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A METHOD FOR EVALUATING THE TECHNICAL CONDITION OF WHEEL RIMS IN SLOW MOVING VEHICLES BASED ON MODAL PARAMETERS

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Summary

The aim of this study was to develop a non-invasive method for analyzing the technical condition of wheel rims in slow-moving vehicles. A vibration spectrum analysis was carried out in the frequency domain of wheel rims which were subjected to vibrations within a given range of parameters. Free vibration frequency and decrement in damping were determined to evaluate the rigidity and damping of the examined wheel rims. Those parameters were applied to evaluate weld joints, detect fatigue cracks and structural damage to the analyzed wheel rims. The proposed method can be used to inspect both brand new and used wheel rims in passenger cars, special purpose vehicles and slow moving vehicles. The developed method is non-invasive, and it does not cause damage to the tested object. The time required to perform measurement is will depend on the size of the wheel rim, but it should not exceed 20 seconds.

Key words: modal analysis, resonant frequency, damping decrement, wheel rim inspection

METODA BADANIA STANU TECHNICZNEGO OBRĘCZY KOŁA Z WYKORZYSTANIEM PARAMETRÓW MODALNYCH

Streszczenie

W artykule przedstawiono koncepcję nieinwazyjnej metody identyfikacji stanu technicznego obręczy kół, w celu wyznaczenia ich aktualnego stanu technicznego. Procedura badawcza obejmuje analizę widma drgań w dziedzinie częstotliwości uzyskanej z badanej obręczy koła, poddanej wymuszonym drganiom mechanicznym o określonych parametrach. W wyniku analizy i obliczeń wyznaczona została częstotliwość drgań własnych oraz dekrement tłumienia badanej obręczy koła, co pozwoliło ocenić sztywność i tłumienie obiektu. Na podstawie tych parametrów określony został aktualny stan połączeń (spawanych, zgrzewanych) oraz zidentyfikowano pęknięcia badanej obręczy koła lub utratę ciągłości struktury. Metoda ta ma mieć zastosowanie do badań zarówno obręczy nowych jak i używanych, pojazdów samochodowych, specjalnych i wolnobieżnych. Metoda badawcza jest nieinwazyjny oraz nie będzie powodował uszkodzeń obiektu badań. Czas pomiaru będzie uzależniony od wielkości obręczy koła, ale nie powinien przekraczać kilkunastu sekund.

Słowa kluczowe: analiza modalna, częstotliwość rezonansowa, dekrement tłumienia, diagnostyka obręczy kół

1. INTRODUCTION

Cold-formed sections are one of the most popular structural elements in engineering. They have a wide range of applications, including in pressure gauge connectors for pipelines, fixtures for photovoltaic and solar panels, traffic signs and billboard posts. Cold-formed sections are also used in highly complex engineering projects such as airplane wings, rotor blades and wheel rims.

Wheel rims are critical determinants of driving safety and vehicle operation safety, and they should be inspected during manufacture and use. Unfortunately, such strict rules are observed only in motorsports where the safety of drivers and the audience is prioritized. In professional racing and motorsports, wheels are inspected visually by qualified and experienced technicians before they are installed on vehicles. Teams of technicians monitor the number of wheel service hours and inspect wheel rims before every fitting. Wheels are inspected by ultrasound scanning and penetrant testing to detect cracks and structural deformations that are not visible to the naked eye. Wheel rims showing any signs of fatigue or damage are scrapped and replaced. In racing events such as Indy Car or F1, brand new wheel rims have to conform to strict requirements, and their service time has to be closely monitored. In line with the technical regulations observed during the above events, wheel rims should be scrapped every 500 miles (800 km). Similar rules apply during road racing events, but longer service times are allowed.

Unfortunately, such rigorous control procedures are not observed in normal vehicular traffic. Wheel rims rarely cause trouble, which is why they are disregarded by most drivers. A long service life and high operating load can ultimately lead to wheel rim damage.

Wheel rim fatigue results from the combined effect of load and loading cycles. Wheel rims subjected to small loads remain in good operating condition for thousands of cycles, whereas wheels exposed to heavy loads are much more prone to fatigue, and the number of cycles to failure (structural damage) is significantly decreased [14].

Wheel rims undergo the greatest deformation during sharp turns. The deformation of wheel rims and disks is relatively low in normal traffic and off-road. Contemporary tires are similar to racing tires from the past, and every turn made at the threshold of tire traction with the surface of the road leads to significantly greater deformation of wheel rim elements. Skidding (excessive application of engine power), crossing hard obstacles (curbs, tracks, terrain drop), off-road driving and vehicle operation at maximum speed and load (chassis dynamics) expose wheel rims to additional load. Wheel rims dissipate the heat of breaking and under extreme conditions, they are heated to temperatures that are not encountered during normal operation. Those cyclic changes in temperature, longitudinal and lateral load, and operating conditions speed up wear and reduce the service life of wheel rims.

