions of the measuring points

structure of the wagon in a scale as well as the model of the track on which the freight car is moving through using the electrically powered locomotive were built up.

The CAD model of the laboratory stand was created and after modal analysis measuring points in which accelerometers and piezoelectric films will be attached were selected. Fig. 3 shows the locations of the measuring points on the model of the superstructure of a freight wagon.

During the measurement of the dynamic response of the system using accelerometers tested wagon model was suspended to separate it from the track. In order to induce vibrations a pendulum was applied. The laboratory stand is shown in Fig. 4. The PCB 352C68 accelerometer and measuring amplifier HBM MGCplus with measurement card AP18i and software CatmanEasy were used [34]. The measurements were repeated five times for each of the measuring points.

Fig. 4. Model of the freight car (the half-determined system) together with the pendulum

During testing of the dynamic response in motion in the role of sensor a piezoelectric MFC film was used. Fig. 5 shows the MFC piezoelectric transducer glued on the surface of the freight wagon model. Macro Fiber Composite piezoelectric transducers are made of rectangular ceramic bars sandwiched between adhesive layers, the electrodes and the polyamide film. They are supplied as ready-to-use transducers that can be glued on the surface of elements or embedded in the composite structure. The transmitters are durable, efficient and resistant to damage. They can be successfully used as actuators or mechanical vibration dampers and sensors [24, 35].

Fig. 5. The MFC transducer type M8514-P1 glued on the tested model

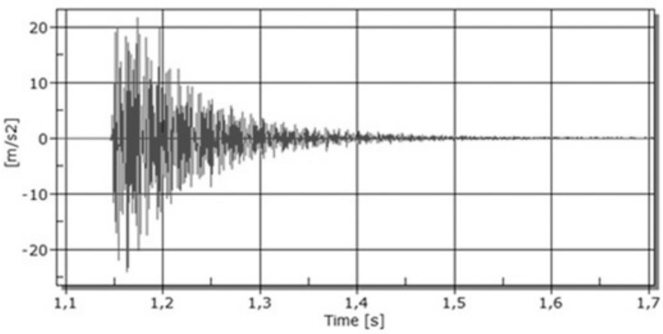
The NI-9215 measurement card was used for data acquisition. It is produced by National Instruments. Its range is ±10 V with 16 bit resolution measurement and sampling frequency of each of the four channels is 100ks/s. The card was installed in the measuring unit NI cDAQ-9191 that enables wireless transmission of measurement data in enclosed areas within 30 meters, while in the open air for a distance of 100 meters. The measuring system was fed with gel battery. This configuration of measurement channel made it possible to carry out the measurements of freight wagon model in motion of the track way. Data acquisition and development were made in LabVIEW.

4. Results

In the first stage of work studies of the dynamic response of a freight wagon model were conducted by using a pendulum. Measurements were performed using the accelerometer successively in five measuring points of the model marked in Fig. 3. The research was carried out without a load wagon, as well as with 20 kg of cargo load. The aim of such actions was to determine the possibility of inference on the state of the object based on the measured responses to extortion and identification of measurement points where such inference is possible. Fig. 6 and 7 show the obtained waveforms of the dynamic response in the case of the selected measuring points.

At the measuring point P3 a change of the measured signal after load of model can be clearly seen. The maximum value of the acceleration measured without load exceeded 20 m·s^{-2}, and after the load has dropped to about 5 m·s^{-2}. The time necessary to completely suppress of the excited the vibration decreased from 0.55 s to 0.2 s. At this measuring point the vibration were measured in the vertical direction and thus perpendicular to the direction of the force.

a)



b)

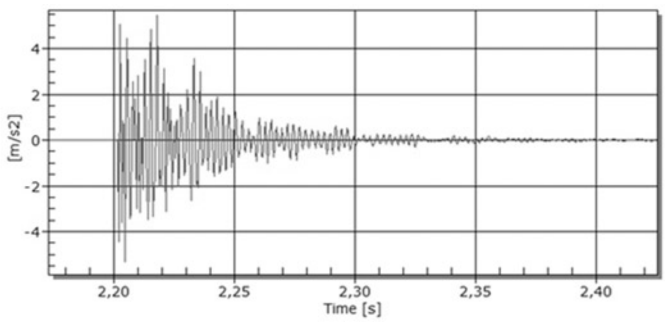
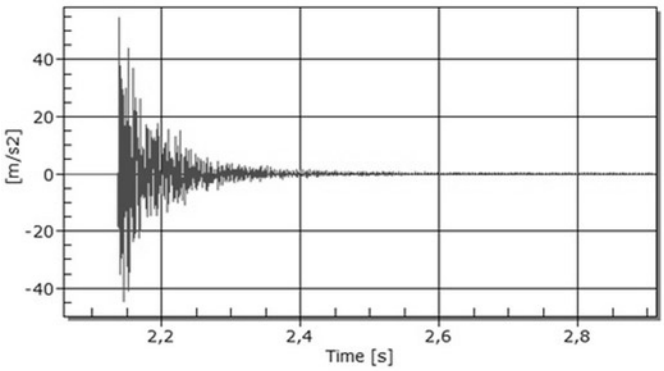


