

MATLAB-Assisted Dynamic Analysis and Balancing Optimization in Railway Wheel Sets

Jeetender Singh Kushawaha

Abstract—This study presents a MATLAB-assisted approach for dynamic analysis and optimization of balancing in railway wheel sets. By simulating multi-plane dynamic balancing equations, critical sources of imbalance were identified and mitigated. The methodology reduced counterbalancing weight consumption by 95.9%, achieving significant cost savings and operational efficiency in production trials. Factors such as wheel eccentricity and machine calibration were addressed comprehensively. This approach validates MATLAB as a cost-effective tool for industrial applications, with the provided code enabling adaptation in similar fields.

Index Terms—Balancing Weight, Dynamic Balancing, Optimization, Press Fitting, Rail Wheel, Wheel Boring, Wheelset

I. INTRODUCTION

THE money saved is money earned, in line with this, the study was performed at a wheel, axle, and brake disc assembly plant in one of the LHB bogie-based rail coach production units of India. It was noticed that excessive consumption of counterbalancing weight is taking place and recognizing the opportunity for improvement, the author obtained permission to investigate and address the issue. The excessive balancing weight consumption resulted in the increased cost of assembling wheel sets for in-house coach production. This prompted a study to reduce of counter of balancing weight consumption [1]. This part of the study elaborates the MATLAB programming for multi-plane dynamic balancing equations for simulating the position and quantification of the counterbalancing weight to match with the actual position and quantity of the unbalancing weight. The significance of dynamic balancing has been very nicely elaborated in reference [2]. The usual method in practice for balancing the wheelset is the addition of external weight by sticking or welding extra material.

II. METHODS

The dynamic model of railway vehicles for weigh-in-motion methodology for railway tracks [2]-[4] motivated further study on the problem at hand. MATLAB programming [5]-[8] for dynamic balancing equations was performed to study the impact of the brake disc and wheel on the un-balancing and its angular positions. Fig. 1, shows the complete assembled wheelset along with bearings, figure also indicates the locations of the six planes considered for dynamic balancing equations. The data and dimensions utilized in this study have been taken from the reference [9] and specifically provided in the supplementary information.

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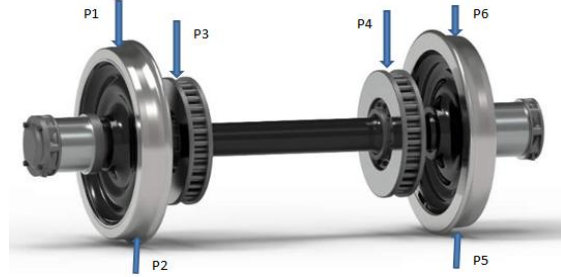


Fig. 1. Wheel set assembly (Courtesy: internet)

Six planes were considered to simulate the requirement of the counterbalancing weights. The planes passing through the point of contact of the tread and midpoints of the brake disc were considered as reference planes $P1$, $P3$, $P4$, and $P6$, these were assumed to be containing the unbalancing weights, m_1, m_3, m_4, m_6 . The planes $P2$ and $P5$ were located considering the location of the fixing of counterbalancing weights m_{c1} and m_{c2} .

The versatile and interactive MATLAB code was developed; and is provided as supplementary material to aid the reproduction ability of the results obtained in this study, to find the counterbalancing weights and their angular positions, in the plane $P2$ and $P5$; about the book by S.S. Rattan [9], the dynamic balancing equations were applied for six planes of LHB bogie wheelset. The equations (1), (2), (3) & (4) are presented in the expanded form:

$$m_1 r_1 + m_3 r_3 + m_4 r_4 + m_6 r_6 + m_{c1} r_{c1} + m_{c2} r_{c2} = 0 \quad (1)$$

$$m_1 r_1 l_1 + m_3 r_3 l_3 + m_4 r_4 l_4 + m_6 r_6 l_6 + m_{c2} r_{c2} l_{c2} = 0 \quad (2)$$

