Journal of civil engineering and transport **transEngin**

Volume **1**, Issue **1** / **2019** **e-ISSN**: **2658-2120**

DOI: 10.24136/tren.2019.001

SELECTION OF SIGNAL REGISTRATION POINTS IN THE MONITORING PROCESS AND DIAGNOSING THE CONDITION OF THE RAIL VEHICLE

Andrzej **Chudzikiewicz**[1*], Anna **Stelmach**[2], Wojciech **Wawrzyński**[3]

[1]Uniwersytet Technologiczno-Humanistyczny w Radomiu, Wydział Transportu, Elektrotechniki i Informatyki; Malczewskiego 29, 26-600 Radom; Politechnika Warszawska, Wydział Transportu, email: ach1@wt.pw.edu.pl,
[2]Politechnika Warszawska, Wydział Transportu, email: ast@wt.pw.edu.pl
[3]Politechnika Warszawska, Wydział Transportu, email: wwa@wt.pw.edu.pl
[*]Corresponding author

Reviewed positively: 09.09.2019

Information about quoting an article:
Chudzikiewicz A., Stelmach A., Wawrzyński W. (2019). Selection of signal registration points in the monitoring process and diagnosing the condition of the rail vehicle. Journal of civil engineering and transport. 1(1), 7-13. DOI: 10.24136/tren.2019.001

Abstract – The article discusses the process of selecting points on a rail vehicle in which sensors recording signals will be located, with a view to their later use in the process of monitoring the condition of the vehicle and in particular elements of the first and second degree suspension system. The number of such points and their location is significant considering the complexity of the monitoring system and thus the costs of its construction and subsequent operation, as well as the possibility of using registered signals in the process of diagnosing the technical condition of the vehicle, bearing in mind the functioning of such a system in on-line mode.

Key words – rail vehicle, measuring points, condition monitoring

INTRODUCTION

One of the methods of diagnosing the condition is monitoring, which means regular qualitative and quantitative measurements or observations of the studied phenomenon carried out in accordance with the developed procedure [1].

Monitoring programs are used to collect information about the quantitative and qualitative status of changes in parameters and characteristics of the studied phenomenon, which can then be used in the process of assessing the condition of a given facility.

The collected data also facilitate the selection of appropriate actions in the event of a harmful effect of this phenomenon on the condition of the object and thus the life and property of a person or the environment. An example of using the recorded signals in the process of assessing the state of the mechanical system, an element of rail infrastructure, in Polish conditions can be found in [6].

At the end of the 1990s, a new area of knowledge developed related to diagnostics based on the concept of integration of elements of the measurement system (sensors, extensometers, miniature amplification systems) with the properties of intelligent materials, information transfer and information technology in the process recognition, localization, estimation and prediction of damage that may cause dysfunction of the structure of the object being monitored currently or in the future. This area has been called Monitoring of the state of life of objects and systems - SHM (Structural Health Monitoring) [2-3]. The idea of SHM is to estimate changes in structure (material) properties and not its structural functions (recognizing changes in function is delayed bearing in mind the tasks of modern service and preventive activities). SHM methods have found application in monitoring the condition of structures and devices in energy, aviation, construction, and in the last period of the end of the twentieth century, they began to be used more and more often by rail transport. The pursuit of increasing the speed of travel, passenger comfort and safety in rail transport resulted in the development of research related to methods and tools aimed at building systems for monitoring and diagnosing the condition of the rail-track vehicle system. An example of such an action was the launch of research in this area under the MONIT project [4] in which one of the work carried out was work [5] concerning the construction and implementation of a system for monitoring the technical condition of a rail vehicle and track with further use in ongoing diagnostics track and truck. The undertaken work began with the formulation of assumptions for such a system, then developed its model, which was analyzed using simulation methods. The results of the analysis were used to prepare the prototype of the system and then its tests were carried out in laboratory conditions.

The final result of this work was the installation of a prototype verified in these tests, on an ED74 vehicle (passenger, electric, four-body rail vehicle). This prototype was then subjected to supervised operation. An important element in the presented process of building a state monitoring system is the selection of the quantity and location of measurement sensors on the monitored facility. A significant number and random placement of sensors cause redundancy and excess information collected, which in this case leads to an extended time to analyze the recorded information, complications in their interpretation and increase the cost of the system. The article will present the tasks of determining the optimal number of sensors and their distribution points on a rail vehicle at the stage of building a system prototype.

