Analysis of Sound Power Level Changes Caused by Wheel with Flat Spot Using Numerical and Physical Experiment

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Abstract: Damage to the running surfaces of wheels on railways poses a threat to road safety. They can lead to accidents and disasters. Wheels with a flat spot are the biggest threat. The paper reviews problems that arise when wheels with a flat spot come into contact with a rail, and the methods of their detection and diagnosis. However, the known methods for their determination are still very complex and not precise enough. The research presented is based on previous theoretical studies, during which a simplified mathematical model of the normal force arising from the contact of a wheel with a flat spot with a rail, assuming that as a result of this, a change in sound power is caused was developed and theoretical calculations were performed. It theoretically determined wheel damage during rolling caused by wheel-induced changes in associated sound power, i.e., preliminary values of diagnostic parameters and applied methods. Although initial theoretical research already exists, there was a lack of physical experiments to support the validity of the results of the theoretical model. This work presents the original plan and methodology of the physical experiment performed. A physical experiment performed with the ATLAS LG system and sound pressure measuring equipment showed the suitability and applicability of the theoretical model for the determination of wheel damage.

Keywords: diagnostic; rolling wheel; flat spot; railways; detection; ATLAS; acoustic measurement; sound power

1. Introduction

The wheel/rail interaction between rolling stock is crucial for road safety, train stability, noise and comfort. As rolling-stock weights and speeds increase, solutions to these interoperability challenges are becoming increasingly relevant. The dynamic processes between track and vehicle are mainly influenced by the force acting on the contact between the wheel and the rail. They depend on the road, the physical and mechanical properties of the wheel, the speed of movement of the wheel and the geometrical parameters. Geometrical parameters are the smoothness and defects of the rail and wheel running surfaces. There is a smooth interaction and smooth predicted dynamic processes for an ideally smooth running surface of a wheel when running at an ideal level on a rail, but when irregularities (defects) occur, the interaction becomes uneven. The forces acting on it range from variable to shock, resulting in vibration noise. In the event of major defects and impact forces (up to several times the original), contact is even lost, which already
poses a risk to road safety, as loss of contact can cause the vehicle wheel to derail and cause an accident. Minor defects in road and wheel operation due to various reasons (sudden braking, defects etc.) increase, so their timely detection and elimination is necessary.

Monitoring of rolling-stock wheels with rolling surface defects and operation restrictions increase the one-off and fatigue (toughness) resistance of the most important structural rolling-stock and track elements. Automated systems for detecting wheels with running surface defects are being developed and used based on the detection of an increase in wheel load on the rail. The WIM-WIM [1], ATLAS LG [2], AGUILA [3] and WILD [4] systems measure (directly) the applied forces, while the other systems—the derived parameters of the change of these forces—measure deviations (LASCA [5]).

Russia began using the PAK system (operation of the acoustic control system for freight car bearings) [6]. It monitors the defects of the bearings of the axle boxes of the passing trains by analyzing the data of the acoustic noise, produced by the vibration of the bearings of the axle box (Shaporov et al. [6]). The German and Dutch company, Muller MMB (Munich, Germany) [7], has also developed an acoustic diagnostics system. However, it is intended for diagnosis of passenger trains. Vibration sensors are installed on wagons, and the changes of acoustic parameters are monitored for each wheel individually. However, this method is not suitable for cargo transport, because wagons are traveling through different countries and it is not possible to regulate the data transmission [7].

In 2010, Greek scientists (Bollas et al. [8]) performed research with the objective to determine the defects and cracks of the wheels in use based on the acoustic noise they generate. The testing data and evaluations are published in this article. During the testing, acoustic noise produced by wheels of the rolling stock (with and without defects) was measured. Even wheels without defects produce noise as they roll along the rail, so this sound is used as a reference when comparing the noise produced by the wheels that have defects. Rolling stock with wagons was moving at different speeds. Sensors attached to the rail neck at the sides of the rail were used to perform measurements. High frequency (30 to 1000 kHz) piezoelectric sensors were used during testing. The R3i, R15, R30 and R50 sensors manufactured by the USA-based company Physical Acoustics Corporation were used. They can record and send to the hard disk signals that are longer than 10 s. The data were collected, recorded and processed using AE-Win and Noesis software, manufactured by the same manufacturer (which manufactures the sensors). Data for this research were collected from three sources in three different locations: two trains and one tram. The research showed that using these sensors installed on the rails can potentially detect the defects of the wheel geometry, e.g., flat spots.

