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NUMERICAL SIMULATION OF THE TREAD DEFECTS' FORM IMPACT ON THE EIGEN FREQUENCIES OF A RAILWAY WHEEL

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Modal analysis is a very important technique which helps in determining the natural frequencies as well as mode shapes of a structure. This work deals with an analysis proposed modal of a railway wheel. The first twelve modes of vibration are extracted for free-free, as well as constrained boundary conditions.

To ensure safety and diminish the service charges in the new railcars, it is necessary to characterize the mechanical behavior of the zone containing tearing of metal resulting into breaks and high vibrations, caused by a manufacturing defect.

In fact, the influence of the wheel metal defects on the natural frequencies was first studied by simulating three geometrical forms: circular defect, elliptical defect and any other form defect with comparison of the natural frequencies. The calculations were carried out using a finite element calculation code (ANSYS Workbench). Therefore, the study focuses on dynamic behavior; initially with a modal analysis for two cases; the wheel with and without defects on the tread.

The obtained results show clearly the influence of the torn mass in different shapes and positions on the stiffness of the wheel and therefore on its dynamic response, translated by the variation of its own frequencies.

Keywords: defects forms, railway wheel, modal analysis, stiffness; numerical simulation

1. Introduction

This study aims at treating a problem that is encountered at the railway maintenance workshop (RMW) in Algeria, metal tearing of the new railcars wheels tread.

This study is carried out on the wheels 66357-25 of the ZZ22 railcar. A request was made to the CAF (Construcciones y auxiliar de ferrocarriles) a Spanish railway constructor, to justify the condition of the affected wheels. The objective of this study is to perform a numerical analysis on the damaged wheel, to see the vibratory response of these wheels and also to test the influence of torn material (mass and stiffness) and the shape of the parts plucked out.

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. The general idea is that the variation of the physical properties (stiffness, mass and damping) causes a variation of the dynamic characteristics of the structure (frequencies of resonances, modal damping and eigenvectors). Indeed the presence of damage causes a decrease in the rigidity of the structure, so an increase in its flexibility [1].

The CAF performs a series of inspections, namely visual inspection, microstructural analysis of the damaged areas, and chemical analysis and duality profile according to the applied standard. The analysis showed extensive damages, with generalized presence of spalls in the entire tread surface. However, the chemical analysis showed that the material is within standards. Whereas the microstructure tread analysis showed that the spalls and the cracks are deep due to sudden cooling (Not yet proven since the same problem is found on new wheels) and require a rapid intervention to repair the wheels. This type of damage can lead to a catastrophic failure of the wheel by rolling fatigue mechanism. Another problem that has been discussed during the inspection is that these wheels can be functional after reprofiled, but since these spalls are relatively deep, which requires a strong reprofiling to recover the wheels, which will reduce the life of the wheel and which will lead directly to the frequent change of the wheels. This means a significant increase in the cost of maintenance.

To our knowledge, the spalling defect is not much treated in the literature and very little information is available. Nevertheless, a series of railway wheel analysis models have been established for various research purposes. Such as: the two-dimensional modeling of a railway wheel; comprising a circular and elliptical manufacturing defects and subjected to Hertzian contact pressure in motion which was made by Taraf MODAR [2]. The damage is quantitated by a fatigue parameter based on the energy density.

S. S. Deshpande et al [3] studied a problem of wheel tread defect observed in coach wheel, after the change in braking system from tread braking to disc braking. The problem identified was spalling damage, and investigation was carried out to determine effect of braking system on wheel spalling.

J. Bian, et al [4] developed a finite element model for another type of wheel defect (flat). The wheel flat is studied and investigated the effect of the wheel flat to impact force on sleepers. The numerical results indicate that flatted wheel induces much larger impact force and Von Mises stress than a perfect wheel.

B. Pecile et al [5] provide a dynamic model of wheel/rail interaction able to take into account any kind of defects on wheel and rail treads. The advantage of their present model is its ability to combine several irregularities on the wheel and rail treads.

Pengfei Zhang et al [6] define the vibration characteristics of the standard wheel and damped wheel. The two models were established in ANSYS, through modal analysis and compared damped wheel with standard wheel. Same modes the natural frequency of damped wheel occur relatively small changes, may be due to the impact of the additional mass change the vibration characteristics of the damped wheel.

The aim of the PhD thesis of Virginie Delavaud [7] is to characterize rolling noise and impact noise through experimentation, in case of large amplitude defaults on the rail and/or the wheel.

Nagvendra Kumar Kanoje et al [8], are modeled the wheel with a flat defect using FEA where two kinds of work has been focused. One of results is on the natural frequency of the normal wheel which is significant very low with respect to a wheel with a flat defect. This is Due to mass removal.

Xin Zhao et al [9] present some field observations and statistical results on LRCF, followed by numerical studies to reveal its initiation mechanism.