$$\tan \theta_{c2} = \frac{-(m_1 r_1 \sin \theta_1 + m_3 r_3 \sin \theta_3 + m_4 r_4 \sin \theta_4 + m_6 r_6 \sin \theta_6)}{-(m_1 r_1 \cos \theta_1 + m_3 r_3 \cos \theta_3 + m_4 r_4 \cos \theta_4 + m_6 r_6 \cos \theta_6)} \quad (3)$$

$$\tan \theta_{c1} = \frac{-(m_1 r_1 \sin \theta_1 + m_3 r_3 \sin \theta_3 + m_4 r_4 \sin \theta_4 + m_6 r_6 \sin \theta_6 + m_{c2} r_{c2} \sin \theta_{c2})}{-(m_1 r_1 \cos \theta_1 + m_3 r_3 \cos \theta_3 + m_4 r_4 \cos \theta_4 + m_6 r_6 \cos \theta_6 + m_{c2} r_{c2} \cos \theta_{c2})} \quad (4)$$

Where, m , r , l and θ , represent the weight, radius, distance from the reference plane, and angular position from the reference line, respectively. The sub-script 1, 2, 3, 4, 5 and 6 indicate the planes of un-balancing weight and subscripts c_1 and c_2 indicate planes of counterbalancing weight.

A. Code verification

The MATLAB code was verified and validated by solving a test example, 14.3 was solved, for the required counterbalancing weights from reference [10] & [11]. The

angular distribution and the un-balancing weights along with the required counterbalancing weights are graphically represented in the Fig. 2 (a). The MATLAB code was further enhanced to include the interactive feature to make the code versatile for multiple planes of un-balancing weights. Exercise problem 16, of balancing chapter of the reference [10], was solved interactively and the results were verified; the results are graphically presented in Fig. 2 (b).

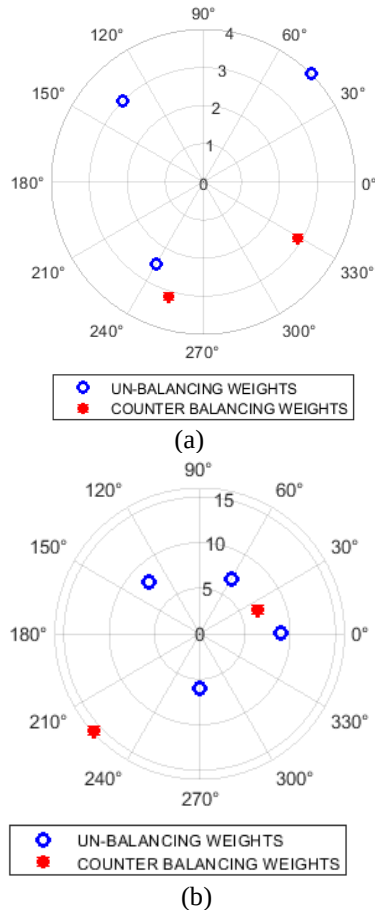


Fig. 2. Un-balancing & counterbalancing weights distribution

B. Screening and exclusion of insignificant wheel set assembly part

To confirm the significance of un-balance contributed by brake discs and wheels, a constant un-balancing weight, of 16 gm was introduced in each one, one by one, and the resulting counterbalancing weight requirement is plotted in Fig. 3. The dynamic balancing wheel set residual unbalanced moment on each wheel plane shall be less than 50 gm as per reference [10]. The static balancing brake disc residual unbalance moment shall be less than 16 gm [10]. Accordingly, a value of 16 gm was considered to be appropriate and introduced as the initial un-balancing weight, to start the analysis.

It can be inferred from Fig. 3 that with an increase in distance from the reference plane the need for counterbalancing weight is increased.