In 2015, Ukrainian scientists (Bondarenko et al. [9]) announced that they had developed a moving wagon wheel defect diagnostics system based on the acoustic sound. They installed microphones under the wagon frame above the wheelset and recorded sound, which was analyzed by the sound analyzer and transmitted through GPS to the control posts. However, this method is only suitable for passenger trains, metro and tram, because these wagons have a permanent location of deployment.

A Russian company claims to have equipment that can help register the data needed to detect wheels with defects. Their offered scheme is provided (Buriak [10]). It uses six BC 501 microphones and two RF603 optical sensors to detect the movement speed and position of the rolling stock; acoustic noise spectrum analyzer Zet017-u8 and Zetlab software are used to process the data.

All of these methods show that such faults can be detected; however, the parameters that allow for clearly determining if the wheelset is defective or not, have not yet been established. Therefore, further research is needed to determine these parameters.

2. Tasks and Objectives of the Work

For the determination of forces (Petrenko and Kukėnas [11]), many different dynamic models of wheel–rail interaction, mathematical models of wheel with flat spot are used, all of them are connected by the fact that vertical dynamic impact forces caused by wheel
or rail defects can increase 3–4 times as compared to the case when the wheel has no defects [11]. Currently, there is an increasing focus on research into the sound generated by wheel–rail interaction forces and attempts to use the results of this research to diagnose wheel defects.

It was determined that the change of the sound power depends on the changes of the forces that occur when the wheel and the rail are interacting. Based on this change, a theoretical model to determine the change of the sound power was established [11]. The objective of the work is to verify the numeric model noted for determining the sound power change by the physical experiment. Three tasks were established for achieving this objective:
- Prepare the plan of the experiment, taking into account the overview of the literature;
- Perform the experiment;
- Perform the analysis and compare it with the results of the theoretical model.

3. Sound Power Change Calculation Model and Plan of the Experiment

3.1. Sound Power Change Calculation Model

The period of repetition of turning and impact forces of a wheel defect on the rail [10,12] is:

$$T = \frac{L_{\text{ried}} - L_F}{v}$$  \hspace{1cm} (1)

where \(L_{\text{ried}}\) is the length of the wheel rolling surface, \(L_F\) is the defect length and \(v\) is the wagon speed.

The angular speed of the wheel \(\omega\) can be calculated:

$$\omega = \frac{v}{R_W}$$  \hspace{1cm} (2)

where \(R_W\) is the wheel radius.

The effect of the wheel defect on the rail is:

$$f = \frac{1}{T}$$  \hspace{1cm} (3)

The sound power level \(L_{\text{sw}}\) is calculated from the total energy of the sound source \(W\) (radiated in all directions over a period of time) [13]:

$$L_{\text{sw}} = 10 \log_{10} \left( \frac{W}{W_{\text{ref}}} \right)$$  \hspace{1cm} (4)

where \(W_{\text{ref}}\) is the reference (background) sound level energy, which is usually \(10^{-12}\) W.

Vibration theory allows for substituting the sound source energy \(W\) (radiated in all directions during the period of time) with other parameters that have linear dependency on energy.

Assuming that \(W = W(F)\), \(W = a \cdot F\) and \(W_{\text{ref}} = a \cdot F_{\text{ref}}\), then

$$L_{\text{sw}} = 10 \log_{10} \left( \frac{F}{F_{\text{ref}}} \right).$$  \hspace{1cm} (5)

where \(W\) is the full sound source energy (radiated in all directions during the period of time), \(W_{\text{ref}}\) is the reference (background) sound level energy, \(a\) is the linear coefficient of the energy dependency on the force, \(F\) is the impact force of a wheel with a defect into a rail and \(F_{\text{ref}}\) is the reference constant wheel force acting on the rail.
Because the sound power change $L_{w}$ in the source is already known, and we can physically measure the sound pressure change $L_{p}$ or sound pressure $P$ at some distance from the source $r$. They can be calculated using the following equations:

\[
L_{p} = L_{w} - 10 \log \left( \frac{Q}{4\pi r^{2}} \right),
\]

where $Q$ is the coefficient that depends on the number of reflecting surfaces in the environment (Figure 1) and

\[
L_{p} = 10 \log_{10} \left( \frac{P}{P_{\text{ref}}} \right).
\]

Using Equations (6) and (7), we can calculate the sound power change $L_{w}$ in the source, if we know the physically measured sound pressure change $L_{p}$.

