PROBLEMY KOLEJNICTWA

RAILWAY REPORTS Zeszyt 182 (March 2019) ISSN 0552-2145 (print) ISSN 2544-9451 (on-line)

Simplified Diagnostics of Drive Systems in the Operation of Railway Vehicles

Tomasz NOWAKOWSKI[1], Mateusz MOTYL[2], Artur BABIAK[3]

Summary

A special case of rail vehicle failures, often related to maintenance levels with partial disassembly of components, include damage to the drive system components, which is only manifested during driving. These cases are difficult to detect with standard stationary methods. The use of selection methods or diagnostic advanced for the location and identification of these failures can contribute to a significant increase in the service cost, which measurably affect the overall cost of vehicle operation. In such a case, it becomes necessary to minimize them, by determining only the degree of disruption to the functioning of individual elements of the vehicle's propulsion system. This will allow for locating the area of damage and take further service decisions. This article presents the results of the test implementation of a simplified control diagnostics of drive systems in the operation of a selected type of rail vehicle. The results of experimental studies based on vibration measurements of drive system components are presented. Based on them, it is possible to develop standard indicators of disturbance of the vehicle's propulsion system components for use in rolling stock control diagnostics.

Keywords: diagnostics, rail vehicle, vibrations, drive system

1. Introduction

The main task of rail vehicles operators is to maintain these vehicles in operable condition [8]. It is possible through conducting time-efficient and cost efficient maintenance operation. All this enables the implementation of foolproof transport process in an economic way. It is especially substantial in the case of systems, units and sub-assemblies, which have a significant impact on the running safety, i.e. running gear and propulsion system [5].

The implementation of operating work in the case of rail vehicles is carried out according to the documentation of the maintenance and the defined scope for the levels of sustainment. It is so-called preventive maintenance, whose structure is constant and independent of the state and age of the rolling stock (with the exception of the post-accident service), however it still facilitates the organization of the survey. Most of the work concerns the examination of the vehicle and the survey in stationary conditions. Those conditions make it impossible to obtain the whole picture of the state of the running gear and propulsion system. Many of the failures are revealed only in the process of driving. Depending of the range of the work, especially during the disassembly of the elements of those systems, the test drive is essential. However, without the diagnostic systems, which are based on the analysis of the vibrations, the process of the service is constricted and non-effective. It is due to the fact that the location of the failure is carried out by the method of selection (foreclosing of the next elements in analysis one by one). The diagnostics of vibration developing since the 70's enables the rating of the dynamic state of the machine, with the use of processes generated by those machines, without the need for the breakup [2].

It is possible to come up with a method, which would allow not only the location, but also the identification of the failure. The process of identification is much more complex and requires the conversance of many parameters of the examined object and the technics of signal-analysis. Currently, it is widely applied in the service of the industrial machines, by the identification of the mutilating of rolling bearing [2] or the elements of the powertrain [6], and the like. Such can also be seen on the railway [1, 3, 9].

---

[1] M.Sc.Eng., Institute of Combustion Engines and Transport, Poznan University of Technology; e-mail: tomasz.zb.nowakowski@doctorate.put.poznan.pl.

[2] M.Sc.Eng., Institute of Combustion Engines and Transport, Poznan University of Technology; e-mail: mateusz.motyl@put.poznan.pl.

[3] M.Sc.Eng.; Arriva RP; e-mail: artur.babiak@arriva.pl.

The location of the failure carries measurable information for the maintenance services, due to which there appear elements of powertrain that require more maintenance work. Thanks to that, it is possible to step aside from the method of the selection, which is often used in the process of location of the failure, which was not detected with the use of standard methods coming out from documentation of the maintenance. All this will also add to the change of the operation management focused on the enhancement of economic indicators [4].

The process of implementation of the simplified diagnostics described in the article, aims only to endow the support service work. This process is to determine the level of the disturbance of functioning of each elements of the propulsion system. This approach will allow only to locate the area in which there is a failure and to make further decisions oriented on diagnostics.