I. Assumptions For the Monitoring System

The rail-track vehicle system belongs to more complex mechanical systems. It can be distinguished by such subsystems as: track, contact zone of the wheel with a rail and a vehicle which, apart from the fact that they themselves constitute complex, non-linear dynamical systems, are also connected with each other through bonds. The structure of this system is shown in Figure 1 [6].
Its basic features are:

- multidimensionality,
- occurring, strong non-linear phenomena (contact zone of the wheel and rail systems prone to dry friction elements, ...),
- complex structure of the track surface,
- dynamic feedback between the vehicle and the track,
- impact of speed on dynamic phenomena.

All the above, mentioned features make the tests of this system, depending on the assumed objective, carried out in one of three frequency areas: up to 80 Hz from 80 Hz to 500 Hz and above 500 Hz. This requires the use of various models, methods and tools in the research.

Subsequent assumptions should take into account these considerations. One of the methods of condition monitoring is on-line diagnosis [7]. In the case of a rail vehicle, the idea of diagnosing the condition on-line is shown in Figure 2. The measurement of diagnostic signals takes place "on a regular basis" while driving under normal operating conditions. Each of the monitored vehicles (wagon, traction vehicle unit) has diagnostic signals recording system installed at selected points. These systems are connected in a network with a bus that "collects signals" from each vehicle and sends them to the Data Acquisition Unit (JAD), on-board computer, where they are registered and processed to obtain information on the status of individual components and systems in vehicles. The data acquisition unit transmits registered signals to the monitoring systems server via radio. In case of an emergency situation, e.g. exceeding the permissible level of the measured parameter, the mechanic operating the train with information about the situation makes decisions about further driving or in a critical situation, the monitoring system automatically activates the emergency braking system, thus interrupting the ride.

Based on the works [7-8] in which various concepts of monitoring the condition of a railway vehicle were presented, the following assumptions regarding the system being built were adopted:

1. The monitoring of both the vehicle and the track will take place from the position of the moving vehicle.
2. In the monitoring process, a vibroacoustic acceleration signal will be used to assess the states.
3. The assessment of the monitored phenomena will be a qualitative assessment and will be based on monitoring of exceeding the permissible vibration levels and comparative analyzes.
4. Monitoring the condition of the track will be based on the assessment of the condition of the track geometry and the condition of the track bed. Used in this case will be vibroacoustic signals from sensors placed on bearing housings of wheelsets.
5. The monitoring of the vehicle will be aimed at monitoring the condition of elements of flexible systems of 1st and 2nd degree of springing and temperature of bearings of wheeled sets of bearings.
6. The monitoring system should be characterized by simplicity and availability having regard to costs.

Rail vehicle testing procedure with regard to driving safety, dynamic properties of the running gear and track influence, is based on the requirements of EN 14363 [9] and UIC 518 [10]. Therefore, in the developed procedure for monitoring the condition of a rail vehicle, the requirements contained therein regarding the critical values of accelerations measured on the trolley and box of the vehicle were taken into account. The vertical and transverse accelerations measured on the trolley allow the assessment of running safety in a simplified manner. In addition, they also allow you to monitor the behavior of the vehicle while driving.

In contrast, to assess the running safety of the vehicle, vertical and transverse accelerations recorded on the vehicle body are used. The requirements contained in the standard [7] and the card [8] were the basis for determining the distribution of measuring points on the trolley frame, bearing housing for wheelsets and boxes as well as the selection of measurement sensors parameters. The next factor that determined the choice of measurement points was the determination of the number and type of statistical measures that will later be used in the signal analysis process, bearing in mind the usefulness of the information contained in the signal for the diagnostic evaluation of the monitored object.

It was assumed initially that the recorded signals will be evaluated using the following measures:

- Pearson's correlation coefficient,
- correlation coefficient,
- intergroup correlation coefficient (intraclass correlation coefficient),
- peak-to-peak value,
- standard deviation,
- kurtosis,
- RMS,
- quartile distribution,
- skewness.

