Postprint: Finite Element Analysis of Wheel-Rail Rolling Contact for Large-Aperture Radio Telescopes

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Abstract

A wheel-rail rolling contact model was established via the explicit finite element method to analyze stress variations when the rollers of a 110-meter aperture radio telescope traverse weld seams. The modeling accounted for not only material property variations at the weld location, but also the influence of surface irregularity and friction coefficient at the rail weld, analyzing the transient response of wheel-rail interaction forces during roller passage over rail welds. The wheel-rail model was preprocessed using hierarchical subdivision techniques, with static analysis results indicating high model solution accuracy. Application of this preprocessed model to transient analysis revealed that surface irregularity at the weld significantly affects wheel-rail interaction forces, increasing the interfacial Mises stress by approximately 20%, which may introduce potential risks to the long-term reliable service of the rail. Consequently, periodic inspection and maintenance of rail conditions are necessary to ensure its long-term reliable service performance.

Full Text

Finite Element Analysis of Wheel-on-Track Rolling Contact for Large-Aperture Radio Telescopes

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Abstract

This study establishes a wheel-on-track rolling contact model using explicit finite element methods to analyze stress variations when the wheels of a 110-meter aperture radio telescope traverse welded joints. The modeling process accounts for material differences at weld locations, surface irregularities at track welds, and friction coefficient effects, enabling analysis of the transient response of wheel-track interaction forces. Hierarchical mesh refinement techniques are employed for model preprocessing, with static analysis results demonstrating high solution accuracy. Transient analysis reveals that surface irregularities at weld locations significantly influence wheel-track interaction forces, increasing Mises stress by approximately 20% and potentially compromising long-term track reliability. Consequently, regular inspection and maintenance of track conditions are essential to ensure sustained reliable service.

Keywords: radio telescope; azimuth track; rolling contact; transient response; finite element method

0 Introduction

Small-to-medium aperture radio telescopes with modest precision requirements commonly employ segmented track technology. However, segmented tracks are prone to jumping and stress concentration when wheels pass over joints, adversely affecting antenna pointing accuracy and track service life [1]. Large-aperture, high-precision radio telescopes have increasingly adopted integral welding technology for their tracks, as exemplified by the U.S. Green Bank Telescope (GBT) [2] and Shanghai Tianma 65m telescope [3]. The under-construction Xinjiang 110-meter fully steerable radio telescope (QTT) [4] will similarly utilize integral welding for its azimuth track. Due to the narrow-groove welding technique employed, three distinct welding materials are required for the buildup layers [5]. The high temperatures during welding alter internal material properties, creating hardness and strength differences between weld locations and base materials. Given the characteristic large-load, small-concentration distribution of wheel-track contact forces, these material disparities at weld locations can induce abrupt changes in contact forces as antenna wheels pass over them. Since stress 突变 is a primary cause of fatigue wear, understanding stress variations during wheel traversal of welds is critically important.

For large radio telescope tracks, traditional experimental research is prohibitively expensive, making simulation-based analysis a practical alternative [6]. Ren et al. [7] investigated wheel-track contact problems for large reflector antennas using comparative analysis across different simulation software to obtain contact stresses, though without addressing transient effects. Juneja et al. [8] employed three-dimensional finite element analysis with a moving load method to simulate wheel rolling, analyzing the mechanical behavior of GBT' s oblique-joint track and fretting wear at the wear plate-base plate interface. However, the moving load method cannot replicate actual wheel-track contact conditions, and material difference effects are difficult to incorporate. Therefore, a complete finite element model is necessary to more accurately and realistically reflect transient wheel-track contact responses.

This study utilizes finite element methods that incorporate actual welding processes for antenna tracks, establishing a QTT wheel-track contact model and applying hierarchical mesh refinement techniques. The "surface-to-surface"Hertz contact algorithm solves contact coupling, and explicit time integration yields transient responses of wheel-track interaction forces under varying friction coefficients and track surface morphologies. The results provide references for fatigue life analysis and maintenance of antenna tracks.