2. Research objects

The objects of the research were the powertrains of two single-switch, four axles rail vehicles of the same type, adjusted to the double-track ride. The first referential vehicle (R) was without malfunctions, whereas the second vehicle (N) was characterized by a malfunction on level P3 after the periodical checkup. In selected vehicles, the torque of the engine (A) is passed from the main gearbox (B) to the first gearbox (D) and the finishing one (E), through the intermediate shaft (C). The first gearbox is located on the second wheelset, and the ending one on the first wheelset. The simplified diagram of the powertrain was presented in Fig. 1.

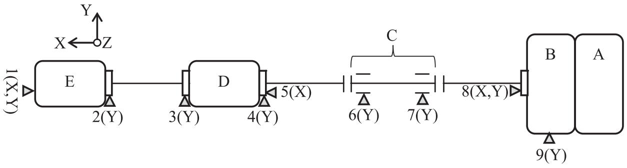

Fig. 1. Location of measurement points and their directivity: A – combustion engine, B – main gearbox, C – intermediate shaft, D –first gearbox, E – second gearbox [own study]

The malfunction of the vehicle N was defined by the support services workers as increased vibratory impact, noticeable on the body vehicle above the speed of 40 km/h above the drive bogie. Those impacts were increasingly falling after hitting 80 km/h. The examination of the technical state of the vehicle and the survey of the measurements' vehicle did not show any malfunctions. Further exploitation of the vehicle in described state significantly lowered the comfort of passengers, who complained about the unpleasant sensations during the ride. This article presents analyzes including the reduction of vibrations at the source. Currently, there are ways to improve ride comfort by reducing their transmission. There can be mentioned tests [9], which confirm the effectiveness of magnetorheological dampers in reducing vertical vibrations in comparison to passive systems.

3. Methodology

To cover the whole complex aspects of the research, the tests were carried out on the two vehicles, meaning the referential one and the one with malfunction. Both vehicles went through the test drive, during which the vibrations of the elements of the powertrain were recorded. The test drives were carried out without any breaks, the only pauses were the stops connected with the rail transport operations. The test track went through: Nowa Wieś Wielka – Inowrocław – Nowa Wieś Wielka (Poland). There were no passengers during the rides, only the support services were present. Weather conditions during the survey enabled to carry out the research without any impact on the quality of the research data. It ensured the repeatability of the measurements. The track of the test drive and the conditions of the movement were identical for both vehicles.

The research was based on the survey of the dynamical phenomenon of the elements of the powertrain, in the form of acceleration of the vibrations for the transverse and longitudinal directions. The location of the points of measurement and their direction against schema of the powertrain were showed in Fig. 1. Example realizations of measuring points are shown in Fig. 2.

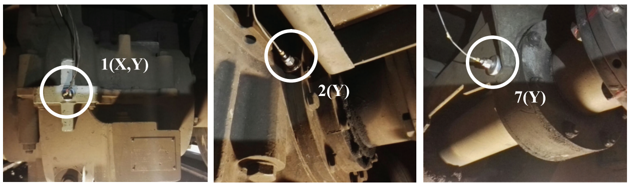

Fig. 2. An example of the implementation of measuring points on the drive system [phot. Of authors]

In the research the piezoelectric vibration transducers Brüel&Kjær, 4514-B, were used for measures in uni-axial and 4504A for tri-axial. The acquisition of signals and archiving of the measurements data was carried out with the use of PULSE® System 3560-C (Brüel&Kjær) with PULSE® Time Data Recorder software. The signals from all the measuring points were recorded synchronously in the frequency range of 1 Hz÷6,4 kHz, with the sampling of 16 384 Hz.

4. Analysis of the results

4.1. Qualitativean analysis

For the analysis of measurements results, the identical parts of measurements were selected, with different speed. Starting from 40 km/h to the maximum of 100 km/h with steps 10 km/h. To ensure the reliable conditions of the analysis, the signal from the part of each speed was characterized by the identical time of 10 sec. (+/–50 ms). Afterwards, the signals were filtered with band-pass filter of 1÷30 Hz. From the filtered signals the value of the root mean square for acceleration from all the points of measurements was computed, according to the formula:

$$a_{RMS} = \left[\frac{1}{n} \sum_{i=0}^{n} a_i^2 \right]^{\frac{1}{2}} \tag{1}$$

where:

a – amplitude of vibration acceleration,
n – number of samples of the analyzed signal.