It is obvious that both the large number of data collection points from the vehicle being monitored and the multiplicity of measures used in the process of analyzing recorded signals will not positively affect the effectiveness of the monitoring system built. In order to achieve "optimality" in this respect, a simulation study of the effectiveness of a formulated method of monitoring the rail-track vehicle system for the adopted assumptions was carried out.

II. Simulation Study of the Effectiveness of the Monitoring Method

As mentioned earlier, the task of simulation research aimed at determining the effectiveness of the monitoring method and diagnosing, it is to determine the points of the sensors in each vehicle unit so that the number of these points is minimal and the information received was enough to assess the condition of selected vehicle components. The mathematical model of the vehicle adopted in simulation tests is:

$$M\ddot{\ } \quad \dot{\ } \quad \dot{\ } \tag{1}$$

where:
M, C, K - matrices: inertia, damping and elasticity;
q - vector of generalized coordinates;
p - vector of forces of the form:

$$p(t,q,\dot{\ } \quad \dot{\ } \tag{2}$$

f(t) – forcing forces vector
h(q,q′) – contact force vector

In the case of contact forces h (q, q'), normal forces necessary to calculate tangential "Kalker's" forces were obtained from the dependence of:

$$\begin{aligned} N_L &= \frac{Q_L}{\cos\delta_L} - T_{2L}\cdot\tan\delta_L \\ N_R &= \frac{Q_R}{\cos\delta_R} + T_{2R}\cdot\tan\delta_R \end{aligned} \tag{3}$$

where:
$Q_{L,R}$ - vertical forces (perpendicular to the track plan),
$T_{2L,2R}$ - tangential forces at the contact points of wheels and rails,
$\delta_{R,L}$ – contact angle for right (R), left (L) wheel.

In turn, the magnitudes that enforce the vibrations of the considered vehicle model are geometric irregularities of the track in the form of vertical unevenness of the track center line (z_t), right lateral inequalities (y_r) and the left rail course (y_l) and the local superelevation (Θ_t).

An important issue in the model of contact forces is the adoption of expressions describing relative slip between the wheel and the rail in the case of rigid track. In this model:

- longitudinal creepage:

$$\begin{aligned} \gamma_{1L} &= \frac{-r_L}{r_t} + 1 + l_0\cdot\left(\frac{\dot{\ }}{v} \cdots\right) \\ \gamma_{1R} &= \frac{-r_R}{r_t} + 1 - l_0\cdot\left(\frac{\dot{\ }}{v} \cdots\right) \end{aligned} \tag{4}$$

- lateral creepage:

$$\begin{aligned} \gamma_{2L} &= \left(\frac{\dot{\ }}{v} \quad \frac{}{r_t}\right)/\cos\delta_L \\ \gamma_{2R} &= \left(\frac{\dot{\ }}{v} \quad \frac{}{r_t}\right)/\cos\delta_R \end{aligned} \tag{5}$$

- spin creepage:

$$\begin{aligned} \omega_{3L} &= \frac{\psi\cdot\cos\delta_L}{v} - \frac{\sin\delta_L}{r_L} \\ \omega_{3R} &= \frac{\psi\cdot\cos\delta_R}{v} + \frac{\sin\delta_R}{r_R} \end{aligned} \tag{6}$$

where:
$\delta_{R,L}$ - contact angle for the right left wheel,
$r_{R,L}$ - rolling radius for the right left wheel,
r_t - mean rolling radius (in the middle position of the set),
l_0 - half track width,
R- radius of curvature of the track,
v - vehicle speed,
y, ψ - coordinates describing the movement of the center of mass of the wheelset.

In this case, by the contact angle we mean the angle between the tangent to the wheel and rail profiles at their point of contact and the track plan.

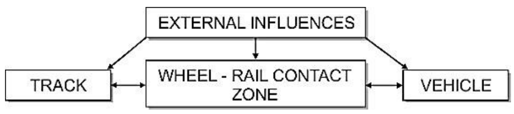

Fig. 1. Structure of the rail-track vehicle system with regard to external influences