1 Wheel-Track Contact Stress Calculation

The large radio telescope wheel-track contact model established in this study operates under conditions where contact patch dimensions are far smaller than wheel-track geometric features, and wheel slip and creep phenomena are neglected. Consequently, wheel-track interaction forces can be calculated using Hertz contact theory [9], with theoretical calculations compared against simulation results to validate model accuracy and establish a foundation for transient analysis.

According to Hertz contact theory regarding elastic body contact patch geometry, wheel-track contact can be treated as the contact between two arbitrarily curved elastic bodies, forming an elliptical contact patch with major and minor semi-axes a and b respectively:

$$a = m\left(\frac{3N}{4(k_1+k_2)}\right)^{1/3}, \quad b = n\left(\frac{3N}{4(k_1+k_2)}\right)^{1/3}$$

where N is the normal force between wheel and track, and m and n are parameters related to elliptical integrals. The relationship between m, n, and can be obtained from reference tables. Parameters k_1 and k_2 represent material properties:

$$k_1 = \frac{1-\nu_1^2}{\pi E_1}, \quad k_2 = \frac{1-\nu_2^2}{\pi E_2}$$

where E_1, E_2 and ${}_1$, ${}_2$ are the elastic moduli and Poisson' s ratios of wheel and track materials, respectively. Constants A and B for the initial clearance function of the wheel-track contact surfaces are determined by:

$$A + B = \frac{1}{2}\left(\frac{1}{R_{11}} + \frac{1}{R_{12}} + \frac{1}{R_{21}} + \frac{1}{R_{22}}\right)$$

where R_{11}, R_{12}, R_{21}, R_{22} are the principal curvature radii of the two contacting bodies. After obtaining contact patch semi-axes a and b, the internal stress distribution can be expressed as:

$$p(x,y) = p_0\sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}}$$

From this equation, the maximum contact pressure p_0 occurs at the contact patch center:

$$p_0 = \frac{3N}{2\pi ab}$$

Since contact locations primarily experience compressive stress, track failure rarely occurs from compression alone. However, if shear stress exceeds allowable values, it can cause plastic flow within the track and lead to rail failure. Maximum shear stress occurs at a certain depth below the contact surface, with a magnitude of approximately:

$$\tau_{\max} = 0.31p_0$$

The maximum shear stress on the contact surface is:

$$\tau_{\text{surface}} = m_0 p_0, \quad \tau_{\text{surface}} = n_0 p_0$$

where m_0 and n_0 relate to the principal curvature radii of the contacting bodies and can be obtained from reference tables [10]. These formulas enable calculation of the magnitude and distribution of antenna wheel-track contact forces.

2.1 Model Establishment

The simulation model is based on QTT specifications, which features four wheel groups with eight wheels per group. The analysis model comprises one wheel and two track sections, as shown in [Figure 1: see original paper]. Track modeling incorporates welding transition layers, filler layers, and surface welding layers. The wheel axle is represented using three-dimensional linear finite element beam elements, with multi-point constraint elements coupling the axle to the antenna wheel. This approach not only uniformly applies the entire antenna load onto the wheels but also enables wheel rolling, effectively simplifying the model without sacrificing accuracy.

Finite element model accuracy heavily depends on meshing precision. When contact patch region mesh size is 1/20 of the contact patch minor semi-axis width, precise wheel-track contact solutions can be obtained; at 1/10 size, accuracy requirements for most engineering problems are satisfied [11]. Hierarchical mesh refinement technology is applied to refine the track and wheel near weld regions, with a minimum mesh size of 1.1 mm. As shown in [Figure 1: see original paper], the model employs 8-node hexahedral elements, with weld locations using shared nodes to reduce contact settings and improve computational efficiency. To ensure mesh quality, all element aspect ratios are maintained below 3.5. The final model contains approximately 790,000 elements and 820,000 nodes, with weld-adjacent meshes accounting for 91% of total mesh count.