Fig. 6. The course of the system response to extortion at the measurement point P3 without load (a) and with load (b)

At the measuring point P5 there was no clear change in the registered system response to extortion. The maximum amplitude of vibration acceleration in both cases reached more than 50 m·s^{-2} and the time of suppress the vibration decreased from 0.5 seconds to 0.4 seconds. For the measurement point P5 vibration parameters of the system were measured in the direction of the force.

Table 1 shows the results of measurements carried out for all measuring points. Change of the measured waveform of the signal after load the wagon are clearly visible in the case of the points at which measurements were carried out in the direction perpendicular to the force (points P2, P3 and P4). In other cases, there were no major changes in recorded waveforms.

a)



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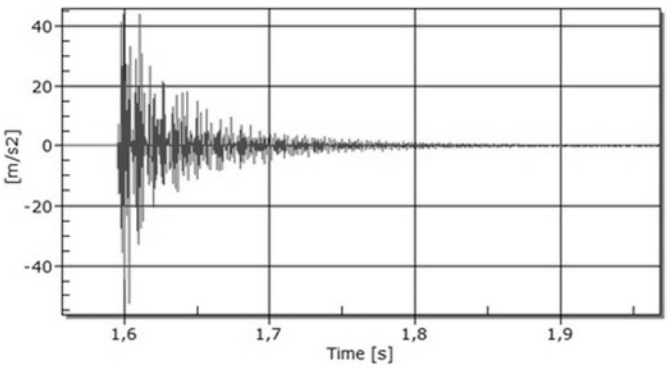

Fig. 7. The course of the system response to extortion at the measurement point P5

Table 1. Comparison of the results of vibration measurements

Measuring point	Without load		With load	
	a [m/s^2]	t [s]	a [m/s^2]	t [s]
P1	40	0,55	40	0,35
P2	14	1	8	0,4
P3	23	0,55	6	0,2
P4	25	0,8	15	0,4
P5	55	0,5	50	0,4

During the further research the model of freight car was moving through the track way with a set speed and registration of its dynamic response was done using a MFC piezoelectric film glued in place of the measurement point P2. Electrical voltage signals generated by the piezoelectric film as a result of its deformation due to vibrations in the system were recorded. In order to allow the free movement of the model the wireless transmission of measurement data was used. Measurements were made for the model with load of 20 kg and without load. Each of the runs was repeated ten times in order to verify reproducibility of results.

Fig. 8 shows the electric voltage waveforms generated by the MFC-type piezoelectric film during the test of wagon model without and with load when there was not any obstacle on the track way.

A significant change in the recorded voltage signal during tests of the freight car model with the load can be observed. The electric voltage generated by the piezoelectric film has an asymmetrical waveform. There is also visible increase in the maximum values of generated electric voltage.

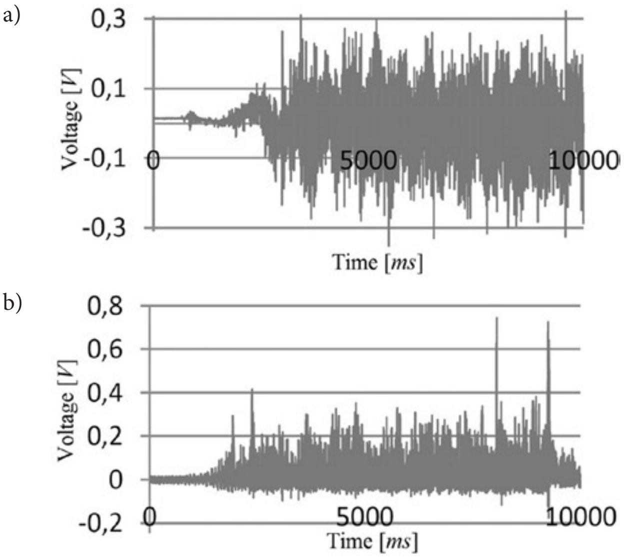

Fig. 8. The waveform generated by the MFC transducer during the movement of the model without load (a) and with load (b), without obstacle on the rail

In further tests an obstacle was placed on a rail way. It had the form of a steel element glued to one or both rails with diameter 25 mm and a thickness of 2 mm. In the case of mounting obstacles on both tracks, they were placed at the same distance from the beginning of the track. In order to verify the reproducibility of measurements they were conducted ten times in situations where an obstacle was mounted on the left rail, right rail or on both of the rails. The recorded voltage signal waveforms generated by the MFC piezoelectric foil glued on the freight wagon model in place of the measuring point P2 are presented in Fig. 9 to 11. Waveforms were recorded wirelessly using NI measurement module cDAQ-9191 and NI 9215 measurement card.