### 3.2. Sound Power Change Experiment Plan

A plan for the physical experiment was developed to verify this model according to the reviewed vibroacoustic measurement methods and ways of detecting the wheel defects. Obviously, to successfully perform a physical experiment, two different measurements are required. These are the measurement of the forces acting on the rail and the acoustic measurement. It is the only way to make sure that the wheelsets of the rolling stock have defects, what forces are acting on them at that moment and check their dependency on the generated sound. As VGTU has only the equipment to measure the sound pressure or sound pressure level, we addressed the operator of the Lithuanian railways infrastructure with a request to use the system ATLAS LG, which they are operating. This system measures the forces acting on the rail, the weight, movement speed of the rolling stock, time of registering the defect and the distance.

The plan of the experiment and process follows:

1. The physical experiment and data recording used the noise (sound pressure) meter to record the cargo trains passing one of the ATLAS LG systems.
   1.1. The noise meter was placed next to the ATLAS LG system (distance from the rail head edge—2.5 m and the height is at the same level as the rail head);
   1.2. Noise meter recordings and measurements were carried out;
   1.3. Time of the recordings was registered;
   1.4. The recordings collected were transferred to a PC for processing.
2. Data processing.
   2.1. Data were taken from the database of JSC (Joint-Stock Company) “Lithuanian Railways” (Vilnius, Lithuania) about the trains that were passing on the day of the experiment. This system registers the speed, time and weight of the passing rolling stock, and the forces that act on the rail.
2.2. An analysis was performed if the defects were registered, i.e., if the wheelset defects had been registered. If yes, then the following data were taken from the database:

- 2.2.1. Time of registration;
- 2.2.2. Wheelset number;
- 2.2.3. Reference force;
- 2.2.4. Maximum force;
- 2.2.5. Wagon speed (m/s);
- 2.2.6. Total mass of the wagon.

2.3. Once the defects of the wheelsets are detected, the following data regarding the defects and dimensions of the wheels were also collected from “Lithuanian Railways” (Vilnius, Lithuania):

- 2.3.1. Wagon number;
- 2.3.2. Wheelset number;
- 2.3.3. Detected defect measurement data:
  - 2.3.3.1. Tools used;
  - 2.3.3.2. Defect dimensions—depth, length and width.

2.4. Collected data were compared with the recordings made by the noise meter (based on time).

- 2.4.1. Possible impact force period was calculated based on the speed;
- 2.4.2. The records were searched by time and the calculated period of repeating acoustic sound changes;
- 2.4.3. Frequencies with the highest amplitude were registered.

2.5. The physically collected values of the results were compared with the static experiment calculations (applying the composed calculation module).

3. Measurement analysis was obtained and conclusions were formalized.

4. Physical Experiment

4.1. Description of the Experiment and the Initial Data

Measurements of the physical experiment were carried out on 3 March 2020. Measurements were performed at the picket 9 of the railway section Stasylos–State border (with Belarus), at 45.6 km, next to the existing ATLAS LG system. The measurement scheme is given in Figure 2.

- Three cargo trains were measured. Two trains were traveling in the direction State border to Stasylos, and one train was traveling in the direction Stasylos to State border.
- Air temperature +5 °C, wind speed 2 m/s;
- Measurement devices—ATLAS LG system and Bruel and Kjær (Nærum, Denmark) Type 9727 measurement equipment;
- General parameters registered by ATLAS LG:
  - Train weight, t; number of wheelsets, pcs.; train length, m; average load ratio; movement speed, m/s; train acceleration, m/s²; train load, t/m; time and date.
- Parameters of each wheelset registered by ATLAS LG:
- Number of axles; alarm signal; maximum force, kN; maximum reduced force, kN; load, t; speed, m/s; distance from the first wheel, m; acceleration deviation from the first wheelset, m/s²; time from the first wheelset, s.
- Sound was measured using Bruel and Kjær Type 9727 measuring equipment (Figure 3a).
- It consists of Type 7910 software (Bruel and Kjaer. Nærum, Denmark); multichannel data storage unit Type PULSE 3560-B (Bruel and Kjaer. Nærum, Denmark); computer and microphones GRAS 46AE 1/2” CCP standard field microphone set (range of measured frequencies: 3.15 Hz to 20 kHz, dynamic range: 17 dB (A) to 138 dB [14].
- Sensitivity: 50 mV/Pa, IEC 61672 class 1); three microphones 186157, 190590 and 270029;
- Microphone layout diagram is given in Figure 4.

Figure 3. Sound measuring equipment. (a) Bruel and Kjær Type 9727 measuring equipment and (b) GRAS 46AE 1/2” CCP microphone.