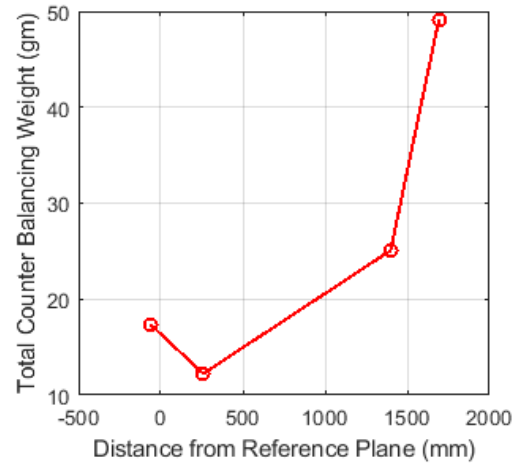


Fig. 3. Significance of distance from reference plane

Further, to exclude the less significant contributing part whether the wheel or brake disc, to reduce the variables for further analysis; a simulation was done to calculate the amount of the required counterbalancing weight by wheels and brake disc, one by one. An un-balancing weight of 16 gm was again considered at the same angular positions and in opposite angular positions, in wheel and brake disc pairs, and the obtained counterbalancing weight was plotted as a bar chart in Fig. 4.

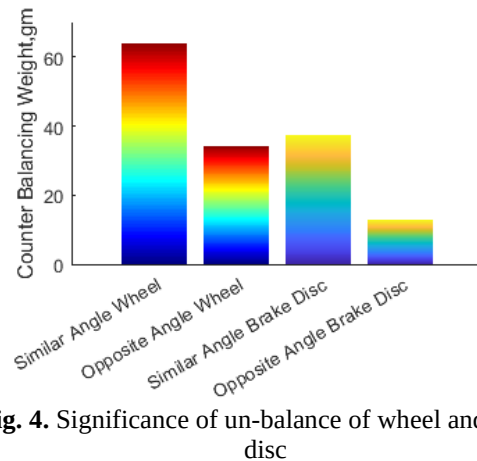


Fig. 4. Significance of un-balance of wheel and brake disc

It was inferred from Fig. 4 that the larger contribution is done by the amount of imbalance in the wheel, so further analysis was focused on the wheel pair and brake discs were assumed to be fully balanced i.e. without any residual amount of imbalance.

C. Analysis of imbalance by varying angular positions relative to the wheel disc

To analyze the significance of imbalance contributed due to angular positioning of the un-balancing weight, 16 gm was introduced in the wheels, and the requirement of the total counterbalancing weight was calculated. In this case, the wheel with reference plane P2 was held stationary and the other wheel was rotated from 0° to 360°. The obtained requirements for counterbalancing weight in every iteration are plotted for easier visualization, in Fig. 5 (a) & (b). Fig. s 5 (a) & (b) provide interesting insights which can be stated that the angular placement of the counterbalancing weights is enclosed within a symmetrical area along the 0° to 180° line, like the wings of a butterfly.

The maximum amount of counterbalancing weight is required when the un-balancing weights are in the same angular position and minimum counterbalancing weight is required when the un-balancing weights are at 90° rotation. Here, the critical finding is that a very highly significant transition of the curve from a low requirement of counterbalancing weight to an extremely large amount takes place within a 30-degree range, i.e. 30 to 90 and 270 to 300.