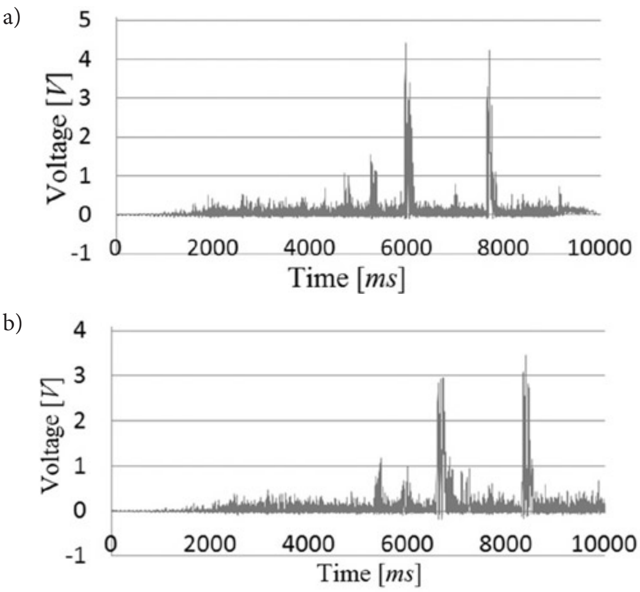

Fig. 9. The waveform generated by the MFC transducer during the movement of the model without load (a) and with load (b), with an obstacle on the left rail

When analysing the received waveforms from tests with the obstacle mounted on the left rail, in both cases (with and without load) it can be seen a significant increase in the voltage generated by the piezoelectric transducer during overcoming obstacles by both wagon axes. It can also to notice increase in electric voltage generated at

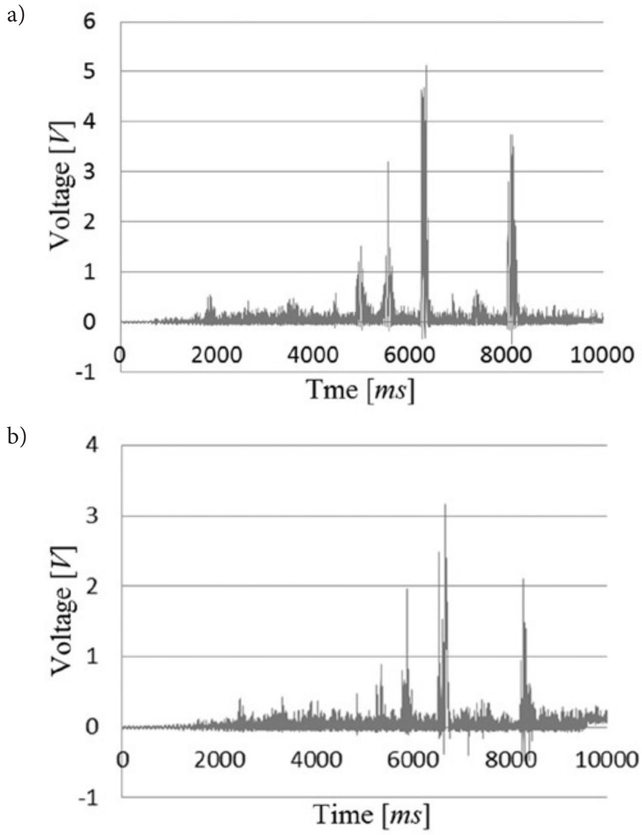

Fig. 10. The waveform generated by the MFC transducer during the movement of the model without load (a) and with load (b), with an obstacle on the right rail