N.A. Akeel, Z. Sajuri et al [10] present the analysis of RCF damage initiation and stress distribution at the wheel rail interface at different directions. A three-dimensional elastic frictional finite element model of the wheel-rail interaction is used to investigate the effect of the applied contact loading force at the straight, transition, and curved areas of the wheel tread and railhead surface who are exhibits small damage problems. Significant effect damages from the contact force on the wheel tread and the curve radius of rail track are observed at the interface.

However, in this study, the interest is given to the mass and stiffness effects on the Eigen frequencies of the wheels with defects in modal analysis. They are characterized by different defects forms on the tread in two cases (new wheel and mid worn wheel). Therefore, we realized the geometric model by creating forms almost like those present on the tread: tearing under circular, elliptical and any shape, with the same dimensions (same mass teared). Firstly, the study has been to compare frequencies values between new wheel without defects and the same wheel with different forms of defects. Secondly, the same comparison using mid-worn wheel is been done. Finally, a comparison between wheels with different position of the defects on the tread and perfect wheel to highlight the influence of the change of stiffness on the natural frequencies was made. The last comparison is about all the results in order to see the variation of the Eigen frequencies about the frequency of the first mode of a perfect wheel. The latter technique is currently widely used in railways. However, it has been noted that damage usually occurs in these areas, which can have serious consequences on safety and comfort during operation.

2. Wheel defects

2.1 Railcar and wheel description

The Diesel Self-propelled Train for the Algerian National Railway Transport Company (SNTF) is a diesel unit for lines with a track gauge of 1435 mm. The autonomous minimum composition is composed of two motor cars and a trailer car, M1-R-M2, coupled pneumatically and mechanically via semi-permanent couplings and electrically through pipes placed in each cross-member [11]. The solid wheel of a railway vehicle (hereinafter “wheel”) consists of three parts, as shown in Fig. 1. They include a hub, where in an axle is inserted, a rim that contacts the rail, and a web that unites the two parts. The outer circumferential surface of the rim, which contacts the rail, is tread, and the projected part is flange, where their functions are:

- The flange assures with the conical shape of the rim guiding the train and preventing its derailment.
- Due to its conical shape, the wheel plays the role of a differential to prevent the sliding of the opposite wheels in turns. The difference in the distance traveled by the two opposite wheels is compensated by the difference in their respective diameters calculated at the contact.
- In the case of braked wheels, the rim can dissipate the friction braking power with soles of brake.
- As for the Web, it provides the link between the hub and the rim and transmits, with some flexibility, the lateral forces of train guiding [12].

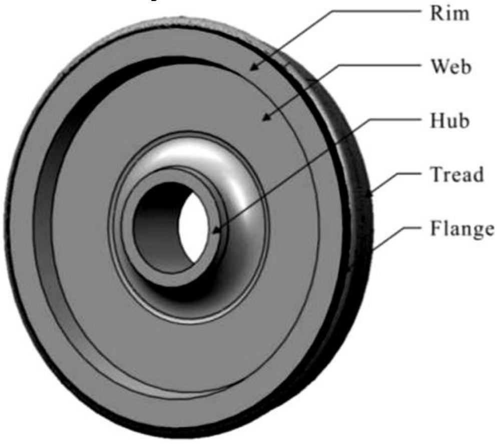


Fig 1. Typical structure of a railway wheel. [13]

Figure 2 represent the wheel plan. The different wheel ribs are resumed in the table1.

Table1

Railway wheel technical features

type	Monobloc wheel
rolling diameters (mm)	
New wheel	850
Latest turning	790
wear limit	780
Mid-worn	810
Width of the rolling surface	135 ± 1 mm
Thickness of flange	31,5 mm
Angle flange	70º
Height of flange	28 mm

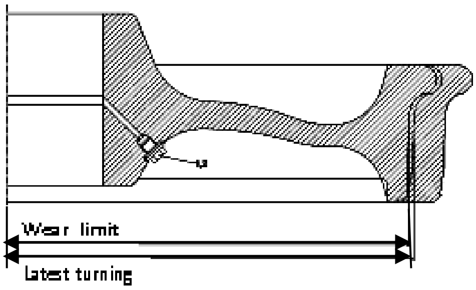


Fig 2. Wheel plan

2.2 Different defects on the tread

Spalling or shelled tread occurs when pieces of metal break out of the tread surface in several places more or less continuously around the tread circumference. Moreover, Spalls can range in size depending on the age and depth of the defect. Their frequency can be such that the entire tread circumference is covered with craters to the extent that they become joined [14]. However, the defects encountered on these wheels are deep spalling probably due to the manufacturing process. This subject remains to be proved. The following figure shows clearly the condition of the wheels at the level of the tread.