The track material is high-quality alloy steel 42CrMo, while weld locations require greater surface hardness to ensure wear resistance and service life. Therefore, the welding groove necessitates a relatively "soft" material transition layer to effectively connect the track material with the surface buildup layer. The transition layer thickness is approximately 4 mm. Since finite element analysis cannot directly characterize material hardness, different elastic moduli are used to approximate the hardness of deposited metals from different welding processes. Experimental analysis in reference [12] indicates that elastic modulus decreases closer to the weld center, reaching a minimum of approximately 90% of the base material' s modulus at the weld center. Consequently, the transition and filler layers are assigned elastic moduli of approximately 90% of the track material, while the surface buildup layer is set at 95%. Specific material parameters are listed in .

2.2 Load and Working Condition Settings

Considering antenna weight and reasonable track loading capacity, single-wheel load is set at 200 tons to ensure operational safety. Loads are uniformly distributed on wheel axles, with track bottom surfaces fully constrained to account for self-weight effects, and wheel lateral degrees of freedom constrained to prevent lateral slip.

Working Condition 1: With rolling speed at 20 mm/s and friction coefficients of 0.3, 0.4, and 0.5, analyze the transient response of wheel-track interaction forces as antenna wheels traverse welds.

Working Condition 2: With rolling speed at 20 mm/s and friction coefficient of 0.3, analyze the influence of weld surface irregularities of 0.1 mm, 0.2 mm, and 0.3 mm on wheel-track interaction forces.

For transient analysis, a steady transition zone is established between the initial wheel-track contact position and the weld-track boundary line to ensure energy from initial disturbances dissipates before wheels enter the weld zone [13]. Through trial calculations, the steady transition zone is set at 70 mm.

2.3 Time Step Determination

Time step selection relates to numerical analysis error distribution, where appropriate time steps ensure numerical stability and computational accuracy. Time step selection should not be arbitrary; rather, results from three time steps at certain intervals should be compared, and if relative deviations are small, the middle time step result can be taken as the reasonable solution [14]. Three time steps were used to calculate stress time-history curves at identical track positions over 2 seconds of wheel traversal. As shown in [Figure 2: see original paper], different time steps produce minimal impact on results, leading to selection of 0.025 s as the time step for transient analysis.

3.1 Static Analysis

Based on Hertz contact theory and considering static conditions with antenna wheels at weld locations, static friction coefficient is set at 0.5. Finite element analysis yields a total static wheel-track contact deformation of 0.147 mm, with maximum track deformation of 0.069 mm. Track stress contours are shown in [Figure 3: see original paper]. Figure 3: see original paper indicates maximum Mises stress of 363 MPa at the wheel-track interface, differing from the theoretical value of 371 MPa by only 2.2%, with maximum Mises stress occurring approximately 4 mm below the track surface. Figure 3: see original paper shows an elliptical contact patch 13 mm wide (theoretical value 13.2 mm), consistent with Hertz contact theory, with maximum contact pressure of 486 MPa (theoretical value 489 MPa), far below the 42CrMo material yield stress of 930 MPa, verifying safety under static conditions. Figure 3: see original paper shows maximum shear stress of 117 MPa (theoretical value 115 MPa), well below the material' s maximum shear stress limit, with the shear stress field appearing below the track surface, reflecting realistic wheel-track contact stress fields. Static analysis validates model accuracy for transient analysis application.

3.2 Transient Analysis

Due to the large mesh count in the complete wheel-track model, transient analysis entails substantial computational demands and high-performance computing requirements. Based on model characteristics, the Z-direction model scale is reduced to decrease computational load. Z-direction scale models of 0.5, 0.2, and 0.1 are compared against the full model in static analysis, with results shown in [Figure 4: see original paper]. As Z-direction scale decreases, error between reduced and original models gradually increases. To balance computational accuracy and cost, the Z-direction thickness scale of 0.2 is selected for transient analysis.

