NURail Project

NURail2012-UIC-R05-combined

The final report for NURail project: **NURail2012-UIC-R05** consists of two distinct documents.

The first six pages are titled “Integrated Dynamic Modeling of Rail Vehicles and Infrastructure: Modeling Switch Geometry” by Ahmed Shabana and Martin Hamper.

The following six pages are a report titled “Integrated Dynamic Modeling of Rail Vehicles and Infrastructure: Wheel Climb at a Large Angle of Attack” by Ahmed Shabana and James J. O’Shea.

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National University Rail Center - NURail
US DOT OST-R Tier 1 University Transportation Center

NURail Project ID: NURail2012-UIC-R05-A

Integrated Dynamic Modeling of Rail Vehicles and Infrastructure
Modeling Switch Geometry

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Modeling Switch Geometry

Introduction

Many procedures have been proposed to solve the wheel/rail contact problem, most of which belong to one of two categories: off-line and on-line contact search methods. This investigation is focused on the development of a contact surface model for the wheel/rail contact problem in the case where an on-line three-dimensional non-conformal contact evaluation procedure, such as the *elastic contact formulation - algebraic equations* (ECF-A), is adopted (Hamper et al., 2015). The goal is to demonstrate that the contact surface must have continuity in the second order spatial derivatives when used in conjunction with ECF-A. Many of the existing rail surface models rely on direct linear interpolation of profile curves which leads to first order spatial derivative discontinuities. This, in turn, leads to erroneous spikes in the prediction of contact forces.

Approach and Methodology

In this project, an *absolute nodal coordinate formulation* (ANCF) thin plate surface model is developed in order to ensure second order spatial derivative continuity to satisfy the requirements of the contact formulation employed. A simple example of a railroad vehicle negotiating a turnout, which includes a variable cross-section rail, is tested for the cases of the new ANCF thin plate element surface, an existing ANCF thin plate element surface with first order spatial derivative continuity, and the direct linear profile interpolation method. A comparison of the numerical results can be used to show the benefits of using the new ANCF surface geometry developed in this investigation.

Findings

The main contribution of the work presented in this area is the development of a new finite element-based procedure for representing the rail surface geometry in railroad vehicle contact problems. This procedure ensures a certain degree of continuity at the element interface, thereby allowing for more accurate predictions of kinetics results that include the contact forces. Specifically, the main contributions of this paper can be summarized as follows (Hamper et al., 2015):

1. The analysis clearly identified and explained the limitations of using curve representations in the description of surface geometry. It also identified and explained the limitations of using low order interpolations with contact formulations that demand higher degree of continuity. These two

geometric approaches for modeling surfaces can lead to fundamental kinematic and kinetic problems that cannot be ignored in the analysis of important engineering applications such as railroad vehicle systems. To this end, the analysis provided a clear explanation of potential loss of accuracy when continuity conditions are imposed in the case a lower order of interpolation is used.

2. A new finite element based surface geometry that ensures higher degree of continuity at the element interface was proposed. The new geometry, which is based on the *absolute nodal coordinate formulation* (ANCF), was proposed in order to address the fundamental problems associated with use of curve representation or the use of lower order interpolation. A bi-quintic interpolation was used in order to address the kinetic problems that result from the use of other existing geometric descriptions.
3. A comparative analysis, both qualitative and quantitative, was presented for the first time to demonstrate the value of using the proposed geometry approach. To this end, three different approaches were compared analytically and numerically. These three approaches are the curve representation for the surface, the low order surface interpolation, and the proposed higher order surface interpolation. The results of this study demonstrated that the use of higher order surface interpolation is feasible in many challenging problems.
4. A numerical example of a rail vehicle negotiating a turnout was used to demonstrate the feasibility of using rail CAD geometry model that can be systematically integrated with complex MBS models. The example presented clearly demonstrated the need for the use of the new geometric approach to model railroad vehicles. The results also demonstrated clearly the limitations of other existing approaches.