Figure 4. Microphone layout diagram. M1—microphone 270029; M2—microphone 190590; M3—microphone 186157

Figure 4 shows:
- Parameters measured by the equipment:
- Sound power, Pa; sound power level of the sound frequencies, dB and Hz.
- Influencing factors/conditions were taken as a benchmark. Changes in sound pressure resulted from changes in wheel force, assuming that the additional factors/conditions remained constant, while only the force changes.

Track condition data were acquired from JSC “Lithuanian Railways” (Vilnius, Lithuania). Rail conditions are presented in Table 1.
### Table 1. Rail conditions.

| Category          | Allowed Speed, km/h | Rail Type | Mounting Type | Sleepers Type | Ballast Type |
|-------------------|---------------------|-----------|---------------|---------------|--------------|
| III               | 100/80              | R65       | PANDROL       | GB            | crushed stone|

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| Jointed/continuously welded road | Number of defective rails in km/year | Number of defective fasteners, % | Number of defective sleepers, % | Ballast contamination, % |
|----------------------------------|--------------------------------------|---------------------------------|---------------------------------|--------------------------|
| 2007 continuously welded         | 3                                    | 20                              | 0                               | ≤20                      |

- Track profile data are also acquired from JSC “Lithuanian Railways” and indicated in Figure 5.

![Figure 5. Road profile.](image-url)
4.2. Physical Experiment Measurement Results

4.2.1. ATLAS LG Measurement Results

ATLAS LG measurement results were received from the Atlas system. Based on their analysis, one wheel with defects was detected in one train and three defects were within the permitted limits. The fault is on the left wheel of wheelset 69 of the third train and three defects were within the normal limits of the valid legislation, they were in wheelsets 71, 85 and 87. The results are presented in Table 2.

Table 2. ATLAS LG results. Maximum force, \( F \); reduced ATLAS LG system (hereafter referred to as reduced) maximum force, \( F_r \); reference force, \( F_{ref} \); reduced reference force, \( F_{refr} \); time, \( t \); wagon speed, \( v \).

| Wheelset | \( F \), kN | \( F_r \), kN | \( F_{ref} \), kN | \( F_{refr} \), kN | \( t \), s | \( v \), m/s |
|----------|-----------|-------------|----------------|----------------|--------|---------|
| 69       | 364.13    | 469.71      | 183            | 290.66         | 17.738 | 12.86   |
| 71       | 307.84    | 414.08      | 183            | 290.66         | 18.467 | 12.81   |
| 85       | 300.29    | 407.38      | 183            | 290.66         | 22.142 | 12.62   |
| 87       | 323.67    | 427.04      | 183            | 290.66         | 22.945 | 12.59   |

Using Equations (1)–(3), the possible repetition frequency and period can be calculated, because the wheelset can be new. The radius of the new wheel is \( R_W = 0.475 \text{ m} \), and radius of the wheelset with maximum wear is \( R_W = 0.4715 \text{ m} \).

We focus on the change in sound pressure when the frequency \( f \leq 200 \text{ Hz} \), in accordance with Equations (1) and (3) and Table 3.

Table 3. Periods (T) and frequencies (f) of the damage repetition of the new and worn wheel.

| Wheelset | T, s | f, Hz |
|----------|------|-------|
|          | If the Wheel Is New | If It Is Worn | If the Wheel Is New | If It Is Worn |
| 69       | 0.2320 | 0.2298 | 4.3111 | 4.3523 |
| 71       | 0.2329 | 0.2307 | 4.2943 | 4.3354 |
| 85       | 0.2364 | 0.2341 | 4.2306 | 4.2711 |
| 87       | 0.2369 | 0.2347 | 4.2206 | 4.2610 |

When values are inserted into Equation (5), the sound power change should be

\[
L_w = 10 \log_{10} \left( \frac{F}{F_{ref}} \right) \quad \text{and} \quad L_{wr} = 10 \log_{10} \left( \frac{F_r}{F_{refr}} \right).
\]

Using Equation (8), the theoretical results are presented in Table 4.