3.2.1 Friction Coefficient Influence Analysis

Different friction coefficients affect wheel-track interaction forces. Comparisons are made for friction coefficients of 0.3, 0.4, and 0.5 against results ignoring weld material effects, with time-history curves shown in [Figure 5: see original paper]. Mises stress exhibits two rapidly changing peaks because deformation differences between the weld transition layer and track create stress concentrations when wheels contact the transition layer, causing rapid load reduction on the transition layer. With only 4 mm thickness, wheels quickly traverse to the high-hardness weld zone, where stress concentration reappears in the surface buildup layer. During wheel entry from track section to weld, the transition layer bears minimal load, ensuring welding success in load-bearing regions. Maximum Mises stress variation throughout simulation is approximately 22 MPa, and such stress 突变 can cause fatigue in weld zones during long-term service.

Friction coefficient has minimal influence on wheel-track interaction forces; the Mises stress difference between friction coefficients of 0.3 and 0.5 is only about 2.5 MPa, making its effect negligible. Friction coefficient primarily affects frictional stress between wheel and track. As shown in Figure 5: see original paper, static and dynamic frictional stresses increase with friction coefficient, with softer materials exhibiting greater frictional stress. Considering weld effects, maximum frictional stress increases by 71% when wheels traverse welds, increasing the likelihood of fatigue wear during long-term service. Large wheel-track antennas, due to high wheel loads and low speeds, generally do not experience sliding friction or wheel slip; therefore, routine maintenance through lubricant application can reduce friction coefficients and corresponding frictional stresses.

3.2.2 Track Surface Flatness Influence

Upon QTT completion, overall track surface flatness peak-to-valley will be better than 0.3 mm. However, manufacturing and on-site welding assembly inevitably introduce surface irregularities. Due to their randomness and complexity, the method from reference [15] simplifies weld surface irregularities using sinusoidal curves. Using the weld center as origin and 60 mm weld width, nodal coordinates at weld locations are modified according to the sinusoidal curve shown in Figure 6: see original paper to adjust the finite element model.

Time-history curves of wheel-track interaction forces under different surface irregularities are shown in Figure 6: see original paper. Mises stress rapidly decreases then increases as wheels enter welds because modifying track surface flatness through coordinate changes creates height differences between adjacent nodes at curved-to-flat transitions. At 0.1 mm surface irregularity, this height difference is approximately 0.005 mm, yet causes severe stress fluctuations, demonstrating that localized micro-defects (surface inclusions, bubbles, etc.) can significantly impact heavy-load antenna wheels and track surfaces. Mises stress increases with track surface irregularity, reaching 442 MPa at 0.3 mm irregularity—approximately 20% higher than smooth track conditions. This indicates weld flatness substantially affects antenna performance, necessitating frequent track inspection and maintenance during operation to ensure surface cleanliness and promptly address wear or assembly-induced irregularities, thereby reducing damage to antenna wheel-track systems.

Conclusion

Analysis shows friction coefficient has minimal effect on wheel-track interaction forces, while material differences at welds and track surface irregularities more readily induce force variations. These stress 突变, accompanied by stress concentration, adversely affect high-cycle fatigue of antenna tracks. This study establishes a QTT wheel-track model incorporating weld location effects on transient contact, investigating contact parameters and track surface morphology influences. Key findings include: (1) Hierarchical mesh refinement preprocessing substantially reduces mesh count and computational cost while maintaining high solution accuracy. (2) Under static conditions considering weld material differences, total wheel-track contact deformation is 0.147 mm, differing minimally from transient analysis deformation values, but Mises stress undergoes severe variation when wheels traverse welds, negatively impacting long-term reliable service. (3) Different friction coefficients minimally affect wheel-track interaction forces, primarily influencing frictional stress, which increases approximately 71% when wheels pass welds. Track surface morphology changes most significantly affect heavy-load antenna wheel-track forces; due to the large-load, small-concentration nature of wheel-track forces, minute surface irregularities cause substantial stress variations. Therefore, maintaining clean antenna track surfaces through regular inspection and prompt treatment of irregularities is essential.

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Note: Figure translations are in progress. See original paper for figures.