The results for selected measurement points are presented in Table 1. The colors in this table mark the placement of the result in regards of the values elicited in the area of all speed and points of measurement. The gradient was set from green (the lowest value) to red (higher value), with the yellow meaning the result of 50 percentile. As it results from Table 1, the vehicle with failure (N), the highest value of a_{RMS} is 10.9 m/s^2 at the speed of 70 km/h in the point of measurement 6Y. Point 6Y is located on the intermediate shaft (C) from the side of the first gearbox (B). The second highest value of a_{RMS} at this speed is 7.7 m/s^2, which concerns the other side of the first gearbox. For comparison, this values with the ride of the referential vehicle (R) were lower speed by more than 70%.

While analyzing the values of the acceleration of vibration in the point 6Y, in the rest of the speed values there is noticeable a close connection with the remarks of maintenance workers form the test drives preceding the vibration research. While driving a vehicle with malfunction up to the speed of 80 km/h the values of vibration from points 6Y and 7Y on the intermediate shaft were dominant – higher than the

Table 1

Values of vibration acceleration a_{RMS} from measuring points for speeds from 40÷100 km/h

Speed [km/h]		a_{RMS} [m/s^2]										
		1X	1Y	2Y	3Y	4Y	5X	6Y	7Y	8X	8Y	9Y
40	R	1.50	1.49	0.35	0.30	0.29	1.11	3.59	0.74	1.22	1.20	1.71
	N	0.14	0.07	0.09	0.12	0.19	0.18	3.08	2.59	0.22	0.26	0.23
+/– [%]		90.8	95.0	74.4	61.0	32.8	83.9	14.4	71.6	81.9	78.0	86.5
50	R	1.75	1.60	0.09	0.13	0.12	0.08	2.22	0.70	0.28	0.18	0.21
	N	0.29	0.16	0.10	0.17	0.14	0.18	8.96	6.11	0.42	0.69	0.45
+/– [%]		83.2	89.8	5.7	19.8	14.1	58.4	75.2	88.5	33.8	74.7	52.3
60	R	0.68	0.34	0.49	0.39	0.45	0.41	1.65	0.25	0.17	0.23	0.18
	N	0.27	0.16	0.06	0.09	0.11	0.18	8.87	4.13	0.17	0.29	0.22
+/– [%]		61.1	53.4	87.3	76.1	75.8	55.6	81.4	93.9	1.5	20.5	18.9
70	R	0.28	0.42	0.16	0.07	0.07	0.15	1.81	2.19	0.08	0.47	0.29
	N	0.10	0.17	0.21	0.23	0.29	0.24	10.87	7.65	0.25	0.51	0.32
+/– [%]		64.6	60.5	25.4	70.6	77.2	38.9	83.3	71.3	67.3	7.0	11.7
80	R	0.23	0.23	0.19	0.47	0.67	0.21	0.93	0.72	0.26	0.15	0.12
	N	0.15	0.17	0.20	0.19	0.22	0.12	7.25	5.88	0.10	0.82	0.62
+/– [%]		34.4	23.1	5.4	60.2	66.6	39.2	87.2	87.7	63.8	82.0	80.5
90	R	0.21	0.24	0.18	0.16	0.22	0.25	0.89	0.50	0.18	0.35	0.19
	N	0.19	0.20	0.14	0.17	0.21	0.15	0.12	0.08	0.10	0.41	0.28
+/– [%]		11.3	15.3	21.5	6.5	5.8	39.5	86.7	84.2	45.6	12.5	31.2
100	R	0.30	0.32	0.31	0.25	0.36	0.26	0.37	0.39	0.09	0.54	0.30
	N	0.07	0.30	0.29	0.24	0.31	0.17	0.17	0.24	0.65	0.67	0.43
+/– [%]		75.2	7.9	5.6	5.2	13.2	34.5	52.3	38.4	85.6	20.4	31.6

R – reference vehicle, N – faulty vehicle [own stady].

rest of the measurement points by 80÷90%. For the speed of 90 km/h and 100 km/h the values of vibrations on the first gearbox were no longer dominant and lower by 70% in comparison to the maximum values for those speeds registered on the entrance of the shaft of the main gearbox. For those speeds the highest results were 0.4 m/s^2 and 0.7 m/s^2. For those speeds it is possible to locate the source of the escalated vibration influences in the powertrain, which is intermediate shaft.