Table 4. Sound power change calculation results are theoretical, at different forces \( F, F_r, F_{ref}, F_{refr} \), and sound force change parameters \( L_w \) and \( L_{wr} \).

| Wheelset | \( F \), kN | \( F_r \), kN | \( F_{ref} \), kN | \( F_{refr} \), kN | \( L_w \), dB | \( L_{wr} \), dB |
|----------|-----------|-------------|----------------|----------------|------------|-------------|
| 69       | 364.13    | 469.71      | 25             | 33             | 11.6332    | 11.5332     |
| 71       | 307.84    | 414.08      | 25             | 33             | 10.796     | 10.9857     |
| 85       | 300.29    | 407.38      | 25             | 33             | 10.796     | 10.9149     |
| 87       | 323.67    | 427.04      | 25             | 33             | 11.1208    | 11.1195     |

4.2.2. Sound Measuring Results

Sound recordings were made using the sound measuring equipment. At the same time, video was recorded and the timestamp taken. The measured parameters include sound power, \( P_a \); sound power level of the sound frequencies, dB; and time of sound recording, Hz. The time is recorded in the sound recording track recorded by the equipment; the
changes of the sound pressure in it are entered in such time intervals with the accuracy of 0.001953125 s. Later, the data of the sound recording were compared with ATLAS LG and the data of the video recording.

Measurements record changes in sound power in the environment and over time. We assume that everything surrounding what is going on is a sound benchmark, and a change in the forces acting between the wheel and the rail causes a change in sound power. We filter these changes based on the repetition time and period.

Comparison of ATLAS LG data, video recordings and sound recordings allowed for determining the possible time of the defect. Data were filtered using the defect repetition period (Table 3) and the time of defect registered by the ATLAS LG system. The results are presented in the Table 5.

Table 5. Recording time of possible damage.

| Wheelset | Possible Fault Repetition Period T, s (Calculated Time) | Start of the Train Sound Recording, Time t, s |
|----------|--------------------------------------------------------|-------------------------------------------|
| 69       | 0.0022 (from 0.2320 to 0.2298)                         | 17.738                                    |
| 71       | 0.0022 (from 0.2329 to 0.2307)                         | 18.467                                    |
| 85       | 0.0023 (from 0.2364 to 0.2341)                         | 22.142                                    |
| 87       | 0.0022 (from 0.2369 to 0.2347)                         | 22.945                                    |

Based on ATLAS LG data, defective wheels were identified. According to the instructions of this equipment, the wheel defect criteria follow:

Fr > 450 kN—is an impermissible fault, i.e., a damage (a flat spot, or wheel flat) depth exceeding 2 mm and length exceeding 100 mm;

450 kN > Fr > 350 kN—there is damage (a flat spot or wheel flat) within the normal range, up to 2 mm depth and up to 100 mm length.

This system records the detected defect time, the wheel number, the force, the speed and the side of the wheel where the damage is. Therefore, taking into account the ATLAS LG fixed time (column 6 of Table 2), the repetition periods of possible wheelset damage (Table 3) and the recorded start time of the recording of sound pressure changes, the data of Table 5 were obtained. This is due to the distance r measured from the microphone to the damage location (Equation (6)); it is difficult to measure accurately until the damage recurs, the rolling stock passes about 3 m, and since the microphone is 1 (200 Hz) and stands 2.5 m from rail, this distance is very important; this problem is also noted in the conclusions.

From Table 3, we see that the frequency of the defect is up to 5 Hz; therefore we only analyze the microphone recording up to 200 Hz. Data of its recordings are given in Figures 6–8.

The entire duration of the recording of the train with defects is 32 s; its data are given in Figure 6. The train is approaching from 0 to 6 s. After 6 s, the train passes the measuring zone. Initially, two locomotive sections and then freight wagons pass. The peaks initially recorded (about 10 s) are the locomotive’s audible signal.
Figure 6. Changes in sound pressure over time.

The video recording showed that the sound recording was started earlier than the train passed, 5.617 s earlier than when the ATLAS LG system started registering the data, so the first two defects (wheelsets 69–71) were registered at the time mark of 23.355 and 24.079 s of the recording, and the other two (wheelsets 85 and 87) at the time mark of 27.73 and 28.59 s. Extracts of the recording are given in Figure 7 (23 to 25 s) and Figure 8 (27 to 29 s). Our goal is to determine the dependence of the magnitude of the change in sound power on the size of the defect—that is, to determine the defect parameter (size) that can be filtered by the repetition period.

Figure 7. Measured sound pressure of 69 and 71 wheelset failure. Area 1 indicates the defect (Figure 6).

Using filters based on possible recorded/detected damage (Table 5), two sound pressure peaks (SPP) were detected for each damage. The results are presented in the Table 6.
Using filters based on possible recorded/detected damage (Table 5), two sound pressure peaks (SPP) were detected for each damage. The results are presented in the Table 6.