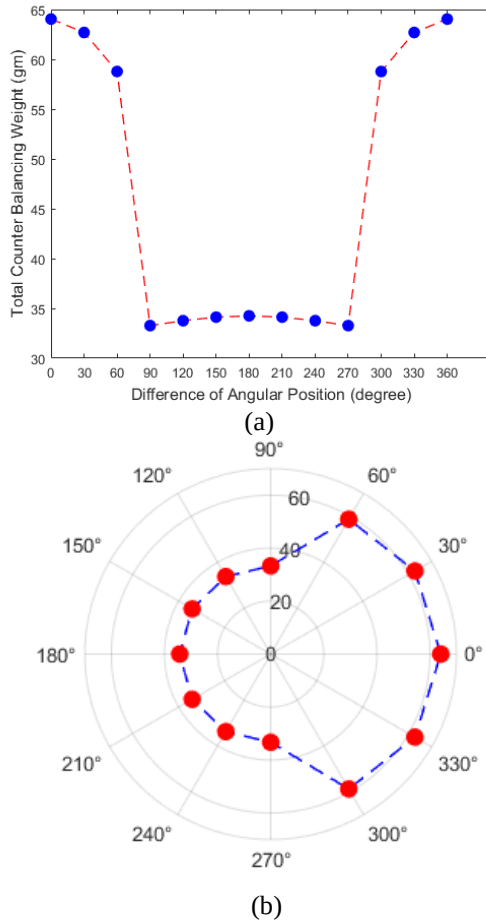


Fig. 5. Effect of the varying angular position of unbalance in the wheel

D. Analysis for varying amounts of imbalance in wheel disc

To analyze the effect of the increase of un-balancing weight in wheels on the requirement of counterbalancing weights, the amount of un-balancing weight was increased, in the optimum angular positions, 90° and maximum angular position, i.e. 0°, difference of angular position.

The increase of the amount of un-balancing weight was done from 20 gm to 120 gm in steps of 20 gm, the obtained the requirement of total counterbalancing weight, and the result was potted in Fig. 6. Fig. 6, is indicative that the increase of requirement of counterbalancing weight increases proportionally and an amount of un-balancing mass of 120 gm will need an approximate amount of 250 gm for optimal angular position and 480 gm, in case if the wheels are having angular position for maximum requirement of counterbalancing weight, i.e. 0°.

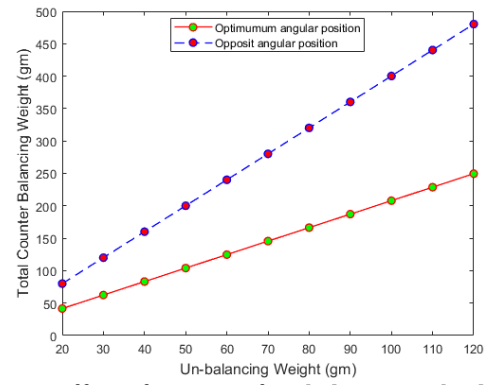


Fig. 6. Effect of amount of un-balance in wheel disc

E. Visualization of axis offset

The further deliberation was based on the assumption that there is an axis offset in the wheel boring machine which leads to un-balancing in the finished wheel, ready for press fitting onto the axle. It was assumed that the offset leaves two arc-shaped volumes in the wheel rim and hub in opposite directions, areas A and B shown in Fig. 7; in the shown figure, the offset was set as 20 mm to make it visible, and the difference of weight corresponding to these area gives the amount of unbalance.

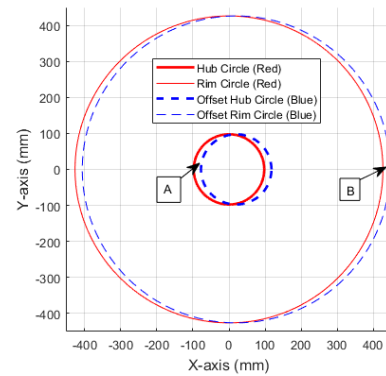


Fig. 7. Visualization for axis offset resulting in un-balancing weight

F. Approximation of un-balancing weight

To approximate the amount of un-balancing weight in the wheel, a mathematical formulation was developed. The developed formulae using the intuition and based on the observation of geometrical area is given as:

$$Un - Balancing Weight = 0.4 \times \pi \times \rho \times Offset \times (R_o \times W_o - R_i \times W_i) \quad (5)$$

Where ρ , $Offset$, R_o , R_i , W_o and W_i , is the density of wheel material, the amount of offsetting (offsetting here stands for the deflection of the dial test indicator and it is twice of *eccentricity*) of the axis of the finished wheel from its initial axis as in raw wheel, the inner radius at wheel rim, inner radius at hub, thickness of wheel rim and wheel hub, respectively. The amount of resulting un-balancing weight in the wheel was calculated using equation (5) and plotted in Fig. 8. Fig. 8 demonstrates the linear relation between the amount of offset and the resulting amount of un-balancing weight.