Fig 3. Spalling on the tread (photo taken at the AMF)

Figure 4 shows a piece of the wheel that the CAF analyzed. They observed very marked damage with a generalized presence of spalls; throughout the surface of the tread. To make a microstructural analysis of the rolling surface, two samples (A and B) were taken from the contact area of the tread (damaged area) [15].

Fig 4. Sample analyzed by CAF [15]

3 Modal analysis of railway wheel

A modal analysis is run to observe the vibration modes of the structure. Every finished structure responds primarily on its resonance modes. The steel railway wheels have a very low damping: their vibrational behavior is marked by sharp resonances. Like all finite structures, the wheel admits a series of resonance modes, at well-defined Eigen frequencies [16]. The modes of a wheel, like those of a disk, are either principally axial or radial. These various modes are categorized by the number of modal diameters (n=2, 3…..) and (for axial modes) the number of nodal circles (m=0, 1, 2,……) [16]; see figure 5.

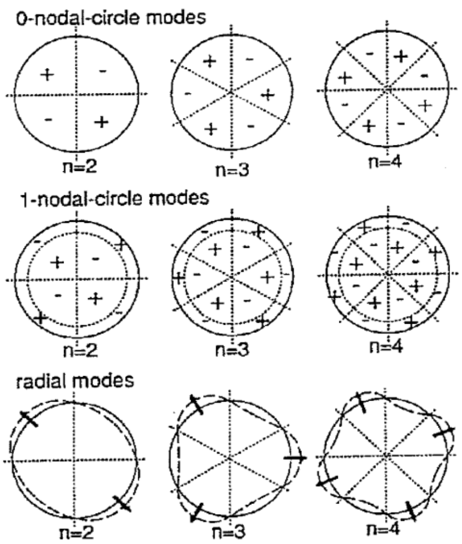


Fig 5. Examples of the mode shapes of the wheel [17]

In this study a comparison between the modal analysis of different case of wheels (without defects, with circular defects, with elliptical defects and with any shape defects) in two cases was made: perfect wheel and mid worn one. It supposed that those wheels are with tread full of defects as the most critical case (20 defects of 14 mm depth in the case of perfect wheel were chosen, which correspond to the same removed mass). After that the same analysis is done but with mid worn wheel (810 mm of diameters with defects depths of 2 mm).

Another case is to make two defects rows, but the same mass teared is maintained in order to see the stiffness influence on the natural frequencies again, knowing that The damage has a considerable effect on the stiffness of the structure. A small change in stiffness leads to a small change in the eigenvectors and frequencies .When damage occurs in the structure, the stiffness matrix of the damaged structure changes. This matrix can be interpreted as the sum of two matrices of rigidities, of the healthy structure and matrix of Elementary stiffness multiplied by the percentage stiffness reduction factor [18].

4. Wheel FE model (description of the model)

The modal analysis is treated with the finite element method which is carried out by ANSYS Workbench 15 software. The solution of the generalized problem to the eigenvalues is defined by an algorithm based on the Lanczos block method that is particularly powerful when searching for eigen frequencies in a given part of the eigenvalue spectrum of a given system [19].

The geometries of wheel are realized with solidworks16.The different defects section choose (circular, elliptic and any shape) located in the tread with depth of 14 mm, (corresponding to the total weight by wheel with 850 of diameter). however The defects area is the same with S=200.96 mm^2 which corresponds to a circular defect with a radius of 8 mm, an elliptical defect with half-axes of 4 mm and 16 mm and a defect of any shape of the same dimensions. The case of mid worn wheel the defects are with depth of 2 mm.

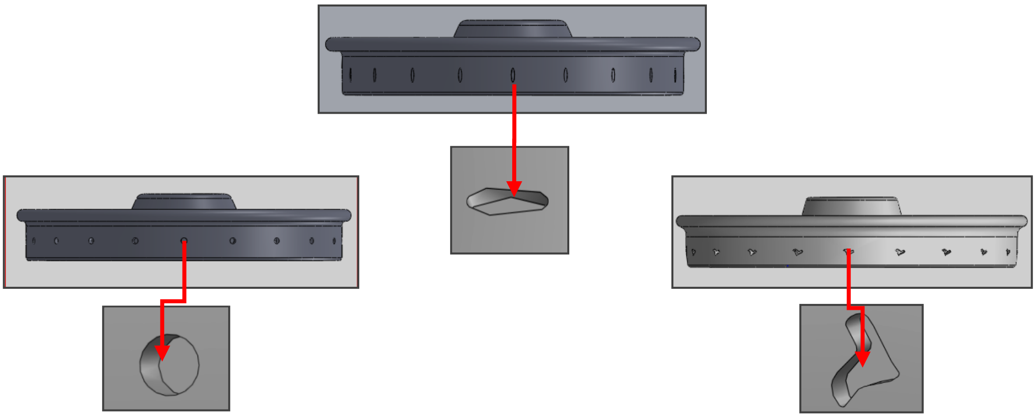


Fig 6. The different approximate forms of defects (circular; elliptic and any form)

4.1 Mesh models and boundary conditions (one row of defects)

The all models are made by 3-dimension modeling software and then it is stored as STEP general 3D model. Moreover, the models are imported into the ANSYS Workbench environment, where are meshed with the volume element solid187 tetrahedral mesh type and rigid part, as mentioned in the software library. After, an embedment stress is applied to the nodes of the inner surface of the hub. This condition reflects the taking into account of the axle. So, the wheels are fixed in the hub.