**Table 6. Results of sound pressure measurements.**

| Wheelset | Time \( t, \text{s} \) | Pressure \( P, \text{Pa} \) |
|----------|-----------------|-----------------|
| 69       | 23.3555         | 15.65           |
|          | 23.5703         | 11.50           |
| 71       | 24.0820         | 11.71           |
|          | 24.2871         | 13.83           |
| 85       | 27.738          | 5.76            |
|          | 27.967          | 8.5             |
| 87       | 28.54           | 7.58            |
|          | 28.81           | 12.33           |

Registered sound pressure data of wheelset 69, (based on ATLAS LG readings) have a maximum force of \( F = 364.13 \text{ kN} \) and \( F_r = 469.71 \text{ kN} \). Registered sound pressure data of wheelset 71, (based on ATLAS LG readings) have a maximum force of \( F = 307.84 \text{ kN} \) and \( F_r = 414.08 \text{ kN} \). Registered sound pressure data of wheelset 85, (based on ATLAS LG readings) have a maximum force of \( F = 300.29 \text{ kN} \) and \( F_r = 407.38 \text{ kN} \). Registered sound pressure data of wheelset 87, (based on ATLAS LG readings) have a maximum force of \( F = 323.61 \text{ kN} \) and \( F_r = 427.04 \text{ kN} \).

![Figure 8. Sound pressure due to the 85th and 87th wheelset defects. Area 2 indicates the defect (Figure 6).](image)

Because the measurements were taken at a distance of 2.5 m, and the reference sound pressure is the average measured pressure, equal to 4.5 Pa, from the Equation (8) we get

\[
L_p = 10 \log_{10} \left( \frac{P}{P_{ref}} \right),
\]

and the sound pressure change level \( L_p \) is calculated.
Sound power change level $L_{w}$ in the source is calculated using the equation derived from Equation (6):

$$L_{w} = L_{p} + 10 \log \left( \frac{Q}{4 \pi r^2} \right). \quad (10)$$

In the Tables 3 and 7, we can see that the results of the experiment differ two-fold from the theoretical calculations. This suggests that the article in preparation for the theoretical model (Petrenko and Kukėnas [11]) contains a mistake, and instead of Equations (4), (5) and (7), the following equations should be used:

$$L_{w} = 20 \log_{10} \left( \frac{W}{W_{ref}} \right); \quad (11)$$

$$L_{w} = 20 \log_{10} \left( \frac{F}{F_{ref}} \right); \quad (12)$$

$$L_{p} = 20 \log_{10} \left( \frac{P}{P_{ref}} \right). \quad (13)$$

The recalculated results using the equations noted are given in Table 8.

Table 7. Experimental results.

| Wheelset | Time $t$, s | Sound Pressure $P$, Pa | Reference Sound Pressure $P_{\text{ref}}$, Pa | Change of Sound Pressure Level $L_{p}$, dB | Change of Sound Power $L_{w}$, dB |
|----------|-------------|------------------------|---------------------------------------------|------------------------------------------|----------------------------------|
| 69       | 23.355      | 15.6500                | 4.5000                                      | 10.8260                                  | 23.7541                          |
|          | 23.5703     | 11.5000                | 4.5000                                      | 8.1497                                   | 21.0778                          |
|          | 24.0820     | 11.7100                | 4.5000                                      | 8.3069                                   | 21.2350                          |
|          | 24.2871     | 13.8300                | 4.5000                                      | 9.7522                                   | 22.6803                          |
| 71       | 27.7380     | 5.7600                 | 4.5000                                      | 2.1442                                   | 16.6559                          |
|          | 27.9670     | 8.5000                 | 4.5000                                      | 5.5241                                   | 20.0358                          |
| 85       | 28.4000     | 7.5800                 | 4.5000                                      | 4.5291                                   | 17.4572                          |
|          | 28.8100     | 12.3300                | 4.5000                                      | 8.7550                                   | 21.6831                          |

Comparing Tables 7 and 8, we can see that the results are very similar.

As noted previously, the aim of our work is to determine the magnitude of sound pressure changes due to damage and its dependence on its magnitude. Knowledge of vertical force is used as confirmation of the reliability of a mathematical model and measurement results. As we can see from the results, Equations (4), (5) and (7) in the mathematical model need to be changed to Equations (11)–(13); moreover, more microphones are needed to obtain more reliable results.

From the diagrams given in Figures 7 and 8, we can see that for each defect only two sound pressure change peaks were registered. This is related to the distance of the device to the point of contact of the wheel defect. The rolling stock is moving, but the place of measurement is fixed. Each defect is repeated only around every 3 m, so in case it is desired to detect two sound pressure change peaks, the rolling stock must travel 6 m, and for three peaks it must travel 9 m. As we can see in Equation (6), the sound pressure depends
significantly on the distance. Thus, in order to register more peaks, more microphones would be needed.