In vehicles that are driven under normal conditions, wheel rims are generally removed every 10,000 km during seasonal tire change and are replaced every 40,000-65,000 km. In motorsports, wheels are removed at the beginning and end of every racing day, during every repair, break service and car lift. The fitting process also has a negative influence on wheel rims, mainly the wheel disk, because it speeds up the wear of screw slots and the opening in the center of the disk.

The aim of this study was to identify the parameters and diagnostic signals which are used to detect structural damage to weld joints connecting the wheel rim with the wheel disk. The author proposed a method for selecting the optimal diagnostic signals and their parameters in the process of describing structural damage to parts subjected to mechanical vibration.

Monitoring methods for detecting and predicting the condition of support structures have become an important area of research. Structural damage to machines and machine parts can be prevented through early detection of fatigue cracks [1, 13] with the use of non-destructive methods. Conventional methods such as penetrant tests, magnetic inspections and ultrasonic tests have their limitations. Some of them are expensive and produce ambiguous results. Alternative methods which identify vibration waveforms and parameters may be a rapid, effective and convenient diagnostic tool for detecting fatigue cracks in machine parts and structural systems.

There are two main types of crack detection methods: linear methods which investigate vibrations in an object and measure changes in modal parameters relative to initial values, and non-linear methods which are frequency response analyses [1, 2, 7, 8, 11, 14]. In the first approach, a crack is always presumed to be open, and it is modeled as local rigidity loss [4]. The size of the crack and its location are analyzed and described based on changes in modal parameters such as natural frequency [9], damping coefficient [10] or rigidity [6]. This approach has two major limitations. Firstly, changes in free vibration frequency are significant only for large cracks [3, 15], and secondly, an intentional shift of free vibration frequency cannot be fully ascribed to the cracking process and can also be caused by other factors, such as corrosive wear and relaxation.

It is generally believed that vibration theory is correlated with modal parameters of the system: free vibration frequency, damping and waveform. This physical system consists of the physical properties of a structural object (mass, rigidity and damping). The modeled parameters are homogeneous systems that can also be described by differential equations of motion in a physical model relative to its mass, damping, rigidity, acceleration, velocity and displacement. For this reason, all changes in modal parameters are directly proportional to changes in the physical properties of a modeled object that result from damage.

The problem of identifying structural damage based on changes in vibration has been widely addressed in the literature [5, 16, 17, 19]. In this approach, vibration parameters of objects are described, and structural damage is defined as a function of changes in an object’s structural parameters, such as rigidity and mass. The presence of structural damage influences the vibration response and the dynamic parameters of a given structural object. Dynamic parameters include natural frequencies as well as damping mode shapes and ratios. Those parameters are used to identify damage to a structural object. Early damage detection during production or operation supports timely repair and extends the life of the system.

A system has to be inspected and serviced on a short-term, mid-term and long-term basis to guarantee that it is operated safely and reliably. Rigidity is one of the main dynamic properties which can induce changes in shape and frequency reduction mode, and it can increase the damping coefficient. This approach was used to evaluate the technical condition of wheel rims in passenger cars and special purpose vehicles during manufacture and operation.

2. MATERIALS AND METHODS

2.1. Aim of the study

The aim of the experiment was to identify diagnostic signals and determine their parameters for the purpose of detecting defective weld joints between the wheel rim and the disk. Analyses of wheel disk defects revealed that incomplete fusion between the disk and the wheel rim is responsible for the absence of connections between one or several disc ribs and the rim. In brand new rims, such defects are caused by inappropriate welding parameters during manufacture. Defects of the type are difficult to detect, but they do not render the wheel rim unsuitable for use. During operation, damage to a wheel rim is usually caused by overloading or extreme driving conditions. Such defects are also observed in wheel rims with a specific service life. The loss of connection between disc ribs and the rim can result from fatigue cracking or changes in structural integrity caused by other factors, such as corrosive damage to the weld, disc or rim.

2.2. Experimental procedure and equipment

The modal parameters of a wheel rim were examined in a wheel balancing machine. The analyzed objects were Polkar Warmia 12x4.25 wheel rims designed for agricultural and heavy duty vehicles where wheel disks have four ribs and are joined with the wheel rim by fillet welds. Four sets of wheel rims were used in the experiment, and every measurement was conducted in five replications. The evaluated rims differed in the number of welds connecting the wheel disk with the rim:

W1 (1/4) – three ribs not joined with the wheel rim,
W2 (2/4) – two ribs not joined with the wheel rim;
W3 (3/4) – one rib not joined with the wheel rim;
W4 (4/4) – all ribs joined with the wheel rim.