4.1.1 New wheel (850mm of diameters)

Figure 7 shows the different wheel geometries and their mesh models.

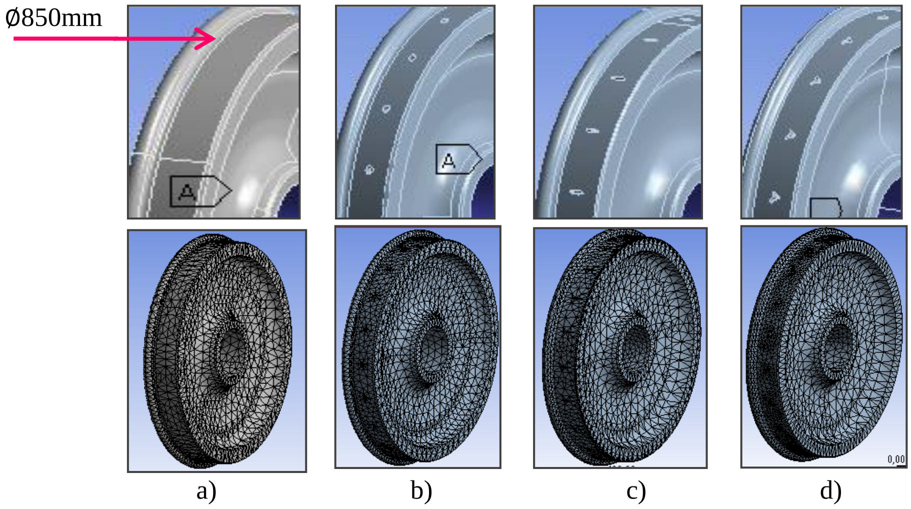


Fig. 7. New Wheel without and with defects on the tread

4.1.2 Mid worn wheel

A mid-worn wheel is a wheel whose diameter has decreased as a result of rolling and braking (the brake pads are acting on the running surface),etc....., however it can still be used. For our case, we chose a mid-worn wheel which is in use and has arrived at 810 mm in diameter (see table 1), and also contains spalls.

Figure 8 shows the different mid- worn wheel geometries and their mesh models.

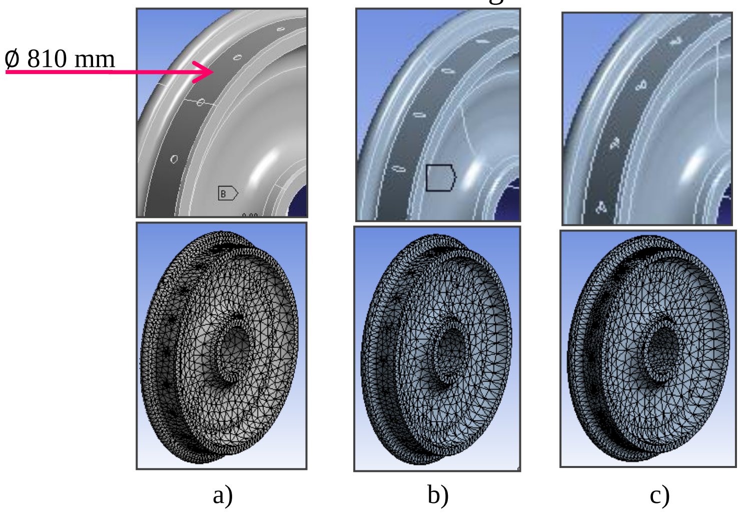


Fig. 8**.** Mid worn Wheel without and with defects on the tread.

5. Numerical applications:

The wheel material is elastic and of nuance, steel ER8. His properties are resumed in Table 2.

Table2

ER8 steel mechanical characteristic [20]

ER8 steel	characteristics
E(Young's modulus) MPa	$2.1x10^5$
υ: Poisson's ratio	0.3
Density (kg/m^3)	7850

The different mode shapes are almost the same for all railways wheels, whether the web is flat or curved. Only natural frequencies depend on the type of wheel, including its diameter therefore its mass and stiffness. However More the diameter is large, more the natural frequencies are low [21].