The reference vehicle was a vehicle in its current operation in good technical condition. The vibration level of individual elements of its drive system can therefore be treated as a model defining the desired quality of the drive system operation. A dimensionless malfunction indicator of drive system elements in the operation (*FI*) at a particular measuring point was created. This indicator is based on the results of the vehicle under test and the results of the reference vehicle. To calculate *FI* it is necessary to normalize vibration values in relation to its maximum value observed for a particular speed in the data set of both vehicles, as in the formula:

$$FI_v = \frac{a_{RMS_i}}{a_{RMS_{\max}}} \tag{2}$$

where:

FI_v – dimensionless malfunction indicator for a particular speed v,

a_{RMS_i} – vibration level value for a particular measurement,

$a_{RMS_{\max}}$ – maximum value of vibration level from all measurements of a particular speed.

The status of the *F* vehicle has been defined, i.e. the failure status f^1 and the non-failure status f^0, as follows:

$$F = \{f^1, f^0\} \tag{3}$$

It was assumed that the failure occurrence status f^1 reaches a point whose *FI* indicator is less than –0.3:

$$FI = \{x : x \in (-1,1)\}\,, \tag{4}$$

$$f^1 = \{FI\colon FI < -0{,}3\}. \tag{5}$$

The calculated *FI* indices are presented in Table 2. The *FI* indices indicating the occurrence of disturbance f^1 were distinguished in this way.

The data showed in Table 2 confirm foregoing conclusions concerning the failure of the intermediate shaft. The smallest levels of the *FI* concerned the points 6Y and 7Y, in the speed from 40 km/h to 80 km/h. Whereby the results of analysis are more readable and their interpretation is clear-cut. What is more, in the point 8X there are noticeable malfunctions of operation (main gearbox) at the speed of 100 km/h.

4.2. Qualitativean analysis

The qualitative analysis was carried out taking into account the results of the quantitative analysis. First, spectral analysis of selected vibration signals was performed using the Fast Fourier Transform (FFT) algorithm. The analysis was carried out with a spectral resolution of 0.625 Hz for signals filtered by a band pass filter with a bandwidth of 1÷30 Hz. The analysis was carried out in a short time with a record length of 1.6 seconds and an interval of 781.3 µs.

The results of the analysis have shown that the significant measuring point is the 6Y point on the intermediate shaft. The results of the spectral analysis of the filtered signal registered at this point for both tested vehicles from the sections for driving at a speed of 40 km/h are shown in Fig. 3.

As shown in Figure 3, the highest amplitude of 6.6 m/s^2 in the spectrum is characterized by a 6Y signal, recorded from the vehicle with malfunction. The amplitude characterizes the signal registered in the ref-

Table 2

***FI* indicators of all measuring points depending on the speed**

Speed [km/h]	Measurement points										
	1X	1Y	2Y	3Y	4Y	5X	6Y	7Y	8X	8Y	9Y
40	0.4	0.4	0.1	0.1	0.0	0.3	0.1	–0.5	0.3	0.3	0.4
50	0.2	0.2	0.0	0.0	0.0	0.0	–0.8	–0.6	0.0	-0.1	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	–0.8	–0.4	0.0	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0	0.0	–0.8	–0.5	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	0.1	0.0	–0.9	–0.7	0.0	-0.1	-0.1
90	0.0	0.0	0.0	0.0	0.0	0.1	0.9	0.5	0.1	-0.1	-0.1
100	0.3	0.0	0.0	0.0	0.1	0.1	0.3	0.2	–0.8	-0.2	-0.2

[Own study].

erence vehicle was much smaller by 79%. Both signals were characterized by a frequency of about 20 Hz.