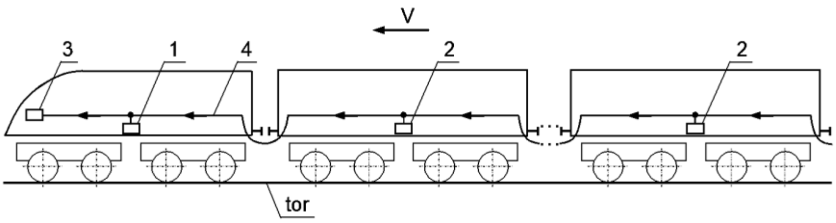

Fig. 2. Diagnosis of the technical condition of the rail vehicle by on-line method, (1 - drive unit recording system, 2 - vehicle status recording system, 3 - on - board computer registering and continuous vehicle condition diagnosis, 4 - monitoring and diagnostic system network vehicle)

Simulations were performed in a multi-variant system, changing vehicle speed, variable track condition and vehicle status (efficient and damaged vehicle). The simulations were performed using our own proprietary package. Damage to the susceptible system was simulated by reducing the value of susceptible parameters in the model. Signals were registered in three places of the vehicle:

- wheelset bearing housing (axle box): M_{1L}, M_{1P}, M_{2L}, M_{2P}, ... M_{ij}, i = 1,2,3,4, j = L, P,
- frame of the bogie: W_{ijk}, i = 1,2, j = L, P, k = 1,2,3,4 (index specifying the points of sensor placement,
- frame beginning (1), center (2), end of the frame (3) on the left (L) or right (P) side, k = 4 (L = P = 0),
- bogie pivot,
- vehicle body: P_{ik}, i = L, P, k = 1,2,3,4 (positioning the point just like on the frame).

For one only rail vehicle trolley frame, these points were 7. It was assumed that the usability evaluation of a given signal will be the result of comparisons of recorded signals and their time and / or frequency characteristics versus the assumed reference point and they will be made between signals of the same physical quantities or their characteristics.

It has been assumed that the reference point (object) will be:

- bearing housing and assembly (right side) and trolley,
- frame I of the trolley (center of the beam of the right part of the frame),
- box (point located above the pivot point).

In order to quantify the conformity of the analyzed signals or their characteristics, an indicator was introduced which is a measure of the compatibility of two signals in the form of:

$$W_{0i} = \int_0^T \left| f_0 - f_i \right| dt \qquad (7)$$

where:
$f_0(t)$ - registered signal (or its characteristic) at the reference point,
$f_i(t)$ - a registered signal (or its characteristics) at the i-th point of reference,
T - registration time.

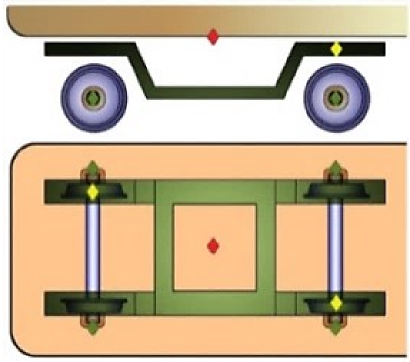

Fig. 3. Locations of acceleration sensors on the frame of the bogie, wheelsets and body

As a result of simulation analyzes, the number of statistical measures necessary to unambiguously determine the state of the vehicle in the diagnostic process was also reduced. Finally, as a result of simulation analyzes, the following measures were adopted as significant, carrying the desired information resource:

- RMS,
- peak-to-peak value,
- kurtosis K
- energy in the band E (0-200Hz).

These measures are defined by the following expressions:

- RMS; squared value (root-mean-square):

$$x_{rms} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} \qquad (8)$$

- Peak to peak value:

$$P2P = \max(x_i) - \min(x_i) \qquad (9)$$

- Kurtosis – a measure of building or convexity:

$$K = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - Mean)^4}{\left(\sqrt{\frac{1}{N}}\sum_{i=1}^{N}(x_i - Mean)^2\right)^2} \qquad (10)$$

$$Mean = \frac{1}{N}\sum_{1}^{N} x_i \qquad (11)$$

- Signal Energy:

$$E = \frac{1}{N}\sum_{1}^{N}(x_i)^2 \qquad (12)$$

III. MONITORING SYSTEM PROTOTYPE

SYSTEM VALIDATION

The system's prototype was validated in two-steps. The first stage is research conducted in laboratory conditions, the purpose of which was to check the formal operation of the system, taking into account the hardware and software part and then checking the correctness of registration and analysis of recorded signals. The second stage of validation is tests carried out on the Railway Institute (IK) test track in Żmigród using an IK measuring train composed of a locomotive, a measuring car and a freight wagon. Both the measuring wagon and the freight wagon were instrumented with sensors of the tested system and sensors mounted by the IK laboratory. Damage to the flexible system was carried out by switching off (removing) the elastic or damping element from the flexible system in the freight wagon. The recorded signals were analyzed independently by the IK measuring system and the prototype system. When considering the results of the comparison, one should bear in mind the fact that both measuring systems were not synchronized with each other. The list of data packets from both systems in terms of the initial location of registration is burdened with an error resulting from determining the location of the wagon in the case of registered signals by the IK system. The IK measuring system did not have a GPS module that would allow precise positioning of the vehicle. The initial location of the registration was identified on the basis of the constant transverse acceleration component (arc travel) and thus the start or end of the given arc was determined. Analyzing the results of the comparison between the two systems, it can be concluded that the assumptions made for the monitoring system prototype proved to be correct. The applied measuring apparatus during the experiment functioned correctly. The largest differences between the data refer to the case of registration of lateral acceleration on the box and partly on the trolley frame. Although the signals have been subjected to filtration, there are some differences in the analysis resulting from a different measurement technology. Nevertheless, it can be concluded that the accuracy of the results obtained in the measurement system being part of the monitoring system built as part of the MONIT project is satisfactory considering the assumed monitoring goal, i.e. a qualitative evaluation of the measured signal. An exemplary result of the comparison of the RMS value of the vertical acceleration signal recorded on the bogie frame by two measuring systems is shown in Figure 4.

From the results shown in Figure 4 and from the other results obtained, it can be concluded that the tested monitoring system meets the assumed conditions regarding the possibility of post-legal registration of acceleration signals at selected points of the vehicle. The difference between the results obtained in the measuring point 5 resulted from the sensor damage in the MONIT system, at this point.

TESTING UNDER CONTROLLED OPERATING CONDITIONS

The prototype of the monitoring system was installed on the ED74 type vehicle (electric traction unit for passenger transport). The installation diagram of local data acquisition units (LJAD) and the central data acquisition unit (CJAD) is presented in Figure 5. As part of the operation of the supervised railway vehicle, it moved on routes: Warsaw - Poznań, Warsaw - Terespol, Warsaw - Krakow, Krakow - Wroclaw. The initial period of the system evaluation in supervised operation is the removal of faults, errors and corrections in the functioning of the system in the field of data analysis in the diagnosis process. In the next period, regular registrations of signals and their analysis were carried out. Example result showing the change in the diagnostic indicator the mean RMS value of the acceleration signal is shown in Figure 6.

All exceedances (critical value of W = 5) on 5 July 2012 were recorded on a straight track (Fig. 6), therefore it is difficult to verify the reason for their occurrence. At the same time, however, it should be noted that exceedances occurred in one sequence of events. After exceeding, another (i.e recorded in the next packet) exceeded, which could indicate a "temporary" problem with the rail vehicle element. Similar analyzes were performed for other diagnostic indicators.

In the current approach to diagnosing the condition of the vehicle's running system, there was no algorithm that would link all analyzed diagnostic indicators. Consideration of each indicator separately is a labor-intensive occupation

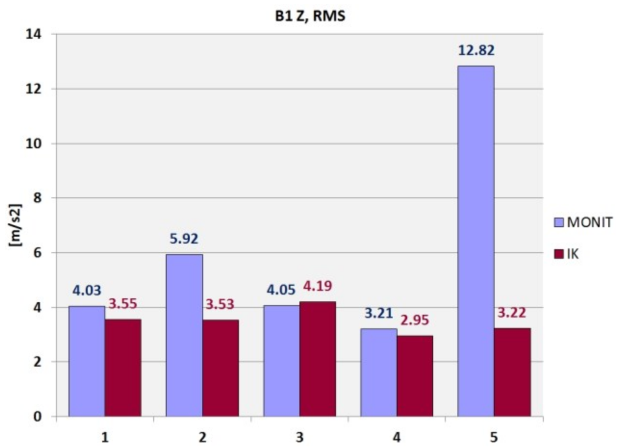

Fig. 4. RMS vertical acceleration values on the vehicle frame, above the first set on the right side of the damaged wagon for speed v=60km/h, signals registered by the IK measurement systems and the MONIT project