5.1 perfect wheel (850mm of diameters)

The figure 9 shows the first twelve distorted modal.

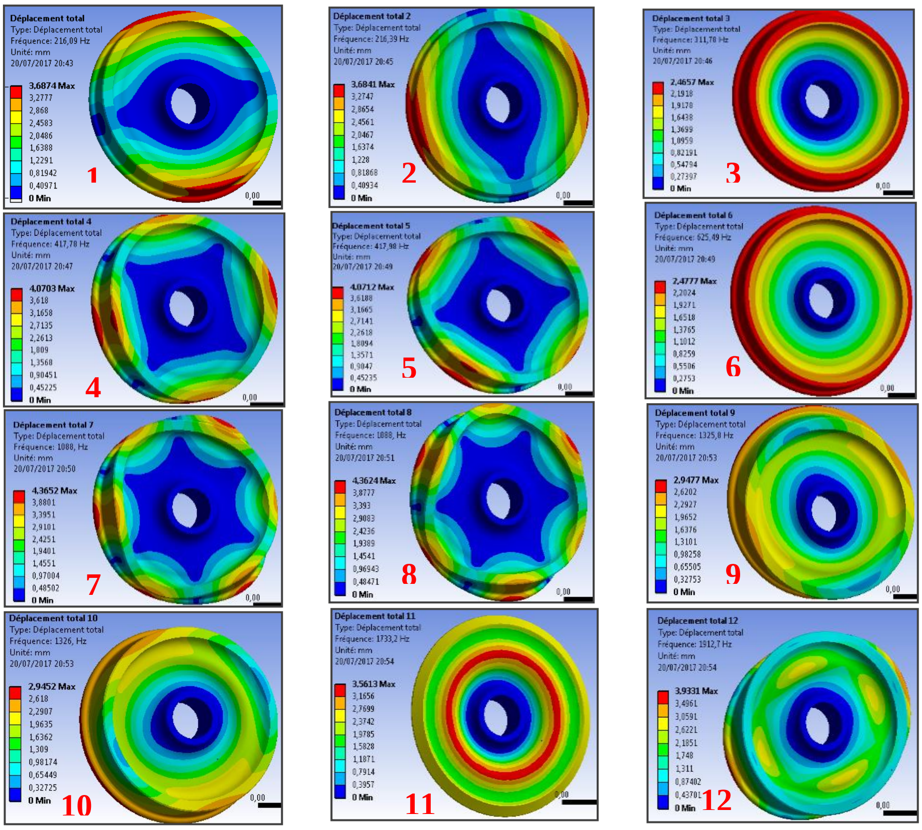
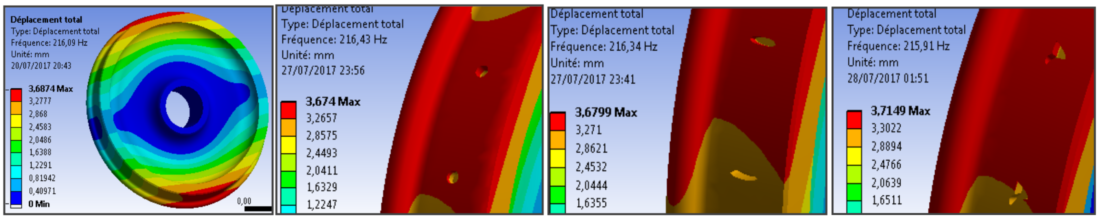


Fig.9**.** The wheel Eigen modes

5.2 Wheel with defects

In the rest of the simulation, the value of the first natural frequency of the new wheel is always taken as a reference in the study of the influence of defects.

Figure 10 shows a comparison between the first mode (fundamental mode) of perfect wheel and the same wheel with circular, elliptical and any form defects (20 defects) with mass equal of 302.86 kg.



mode1 (f_1=216.08 Hz) mode1 (f1= 216.43 Hz) mode1 (f1= 216.34 Hz) mode1 (f1= 215.91 Hz)

Fig 10. Comparison on the natural frequencies between the different wheels state

It can be noticed that there is a slight difference in natural frequencies and this is due to the mass removed which is only 0.5 kg (20 defects with depth 14 mm so around 0.5 kg) of the total mass of the wheel which is 303.41 kg. However it can also be noticed that the frequencies value decreases a little more in the case of an elliptical defect and any form defect but the difference is still slight as it is the same torn mass.

The table 3 summarizes the modal analysis results (natural frequencies) of the wheel in the case of new wheel (with and without defect) and the difference between them. The results are represented clearly by a histogram (figure 11).