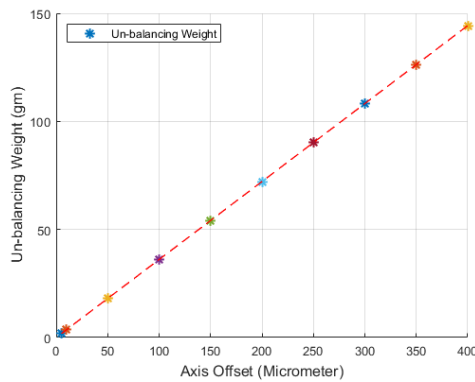


Fig. 8. Approximation of un-balancing weight

This observatory figure leads, to a strong opinion that there is certainly an axis offset in the finished wheel in comparison to the semi-finished wheel. Most of the assembled wheel sets needed approximately, 125 gm, counterbalancing weight per wheel. So, an approximate value for the amount of offset was assumed to be in the range of 310 microns to 340 microns. This also corroborated with the observation in Fig. 6, indicating that an un-balancing weight of 120 gm needs to be counterbalanced by approximately 250 gm of total counterbalancing weight; if the wheels have the optimum angular position.

III. RESULTS AND DISCUSSION

The numerical study confirmed the presence of eccentricity in the finished wheels, with values ranging between 310 and 340 microns. Practical measurements taken on the wheel boring machine further validated this finding, indicating an offset of 328 microns. Such eccentricity can significantly impact the balance and performance of rotating machinery, necessitating corrective measures to improve efficiency and reduce material consumption. To address this issue, specific adjustments were introduced, leading to a considerable reduction in the counterbalancing weight required per wheelset. Initially, on January 24, 2020, the counterbalancing weight used per wheel set was recorded at 250.13 grams. Following the implementation of the suggested modifications, this weight was significantly reduced to 10.19 grams by March 24, 2020. This reduction translates to a total weight savings of 239.94 grams per wheelset, representing an impressive 95.9% decrease in counterbalancing weight usage.

Beyond the direct material savings, these adjustments also contributed to significant improvements in the wheel assembly process. By optimizing machine calibration, the need for rework due to imbalances was minimized, reducing the requirement for repeated processing and balancing checks after applying counterbalancing weights. This improvement not only enhanced the precision of the assembly process but also led to increased operational efficiency, as less time and resources were spent on corrective procedures. The reduction in counterbalancing weight further implies lower overall production costs, improved longevity of machine components, and a decrease in unnecessary material wastage, making the process more sustainable and cost-effective.

In addition to these practical benefits, the study also provides a framework for broader applications. The MATLAB code and data used in this research are made available as supplementary information, enabling replication and adaptation for academic studies or laboratory experiments. Researchers and industrial practitioners can utilize these resources to conduct further studies or refine their balancing processes. Additionally, industries that employ rotating machinery, such as automotive, aerospace, and manufacturing sectors, can customize the provided MATLAB code using data from their specific work parts to optimize balance corrections and improve efficiency.

This study highlights the importance of precise calibration and systematic adjustments in industrial machining processes, demonstrating how small but critical modifications can lead to substantial improvements in both material usage and operational efficiency. The findings provide valuable insights for industries aiming to enhance their manufacturing processes through better balance optimization techniques. For those interested in further exploration or industrial application of this research, the author is available for consultation and collaboration.

VI. CONCLUSION

The numerical study to resolve the problem of increased consumption of counterbalancing weight, using MATLAB programming effectively solved the problem without affecting the production; resulting in improved efficiency of the wheelset assembly plant. Consequently, it can be concluded that the consumption of counterbalancing weights in rail wheel sets serves as a useful grading criterion for assessing the condition of wheel boring machines. The key finding of significance, from this study, can be stated as if the requirement of external counterbalancing weights is increasing, in real-time, that means the wheel boring machine has deviated from its calibration due to wear and tear and needs to be re-calibrated immediately.

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