4.3. Comparison of Measurements Results with the Calculations of the Mathematical Model of the Numerical Experiment. Results of the Calculations According to the Data of the Physical Experiment

In this section, a numerical mathematical model (Petrenko and Kukėnas [11]) is considered, which is obtained by considering the dependence of the change in the forces acting on the change in sound pressure as a test/check in this work by physical experiment.

Calculations were made taking into account the physical experiment data of the track condition, wheelset load and speed. Maximum and reference forces were obtained. The results are presented in the Table 9 and in Figures 9–12.

| Wheelset | Speed, m/s | Defect Depth, mm | Wagon Weight, t | Max. Obtained Impact Forces, kN | Min. Obtained Impact Forces, kN | Average Obtained Impact Forces, kN | Reference Obtained Impact Forces, kN | Average Period of Repetition, s |
|----------|------------|------------------|-----------------|---------------------------------|---------------------------------|-----------------------------------|-----------------------------------|----------------------------------|
| 69 (Figure 9) 71 (Figure 10) | 12.86      | 2                | 91.02           | 334                             | 307                             | 315                               | 25                                | 0.232                            |
| 85 (Figure 11) 87 (Figure 12) | 12.81      | 1.8              | 84.5            | 312                             | 285                             | 294.96                            | 25                                | 0.233                            |
| 87 (Figure 12) | 12.62      | 1.8              | 84.5            | 306                             | 258                             | 293.46                            | 25                                | 0.2364                           |
| 87 (Figure 12) | 12.59      | 1.9              | 84.5            | 317                             | 282                             | 293.73                            | 25                                | 0.237                            |

Figure 9. Calculated force values of the 69th wheelset.
Figure 10. Calculated force values of the 71st wheelset.

Figure 11. Calculated force values of the 85th wheelset.
Calculations were performed according to Section 3.1, replacing Equations (4), (5) and (7) with (11)–(13), respectively. The results are presented in Table 10 and in Figures 13–16.

Table 10. Results of sound power level calculation.

| Wheelset | Max Sound Power Level, dB | Min Sound Power Level, dB | Average Sound Power Level, dB |
|----------|---------------------------|---------------------------|-------------------------------|
| 69 (Figure 13) | 22.52                     | 21.30                     | 22                            |
| 71 (Figure 14) | 21.26                     | 20.12                     | 20.77                         |
| 85 (Figure 15) | 21.7                      | 20.25                     | 21.39                         |
| 87 (Figure 16) | 22.07                     | 20.03                     | 21.17                         |

It should be mentioned that only two sound pressure peaks (SPP) can be detected with one microphone; more microphones are needed to detect more SPP. Table 10 shows the changes in sound pressure at the source. The difference between them is 2 dB, but the existing damage within the normal range should already be repaired. Therefore, this is sufficient to detect damage. Since different countries may have different possible and forbidden damage parameters, we provide Equations (6), (12) and (13) according to which the corresponding SPP parameters can be determined.
Figure 13. Calculated sound power level values of the 69th wheelset.

Figure 14. Calculated sound power level values of the 71st wheelset.
Comparison of the results of the physical and the numerical experiments shows correlations. Force correlations are shown in Figure 17.

Figure 15. Calculated sound power level values of the 85th wheelset.

Figure 16. Calculated sound power level values of the 87th wheelset.
Figure 17. Comparison of physical and numerical experiment results. F-F—force results obtained from the physical experiment, F-T—force results obtained from the numerical experiment.

As we can see from the Figure 18, the impact force results obtained during the numerical experiment and the results registered during the physical experiment correlate. Correlations of the sound power level are indicated in Figure 18. Here we can see that the sound power level differs within 0.3–1.5 dB limits.

Figure 18. Comparison of physical and numerical experiment results. Lw-F—sound power level results obtained from the physical experiment, Lw-T—sound power level results obtained from the numerical experiment.

This is most probably related to the selected methodology of the physical experiment, i.e., with the distance of the microphone from the spot where the wheel defect contacts the rail. During the physical experiment, there was virtually one fixed microphone, and the rolling stock was moving. As we can see from the Equation (7), the sound pressure depends significantly on the distance between the measuring device and the measured object (source of the sound pressure impact force caused by the wheel defect). Each impact force caused by the wheel defect repeats at a specific period according to Equation (1);
however, in practice, this happens after traveling some distance, i.e., every 3 m. So in case it is desired to detect three sound pressure change peaks, the rolling stock must travel 6 m, and for four peaks it must travel 9 m. Due to the changes of the sound pressure peaks, two peaks were registered during the physical experiment, and the theoretical sound power changes were different from the ones registered during the physical experiment.