Table3

The Different values of natural frequencies for the 4 cases

Mode	Frequency (Hz) Case1	Frequency (Hz) Case 2	Frequency (Hz) Case 3	Frequency (Hz) Case 4	Difference : case 1-		
					Case2	Case 3	Case4
1	**216,08**	**216,43**	**216,34**	**215,91**	-0,35	-0,26	0,17
2	216,53	216,53	216,62	216,35	0	-0,09	0,18
3	313,45	313,29	312,66	311,33	0,16	0,79	2,12
4	420,66	419,41	417,95	413,59	1,25	2,71	7,07
5	420,8	419,45	417,98	413,66	1,35	2,82	7,14
6	624,96	625,85	626,27	622,95	-0,89	-1,31	2,01
7	1097,5	1093,9	1089,2	1076,6	3,6	8,3	20,9
8	1097,6	1094	1089,3	1076,6	3,6	8,3	21
9	1331,8	1331,6	1329,4	1316,4	0,2	2,4	15,4
10	1332,3	1332,2	1329,7	1316,7	0,1	2,6	15,6
11	1737,9	1737,1	1736,8	1721,6	0,8	1,1	16,3
12	1920,7	1920,2	1918,2	1897,9	0,5	2,5	22,8

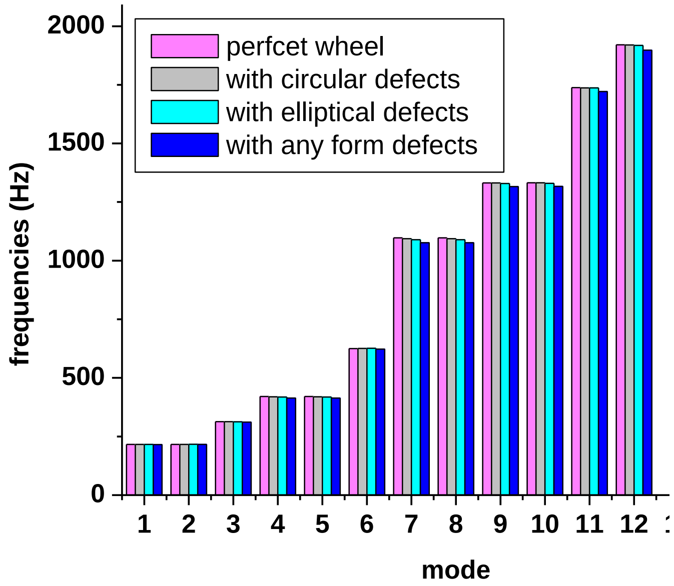
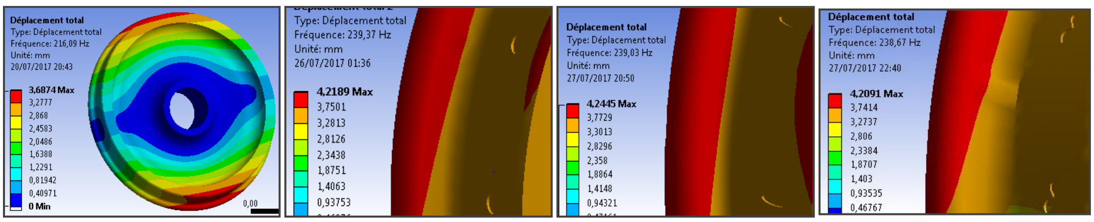


Fig 11. Comparison between the 4 cases in frequencies

5.3 Mid worn wheel (810mm) with defects

Figure 12 shows the comparison between perfect wheel and mid worn wheel with defects on the natural frequencies**.**



mode1 (f_1=216.08 Hz) mode1(f1= 239.37 Hz) mode1(f1= 239.03 Hz) mode1 (f1= 238.67 Hz)

Fig 12. Comparison between the fundamental mode (new wheel) and the mode1 of mid worn wheels (with defects).

Table 4 and figure 13 present the results of the modal analysis (natural frequencies) of the perfect wheel and mid worn wheel (with different defects) and also the difference between them.

Table4

The different values of natural frequencies (mid worn wheel)

Mode	Frequency (Hz) case1	Frequency (Hz) case2	Frequency (Hz) Case3	Frequency (Hz) Case4	Difference : case 1-		
					Case2	Case 3	Case 4
1	**216.08**	**239,37**	**239,03**	**238,67**	-23,29	-22,95	-22,59
2	216.53	239,93	239,38	239,05	-23,4	-22,85	-22,52
3	313.45	335,32	333,69	334,27	-21,87	-20,24	-20,82
4	420.66	383,28	376,29	382,36	37,38	44,37	38,3
5	420.8	383,39	376,42	382,43	37,41	44,38	38,37
6	624.96	625.85	699,26	702,58	-0,89	-74,3	-77,62
7	1097.5	1093.9	961,57	974,41	3,6	135,93	123,09
8	1097.6	1094	961,64	974,9	3,6	135,96	122,7
9	1331.8	1331.6	1378,8	1381,6	0,2	-47	-49,8
10	1332.3	1332.2	1379,3	1382,4	0,1	-47	-50,1
11	1737.9	1737.1	1707,2	1725,1	0,8	30,7	12,8
12	1920.7	1920.2	1707,6	1725,9	0,5	213,1	194,8