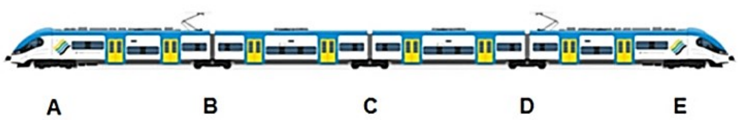

Fig. 5. Vehicle ED74 and the location of data acquisition units on the vehicle. A, E – motor bogie, B, C, D – trailing bogie. A – CJAD, LJAD5, B – LJAD4, C – LJAD3, D – LJAD2, E – LJAD1

and requires the setting of separate limit values for each of them. In addition, in some cases - as shown by the analysis - it is impossible to determine the relationship between several parameters. In order to eliminate these disadvantages and improve the diagnosis process, it was proposed to use a combined approach to monitoring the condition of the vehicle [11].

The basic assumptions of a combined approach are as follows:

- selected statistical parameters carrying diagnostic information can be used to build a multidimensional diagnostic space,
- the point of multidimensional diagnostic space is characterized by coordinates with the values of individual diagnostic indicators,
- 3 diagnostic indicators were selected for the analysis of the suspension status: Mean square value, Inter-quartile range and Amplitude.

The diagnostic space consists of three dimensions defined by three diagnostic indicators. Figure 7 shows an example of a space with points representing the damaged state of the vehicle.

Analysis of the distribution of points representing diagnostic indicators obtained during the process of condition monitoring during operation, relative to the reference point representing diagnostic indicators for a vehicle with nominal parameters, allows to draw an application on the current state of the vehicle.

Conclusions

Monitoring of the technical condition of railway vehicles is a necessity resulting from the requirements imposed by entities responsible for the safety of transport and passengers, operators implementing freight and passenger transport. Monitoring methods have been developed in the last dozen or so years both in the field of equipment and

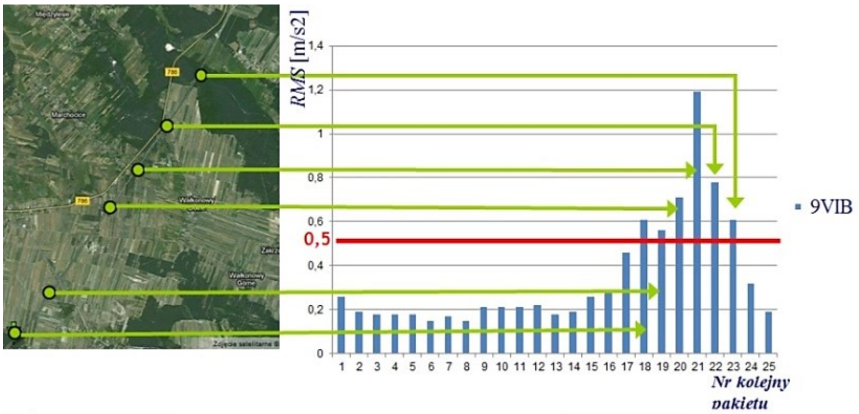

Fig. 6. List of transverse accelerations on the A-body, measured in the transverse direction, determined in the form of the mean square-mass value for July 5, 2012, along with an indication of places where the exceedances occurred