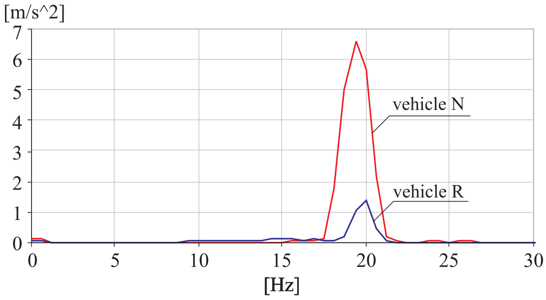

Fig. 3. Signal spectrum for the 6Y measurement point at 40 km/h; main components: vehicle N – 19.38 Hz, 6.6 m/s^2, vehicle R – 20.00 Hz, 1.4 m/s^2 [own study]

Analogous calculations were made for signals from a failure vehicle characterized by the highest values of a_{RMS}, i.e. for signals from a speed of 70 km/h (Figure 4).

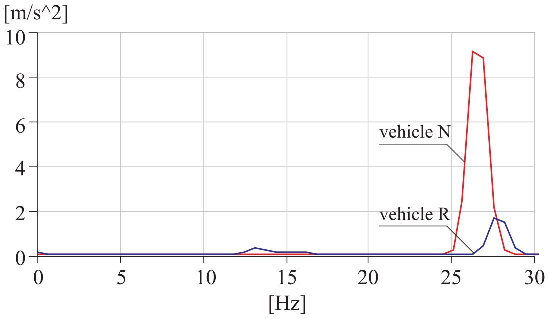

Fig. 4. Signal spectrum for measuring point 5 at the speed of 70 km/h; main components: vehicle N – 26.25 Hz, 9.2 m/s^2, vehicle R – 27.50 Hz, 1.6 m/s^2 [own study]

As shown in Figure 5, the highest amplitude value in the spectrum of 9.2 m/s^2 is characterized by a signal recorded from a vehicle with a failure. The significantly lower (by 83%) amplitude characterizes this signal recorded from the reference vehicle. The frequencies of both signals are similar and value to approx. 27 Hz.

In addition, the spectra of signals from the vehicle with failure were compared with all measurement points registered on the driving section at a speed of 70 km/h, as shown in Figure 5.

As shown in Figure 5, the highest frequency components concern the 6Y and 7Y measuring points located on the intermediate shaft. Their frequency is about 26.5 Hz. Other measuring points are not characterized by higher amplitudes. The next highest amplitude was characterized by the 8Y signal and was 96% lower than the amplitude of the 6Y signal.

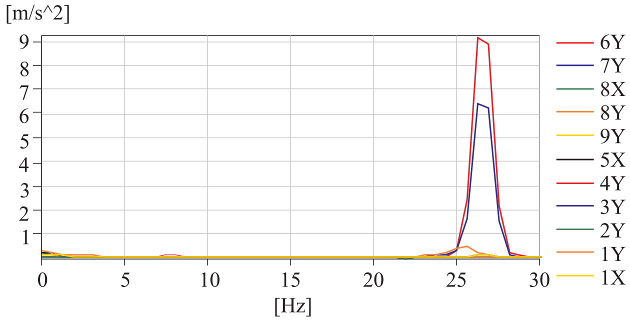

Fig. 5. Signal spectra for all measuring points on an inoperative vehicle at a speed of 70 km/h [own study]

5. Summary and conclusions

The diagnosis process based on the drive system vibration analysis was implemented at the test drive stage, which is an inseparable part of the standard repair service. This allowed the location of failures in the form of unbalance of the intermediate shaft, the detection of which is not possible in stationary conditions in the service depot. The effectiveness of the implemented simplified diagnostics for the discussed case can also be presented in the costs of maintenance work, as shown in Figure 6.