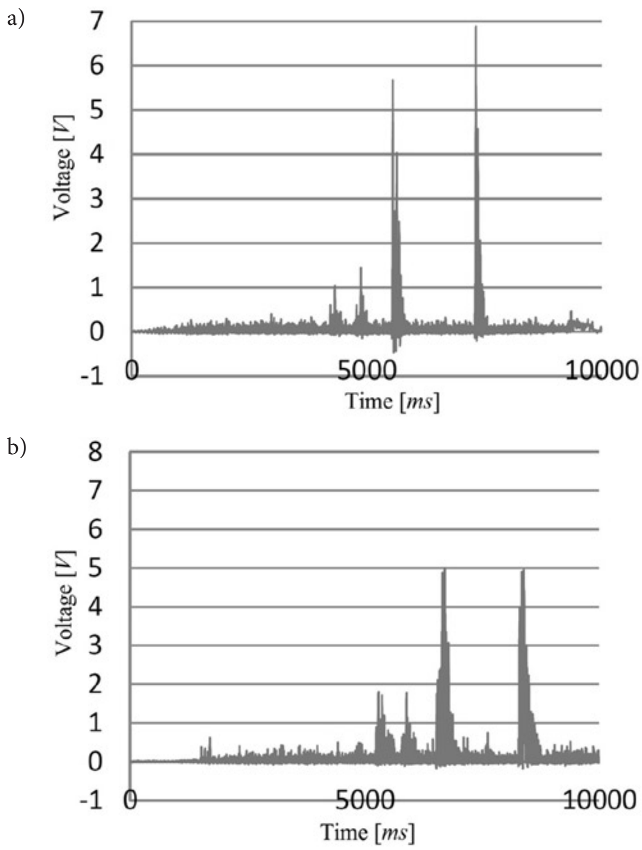

Fig. 11. The waveform generated by the MFC transducer during the movement of the model without load (a) and with load (b), with an obstacle on the both rails

the time of overcoming obstacles by trolley drive system. The peaks of voltage in this case do not have high value and can be interpreted ambiguously by the level of signal generated throughout the test. In the case of model with load slight decrease in the maximum values of generated electric voltage can be observed.

After placing obstacles on the right rail there was an increase in the value of the voltage generated by the piezoelectric film during the test. In this case, the obstacle is positioned on the same side of model that the piezoelectric transducer is glued. The signals generated by the piezoelectric film can be clearly interpreted. During the tests with load also the decrease in maximum values of recorded signal relative to the tests without load can be observed.

The last stage of the research was test with obstacles placed on both rails. Registered waveforms of electrical voltage generated by the piezoelectric transducer are given in Fig. 11.

In the case of the distribution obstacles on both rails of the track a considerable increase in the maximum values of generated signals can be observed. Unambiguous interpretation of signals generated by the piezoelectric transducer, both during transit of freight car model and the trolley through the obstacles is possible. At the same time, as in earlier measurements, there was a decrease of maximal values of the signal in tests with the load relative to the model unloaded.

5. Conclusions

The paper presents a report on the examinations of dynamic response to the excitation of a freight wagon type 1415-A3. The model of the wagon was studied in conditions of isolation from the rail tracks and while driving. Measurements were made using accelerometers and MFC piezoelectric transducers. The system was excited to oscillate by the pendulum in the case of half-determined system or through the obstacles placed on the track way. The possibility to infer about the state of the object on the basis of received signals was studied. Work is an introduction to the establishment of a system of non-destructive techniques for inspect freight wagons during their exploitation. Operation of the system will be based on the analysis of the dynamic response of the object measured using piezoelectric transducers glued to the selected points on object. The aim of the work was to verify the possibility of infer about the state of the object by measuring its response to the dynamic excitation and the possibility of its separation from the noise, which is the result of his work in normal operating conditions. It was shown that, as in the case of a measurement vibration forced by trains movement in which the sensors are mounted on elements of the railway infrastructure or surrounding buildings [29, 30], it is possible to verify the condition of the object based on the signals generated by respectively disposed piezoelectric sensors.

Measuring points on the created freight wagon model were selected in the study and a series of tests was conducted. It was proved that when accelerometers are used to measure the dynamic response of the system, changes are clearly visible only in the case of measuring the parameters of vibration in a direction other than the direction of excitation. Such a measurement would be impossible in the case of a real object that is excited to vibrations by forces acting during its normal operation. In this case, it may be an effective solution to use of piezoelectric foil glued on the surface of selected elements of the object, which in the proposed system will function as sensors. Preliminary studies conducted on the created laboratory stand proved the effectiveness of the proposed method. The electric voltage signal generated by the piezoelectric film glued on the surface of objects can be analysed and interpreted in order to infer for his condition. The decrease in the voltage generated by the piezoelectric transducers after model loading was observed during all tests. It is a result of its greater stiffness. It is also possible to uniquely identify signals generated in the course of passing over an obstacle, both the model of freight wagon as well as the trolley drive.

Tests on real objects – freight cars type 1415-A3 will be carried out as a part of further work. On the basis of modal analysis carried out for the created CAD model of the considered freight wagon measuring points in which piezoelectric films should be glued will be selected.

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