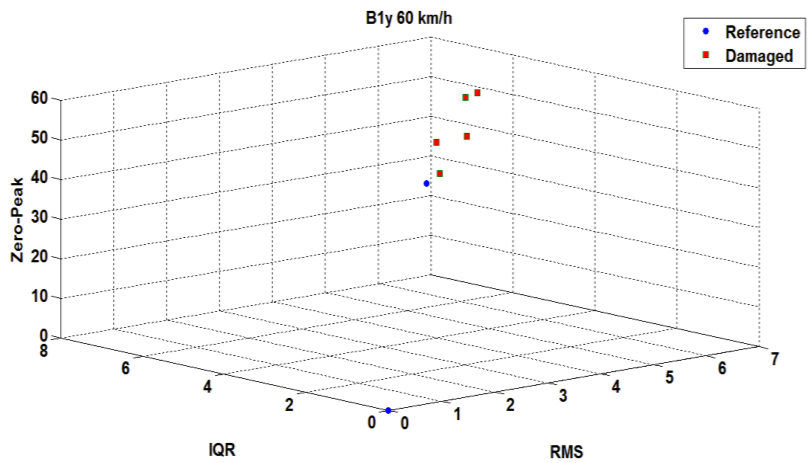

Fig. 7. Three-dimensional diagnostic space

software, but bearing in mind the costs of the monitoring process, it is important to choose the installed sensors and the time of analyzing the recorded signals so that the installation costs are acceptable to ordering vehicles with installed systems and monitoring could be performed in "on-line" mode. The article presents the process of building a system for monitoring the technical condition of a rail vehicle, bearing in mind the above-mentioned criteria. From the 7 possible points of registration of signals on a rail vehicle trolley, it was possible to reduce their number to 4 in the results of the research, and it was possible to reduce the number of statistical measures used to assess the suitability of the recorded signal from 9 to 4. This was possible by using in the process of designing a monitoring system, a simulation method of proto-type testing of such a system, which is based on the analysis of the model of the designed system. This made it possible to significantly simplify the structure of the system both in the equipment and program layer. The supervised operation of the ED74 type rail vehicle with the installed system prototype confirmed the validity of the adopted assumptions and allowed to assess the suitability of the defined diagnostic indicators. The directions of further work in the scope of corrections of the developed diagnostic method were also determined.

DOBÓR PUNKTÓW REJESTRACJI SYGNAŁÓW W PROCESIE MONITORINGU STANU POJAZDU SZYNOWEGO

W artykule omówiony został proces wyboru punktów na pojeździe szynowym, w których ulokowane będą czujniki rejestrujące sygnały, mając na uwadze późniejsze ich wykorzystanie w procesie monitorowanie stanu pojazdu a w szczególności elementów układu podatnego I i II stopnia usprężynowania. Liczba takich punktów oraz ich rozmieszczenie ma istotne znaczenie biorąc pod uwagę złożoność systemu monitorowania a tym samym koszty jego budowy i późniejszej eksploatacji a także możliwość wykorzystania zarejestrowanych sygnałów w procesie diagnozowania stanu technicznego pojazdu mając na uwadze funkcjonowanie takiego systemu w trybie on-line.

Słowa kluczowe: pojazd szynowy, punkty pomiarowe, monitoring stanu

BIBLIOGRAPHY

[1] Barszcz T., Uhl T. (2009) Założenia do specyfikacji systemu monitorowania i diagnostyki, Kraków

[2] Uhl T., Mendrok K., Chudzikiewicz A. (2010) Rail Track and Rail Vehicle Inteligent Monitoring System. The Archives of Transport, Vol. XXII No. 4, pp. 495-510

[3] Chudzikiewicz A., Droździel J., Sowiński B. (2012) Practical Solution of Rail Vehicle and Track Dynamics Monitoring System. STRUCTURAL HEALTH MONITORING II Book Series: Key Engineering Materials, tom 518, pp. 271-280

[4] Monitorowanie Stanu Technicznego Konstrukcji i Ocena jej Żywotności - MONIT, Program Operacyjny Innowacyjna Gospodarka, 2008-2012.

[5] Chudzikiewicz A., Sowiński B. (2011) Concept of online monitoring of railway vehicle suspension elements. 8th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, p. 49, Cardiff, UK, 20-22 June 2011

[6] Kisilowski J. (1978) Dynamika układu tor - pojazd. Prace Instytutu Transportu Politechniki Warszawskiej, z. 15

[7] Chudzikiewicz A. (2002) Elementy diagnostyki pojazdów szynowych. Biblioteka Problemów Eksploatacji, Warszawa - Radom 2002

[8] Droździel J., Sowiński B. (2006) Railway car dynamic response to track transition curve and single standard turnout. Computers in Railways X, WIT Press, Southampton, Boston. ISBN: 1- 84564-177-9, pp. 849-858.

[9] EN 14363: Testing for the acceptance of running characteristics of railway vehicles - Testing of running behavior and stationary tests. 2005

[10] Karta UIC 518: 2009, 4th edition, Testing and approval of railway vehicles from the point of view of their dynamic behavior - Safety - Track fatigue; Ride quality.

[11] Melnik R. (2013) Dobór parametrów statystycznych sygnałów pomiarowych w procesie diagnozowania stanu zawieszenia pojazdu szynowego. Rozprawa doktorska. Politechnika Warszawska, Warszawa