In order to obtain more accurate data, Equations (1) and (6) should be taken into account. In addition, when performing a similar physical experiment, more microphones should be used in a longer measurement field; i.e., the measurement area should be around 9 m, and there should be at least seven microphones if they are placed every 1.5 m, and at least nine or ten, if they are spaced every 1 m.

Sound pressure change data and their peaks must be filtered by the periods of their repetition, which is calculated using Equation (1).

5. Conclusions

This work presented the design and development of a physical experiment to validate the theoretical model for the determination of wheel damage in a real scenario. The plan and process of a physical experiment aimed at confirming the results of a mathematical model of the change in sound power of a simplified wheel with flat spot contact, and a method and algorithm model for calculating theoretical defect parameters in a real environment. The physical experiment plan was developed taking into account the methodologies of related physical experiments, available equipment and capabilities, and performed under real conditions while running freight trains. Measurements and analysis of the results showed that the impact forces caused by the damaged wheel of the freight wagon are in the speed range of 12.59–12.86 m/s at the flat spot depth of the wheelset of 2, 1.8 and 1.9 mm. Comparing the results of the physical and numerical experiment, it was observed that when analyzing the obtained impact force, the results are close (the difference is from 1.8 to 8.4 percent). Meanwhile, the changes in the sound power level of the damaged wheel of the wagon in the speed range 12.59–12.86 m/s at the flat spot depth of the wheelset of 2, 1.8 and 1.9 mm are 22–20 dB, which is twice the result of the numerical experiment. Therefore, when considering the mathematical model of the change in sound power of a simplified wheel with flat spot contact and the method of calculating the theoretical defect parameters, Equations (4), (5) and (7) need to be replaced with new Equations (11)–(13). After changing the equations, new theoretical calculations and comparisons of results were performed, which showed that the results are close (difference from 1.4 to 6.26 percent). Thus, this experiment showed that a simplified mathematical model of the sound power change during wheel contact and a theoretical method and algorithm for calculating defect parameters can be used for further research or for developing new diagnostic systems and methodologies for damaged wheels, setting diagnostic parameters, i.e., sound power, pressure and their levels, filtering them according to the repetition periods, frequencies of sound power changes, depending on the geometrical parameters of the wheel and the rolling speed. However, in order to perform further physical experiments, the experimental methodology should be improved. This is related to the distance of the microphone device to the point of contact of the wheel with the rail. The vehicle is moving and the measuring point is fixed. Each repetition of the damage occurs after passing about 3 m, so if at least three peaks of the change in sound pressure are to be detected, it must travel 6 m, and the four peaks already 9 m. The sound pressure, as we can see from Equation (6), is highly dependent on the distance between the measuring device and the measuring object. More microphones and a longer measurement zone should be used to obtain more accurate data; i.e., the measuring zone should be about 9 m and the number of microphones should be at least seven if the distance between them is 1.5 m and not less than nine or ten microphones if the distance between them is 1 m.

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Abbreviations

Roman
- \( a \): linear coefficient of the energy dependency on the force;
- \( f \): frequency of the wheel defect impact on the rail (Hz);
- \( F \): impact force of a wheel with a defect into a rail (N);
- \( F_r \): reduced ATLAS LG impact force (N);
- \( F_{ref} \): reference constant wheel force acting on the rail (N);
- \( F_{ref} \): reduced ATLAS LG reference force (N);
- \( L_F \): defect length (m);
- \( l_r \): length of the wheel working surface (m);
- \( L_p \): sound pressure change (dB);
- \( L_{ried} \): length of the wheel rolling surface (m);
- \( L_w \): sound power level (dB);
- \( L_{urr} \): sound level from the reduced ATLAS LG force (dB);
- \( P \): sound pressure (Pa);
- \( P_{ref} \): reference sound pressure (Pa);
- \( Q \): coefficient that depends on the number of reflecting surfaces in the environment;
- \( r \): distance from the sound source (m);
- \( R_w \): wheel radius (m);
- \( T \): defect repetition period (s);
- \( T \): time (s);
- \( v \): wagon speed (m/s);
- \( W \): full sound source energy (radiated in all directions during the period of time) (W);
- \( W_{ref} \): reference (background) sound level energy (W).

Greek
- \( \omega \): wheel angular speed (s\(^{-1}\)).

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