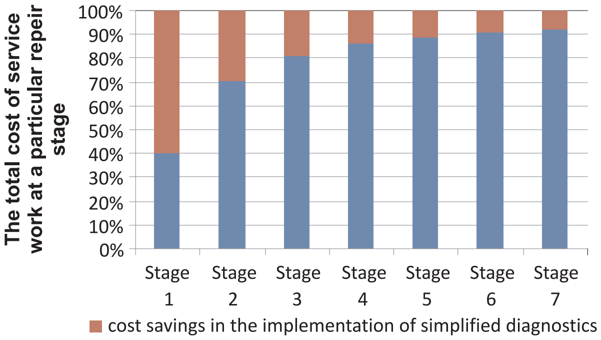

Fig. 6. Maintenance costs for particular stage of service work against the cost of implementation of simplified diagnostics [own study]

Taking into account standard maintenance procedures, the cost of service work related to the replacement of the intermediate shaft (stage 1) would be 40.2% higher compared to the actual service work taking into account the results of simplified diagnostics. In this case, it is not necessary to carry out additional test drives of the vehicle in order to check the correctness of the servicing work. In the case of replacement of all shafts using the selection method (step 1÷4), the cost of service work would exceed 85%. Taking into account the additions of all transmissions (stage 5÷7), the cost would have been 91.6% higher.

The presented results indicate the possibility of an effective implementation of simplified diagnostics in the process of drive systems operation. The presented results make it possible to analyze the data in quantitative terms basing on the *FI* indicator and in qualitative terms by analyzing the amplitudes of vibration accelerations in relevant frequency ranges. Both approaches make it possible to located failures in a manner unambiguous with high dynamics of changes in observed parameters. The method based on the *FI* indicator is more intuitive due to the analysis only in the time domain. The implementation of simplified diagnostics allowed to obtain in the described case about 40% lower costs of service work compared to currently used selection methods. It should be added that the main goal of simplified diagnostics was only the location of the failure. The vehicle's readiness for use and the improvement of the passengers' comfort are not measured, but is an important parameter by eliminating the direct impact of increased dynamic interactions on the vehicle's body.

Literature

1. Amin A., Entezami M., Papaelias M.: *Onboard detection of railway axle bearing defects using envelope analysis of high frequency acoustic emission signals*, Case Studies in non Destructive Testing and Evaluation, 6 (2016) 8–16. doi:10.1016/j.csndt.2016.06.002.
2. Cempel C.: *Podstawy wibroakustycznej diagnostyki maszyn*, Wydawnictwo Naukowo-Techniczne WNT, Warszawa, 1982.
3. Chudzikiewicz A., Deuszkiewicz P., Radkowski S.: *Wieloparametrowa diagnostyka wibroakustyczna stanu technicznego łożysk tocznych pojazdów szynowych*, Napędy i Sterowanie, nr 5 (2000).
4. Drelichowski L., Bojar W., Żółtowski M.: *Elementy zarządzania eksploatacją maszyn*, Wydawnictwo Uczelniane Uniwersytetu Technologiczno-Przyrodniczego w Bydgoszczy. (2012). http://www.wimpoig.utp.edu.pl/ [dostęp 14.05.2018].
5. Knothe K., Stichel S.: *Rail Vehicle Dynamics,* Springer International Publishing, Cham, 2017, doi: 10.1007/978-3-319-45376-7.
6. Liu B., Riemenschneider S., Xu Y.:*Gearbox fault diagnosis using empirical mode decomposition and Hilbert spectrum*, Mechanical Systems and Signal Processing, 20 (2006) 718–734, doi:10.1016/j.ymssp.2005.02.003.
7. Sharma S.K., Kumar A.: *Ride comfort of a higher speed rail vehicle using a magnetorheological suspension system*, Proc. Inst. Mech. Eng. Part K J. Multi-Body Dyn. (2017). doi:10.1177/1464419317706873.
8. Zalewski A., Siedlecki P., Drewnowski P.: *Technologia transportu kolejowego*, WKŁ, Warszawa, 2003.
9. Zhang B., Tan A.C.C., J. hui Lin: *Gearbox fault diagnosis of high-speed railway train*, Engineering Failure Analysis, 66 (2016) 407–420. doi:10.1016/j.engfailanal.2016.04.020.

Acknowledgements

All presented work is partly funded by Statutory Activities fund of the Institute of Combustion Engines and Transport, PUT (PL) 5/52/DSPB/0259.