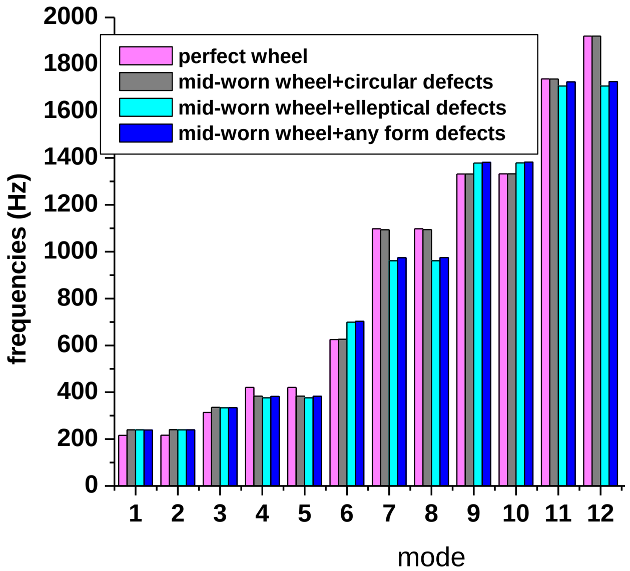


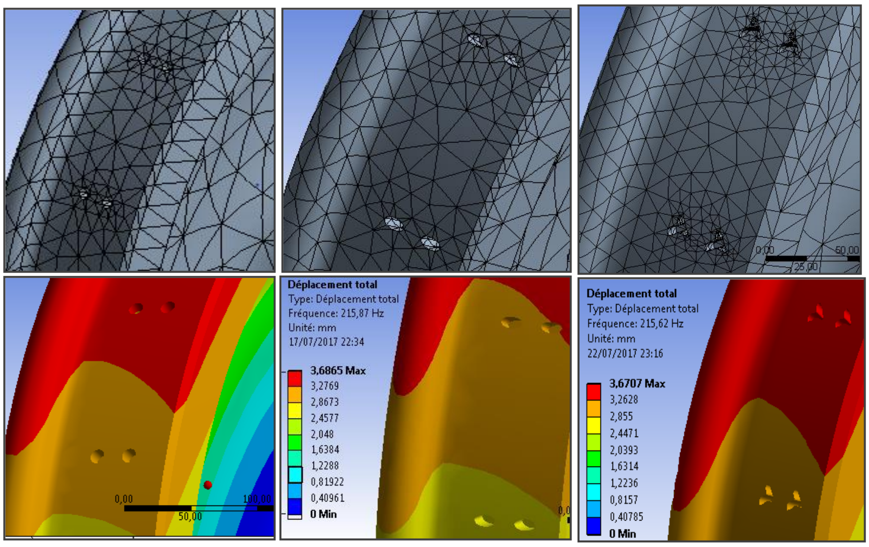
Fig 13. Comparison between the 4 cases in frequencies.

The results obtained from the different cases show a slight difference in the frequencies for the wheels of the same diameter, and with respect to the wheel without defects, which is due to the decrease in mass and especially to the stiffness caused by the difference of shape defects. The meaning of the slight decrease in frequency is that the defects are of the same size (mid worn wheel with defects mass is 257, 78 kg). .

On the other hand, a significant increase in the natural frequencies is observed, especially after the first 6 modes (rigid body modes) in the case of the mid-worn wheels. This is due to the great reduction in the mass of the worn wheel (around 45 kg).

5.4 Two rows of aligned Defects (new wheel)

The new wheel is characterized in all the following cases with all the types of defect seen previously but in two rows, that is to say aligned in the width of the tread by designing the same torn mass and observing the variation and especially the decrease of the eigen frequencies due to the shape of the defects. In the rest of the simulation, the value of the first natural frequency of the new wheel is always taken as a reference in the study of the influence of defects. Different deformed shapes and finite element models are shown in the figure 14.



Mode1 (F1=215,94 Hz) mode1 (f1=215. 87 Hz) mode1 (f1= 215,62 Hz)

Fig 14. 20 defects with two rows with the same area (200.96mm^2)

The deviation on the fundamental frequency is somewhat more significant compared to the case of a single row of defects. The defect in mass and especially in stiffness is a little more important. Table 5 shows the different frequencies and the difference always with compared to the first mode for the perfect wheel and are represented in figure 15 as a histogram.