The modal parameters of wheel rims were analyzed in response to mechanical vibration induced with an impact hammer.

Wheel rims were mounted onto the spindle shaft of the balancing machine through the central opening in the wheel disk and were secured with a quick-locking nut. The test stand, the wheel rim and the distribution of weld joints between the disk and rim are shown in Figure 1.

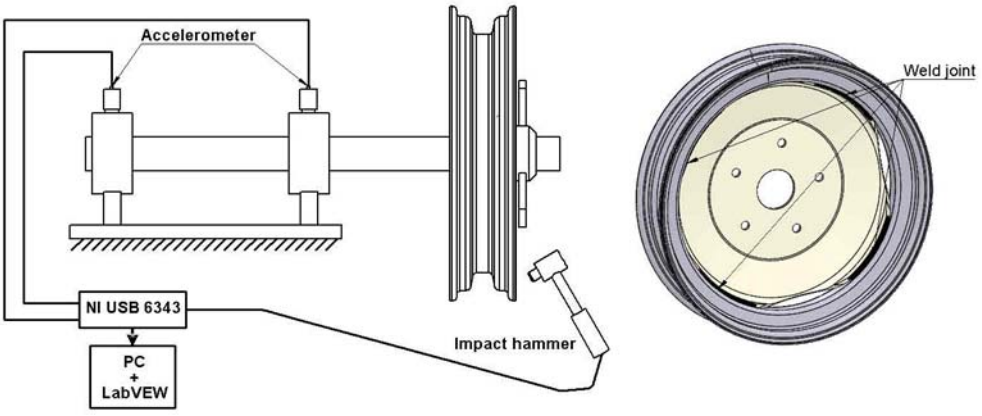

Fig. 1. Test stand and distribution of weld joints between the disk and rim of a 12x4.25 wheel

The balancing machine was provided with two piezoelectric accelerometers (ICP-100, 100 mV/g) for registering vibrations in the horizontal plane on both bearing units of the spindle shaft in the wheel balancer.

The wheel rim was mounted on the spindle shaft of the wheel balancer, and it was hit with an impact hammer (with known mass and fixed initial angular displacement). The wheel rim was set into vibration which was registered by accelerometers on the spindle shaft. The signal registration procedure in the LabVIEW environment was initiated when the wheel rim was hit with the impact hammer. Rim excitation energy was 0.5±0.1 J. Sampling rate was 2 kHz per channel.

3. RESULTS

The acceleration and frequency characteristics of the analyzed wheel rims’ responses to vibration were subjected to quantitative and qualitative analyses. The results are presented in Figure 2 for wheel rims with a different number of weld joints between the rim and the disk.

The results of the analysis were used to determine the free vibration frequency of 12x1.25 wheel rims with a different number of weld joints connecting disc ribs to the rim. The results are presented in Table 1.

The acceleration and frequency characteristics of the evaluated wheel rim variants were compared to determine the relationship between the presence of weld joints connecting the disk to the rim and free vibration frequency. An inverse relationship was observed: the smaller the number of weld joints between disc ribs and the wheel rim, the higher the free vibration frequency. The analyzed wheel rim variants were also characterized by different vibration spectra in the amplitude and frequency analysis.

The logarithmic decrement in damping for different wheel rim variants was determined based on the results of direct measurements. It was defined as the ratio of the absolute values of two successive extreme displacements. The results are presented in Table 2 and Figure 3.

The diagram indicates that the logarithmic decrement in damping decreases with an increase in the number of weld joints between the wheel disc and the wheel rim. The small differences between logarithmic decrement in damping in variants W1, W2 and W3 resulted from the sampling location (bearing units of the spindle shaft in the wheel balancing machine) and high damping between the signal source and the sampling location.