Table5

The different values of natural frequencies

Mode	Frequency (Hz) Case1	Frequency (Hz) Case2	Frequency (Hz) Case 3	Frequency (Hz) Case4	Difference : Case1 -		
					Case 1	Case 2	Case3
1	**216.08**	**215,94**	**215,87**	**215,62**	0,14	0,21	0,46
2	216.53	216,14	216,36	216,04	0,39	0,17	0,49
3	313.45	311,27	312,14	312,19	2,18	1,31	1,26
4	420.66	416,54	418,02	419,15	4,12	2,64	1,51
5	420.8	416,63	418,07	419,23	4,17	2,73	1,57
6	624.96	626,15	626,41	625,23	-1,19	-1,45	-0,27
7	1097.5	1084,6	1089,8	1093,1	12,9	7,7	4,4
8	1097.6	1084,7	1090,	1093,2	12,9	7,6	4,4
9	1331.8	1325,3	1329,	1328,5	6,5	2,8	3,3
10	1332.3	1325,4	1329,1	1328,8	6,9	3,2	3,5
11	1737.9	1731,3	1734,3	1734,1	6,6	3,6	3,8
12	1920.7	1912,1	1916,7	1916,6	8,6	4	4,1

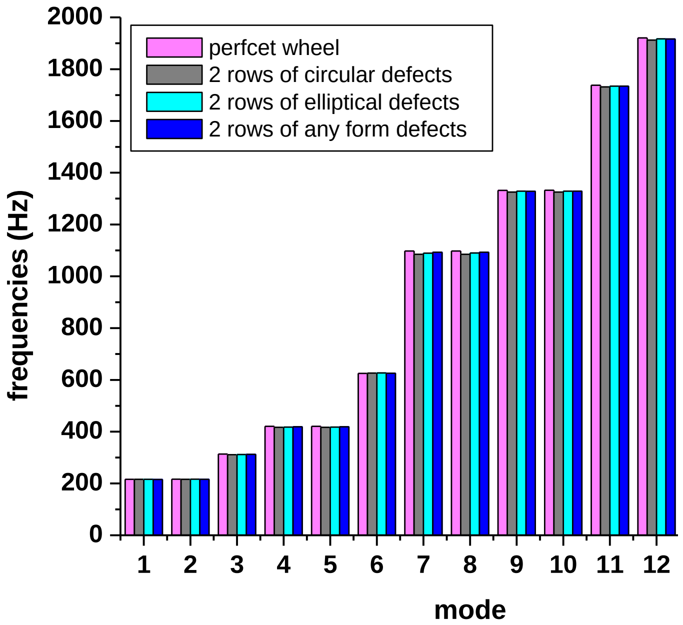


Fig 15. Comparison between the 4 cases in frequencies.

6 Conclusions

The aim of this study has been to see the influence of defects on the tread surface with the basic dynamic parameters (natural frequencies and modal vectors) of the train wheel by varying mass and stiffness. Many simulations are processed using different defect shapes (circular, elliptical and any shape) in a single row and in two rows (defects aligned horizontally on the tread). Thus, in this study, the modal analysis for various wheels geometries has been established. The methods used consist of calculating the modes frequencies of vibration of the wheel using finite element model with ANSYS Workbench 15 software.

The first study established the comparison between different wheel cases of 850 mm diameter with and without different forms of defects. The second study is similar but with the mid-worn wheel. The latest study consists of making a comparison, but with wheels containing two rows of defects aligned, to see the influence of the change in stiffness on natural frequencies.

For the first case, we note that the frequency is slightly higher for the case of the wheel with circular defects, due to the slight decrease in mass (about 0.5 kg); but it also decreases slightly for other forms of defects. This is explained by the decrease in the stiffness of the wheel, since the torn mass is the same.

For the second case (mid-worn wheel), it is clear that the difference is greater in natural frequency, because there is a difference of about 45 kg by mass, which confirms the influence of the mass reduction on the vibratory parameters of The wheel (especially the frequencies). It can also be seen a slight decrease in the case of elliptic defects, then any defects shape, which also confirms the diminution of the rigidity from one form to another, while retaining the same torn mass.

Finally for the third case, we also clearly see the decrease in frequency (slight decrease) when the defects are spread over the width of the tread, which again confirms the decrease in stiffness, because we retained the same torn mass (about 0.5 kg).

The cases studied highlight the influence of the singularities (metal tearing) on the vibratory behavior of the wheel as modal deformations and natural frequencies. The study takes into account the torn shape, which leads directly to the decrease in mass and the stiffness, because the occurrence of a defect (defect corresponding to a loss of material) modifies the dynamic behavior of the wheel with variations in modal frequencies. This modification could increase the risk of damage and cause irreversible damage to the wheel-wagon torque. In order to quantify the potential risk, the prospects must focus on determining excitation frequencies.

These types of defects were encountered on many mid-worn wheels railcars and even on new wheels, which generated a great concern for the railway company that requested an expertise.

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