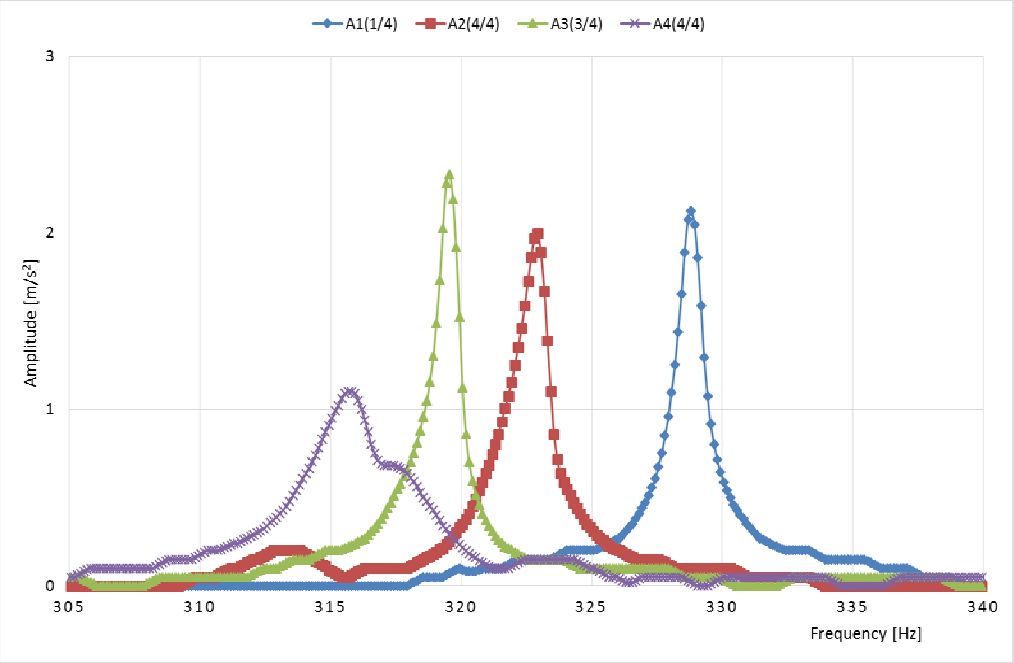

Fig. 2. The results of the FFT analysis of 12x4.25 wheel rims with a different number of weld joints between the rim and the disk (fragment of the spectrum).

Table. 1. Free vibration frequency of 12x4.25 wheel rims with a different number of weld joints between the disc and the rim.

Variant	**Free vibration frequency f_o [Hz] – average value**	**Standard deviation**
	for the analyzed wheel rims	
W1 (1/4)	329.1	1.556
W2 (2/4)	323.4	2.546
W3 (3/4)	319.5	1.768
W4 (4/4)	316.1	1.414

Table 2. Logarithmic decrement in damping for different wheel rim variants.

Variant	**Logarithmic decrement in damping δ – average value**	**Standard deviation**
	for the analyzed wheel rims	
W1 (1/4)	0.002547	0.000264
W2 (2/4)	0.002873	0.000410
W3 (3/4)	0.007076	0.000784
W4 (4/4)	0.049467	0.005660

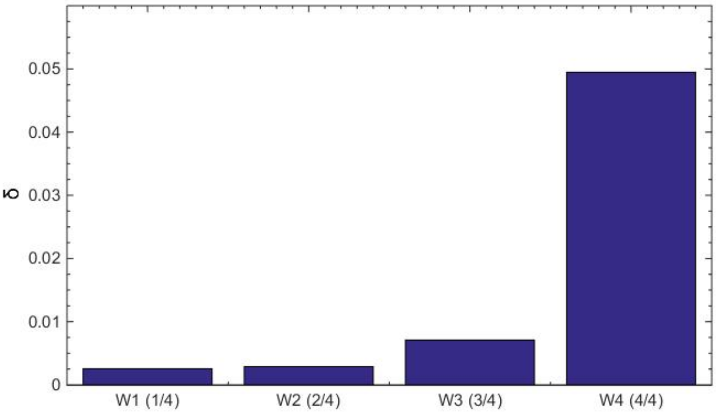

Fig. 3. Average decrement in damping for 12x4.25 wheel rims with a different number of weld joints between the disk and the rim

4. CONCLUSION

The following conclusions can be formulated based on the results of this study:

- the number of weld joints between wheel disc ribs and the wheel rim influences the FFT spectrum and the free vibration frequency of the wheel rim;
- the results of the analysis performed in the study cannot be used to determine which weld joints (disc ribs) are missing in the analyzed wheel rims, but can only be used to ascertain that not all joints are present;
- acceleration and frequency characteristics were used to describe the relationship between the number of weld joints connecting the wheel disc with the wheel rim and free vibration frequency. An inverse relationship was observed: the smaller the number of weld joints connecting disc ribs with the rim, the higher the free vibration frequency;
- a vibration spectrum analysis of the examined wheel rims revealed that the registered vibrations were composed of two waveforms: waveforms related to the test stand (low frequency) and the examined rim (high frequency), which significantly obstructed the calculation of the logarithmic decrement in damping;
- the logarithmic decrement in damping decreased with an increase in the number of weld joints connecting disc ribs to the wheel rim (greater system damping);
- the wheel rim is the optimal sampling location for analyzing the logarithmic decrement in damping, which was confirmed by the results of the preliminary study. However, this signal source requires the application of a contactless measurement system, which is presently not economically or technologically justified in industrial applications of the presented method;
- the proposed method can be used to determine the modal parameters of both brand new (during manufacture – the presented method is being implemented in the quality control system of Polkar Warmia) and used wheel rims;
- the proposed method can also be used to conduct periodic inspections of wheel rims (structural damage resulting from fatigue cracks, corrosion or wear) and diagnose other rim defects in technical facilities.

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