Conclusions

In this project, three different methods that define a variable geometry surface are presented. In the first method, a linear interpolation between two profiles is used to define the surface between them. As a consequence, fictitious spikes in the contact forces are produced due to first and second order derivative discontinuities which are unavoidable with this method. In the second method, a surface mesh is produced using a collection of cubic ANCF thin plate elements. This method shows marked improvement over the direct profile interpolation method, however some small fictitious spikes in the contact forces are predicted due to second order derivative discontinuities at the element boundaries. In the third method, a surface mesh is produced using a series of the newly developed quintic ANCF thin plate elements. This element has natural C^2 continuity and as a result does not produce fictitious spikes in the forces due to spatial derivative discontinuities when used in combination with the on-line ECF-A approach. It was shown that a linear transformation may be used to convert this quintic plate element to a quintic Bezier patch. This allows for a simple conversion from CAD geometry to the surface geometry used in the contact evaluation procedure. Since this quintic plate element does not rely on geometry lofted along a curve, a surface of arbitrary shape may easily be created using this element type. This would allow, for example, a simple procedure to develop irregular terrain geometry for use in the simulation of various vehicle types (Hamper et al., 2015).

With regard to the simulation of railroad vehicles on variable profile rails, it was shown that the linear interpolation method produces reasonable accuracy in predicting the location of the contact point. For such analyses that are not highly concerned with the contact forces, this method is ideal due to the simplicity of model creation. The cubic ANCF thin plate model produces nearly identical results at the position level when compared with the quintic ANCF thin plate model; the only discrepancy is related to some small fictitious spikes in the normal contact forces. Taking into consideration that model construction and implementation is nearly identical for the two types of ANCF thin plate elements and the relatively small difference in the CPU time, it is advisable to choose the quintic plate in place of the cubic plate as the increased accuracy in the force prediction outweighs the increase in the required CPU time when the quintic plate is chosen.

Recommendations

The results obtained in this research project demonstrated the feasibility of using higher order finite elements to describe the switch geometry. It is recommended to pursue research in this area by exploring other and more general interpolation functions. It is also recommended to develop more simulation models in order to test the implementation.

Publications

This study is documented in a journal paper published in the ASME Transactions (Hamper et al., 2015). This journal paper was structured as follows: Sections 1 and 2 provide an introduction and a definition of the scope of the investigation. The curve network representation of a surface is reviewed in Section 3 in order to shed light on the problems of discontinuity of the spatial derivatives and how this problem negatively impacts the force prediction. The C^1 ANCF thin plate element and the associated spatial derivative continuity constraints are discussed in Section 4. This section explains the fundamental geometric problems that result from the use of low order of interpolation. In Section 5, the new approach based on a higher order interpolation is proposed using a new C^2 ANCF thin plate element. In Section 6, some considerations for the construction of the surface mesh from ANCF thin plates are discussed, while Section 7 presents a method with which the C^2 plate may be converted to a Bezier patch. The three dimensional non-conformal contact formulations are presented in Section 8. The equations of motion and the solution procedure are briefly discussed in Section 9. In Section 10, a numerical example comparing the results of three different methods: the direct profile interpolation, the lower order ANCF interpolation, and the higher order ANCF interpolation, is presented. Section 11 summarizes the conclusions drawn in this investigation.

Hamper, M.B., Wei, C., and Shabana, A., 2015, "Use of ANCF Surface Geometry in Rigid Body Contact Problems", *ASME Journal of Computational and Nonlinear Dynamics*, Vol. 10, pp. 021008-1 - 021008-12.

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Integrated Dynamic Modeling of Rail Vehicles and Infrastructure
Wheel Climb at a Large Angle of Attack

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TECHNICAL SUMMARY

Title

Wheel Climb at a Large Angle of Attack

Introduction

There are two common derailment scenarios which have been investigated in the railroad vehicle dynamics literature: *flange wheel climb* and *wheel lift*. Flange climb derailments are more frequent and can occur at low velocity. It is believed that the flange wheel climb, which is often associated with a large *angle of attack* (AOA), is the result of a tangential force that produces a contact force that acts upward at the wheel/rail contact point. The wheel lift, on the other hand, can be the result of hunting-produced high lateral velocity and large impact forces that can cause derailments. In this derailment scenario, the tangential force at one wheel can be downward as the result of the wheel lift at the other wheel. This project is concerned with flange wheel climb derailments that occur at a large wheelset angle of attack. The wheelset angle of attack is defined to be the angle between the vector defining the wheel forward velocity and the tangent to the rail at the contact point. When the angle of attack differs from zero, contact may occur exclusively at the wheel tread surface, exclusively at the wheel flange surface, or at both the wheel tread and flange surfaces. As previously mentioned, the contact of the wheel flange with the rail produces contact and reaction forces that can have significant magnitude and restrict the motion of the wheel, causing wheel climb and derailment. These contact forces act in addition to the inertia, gravity, and suspension forces that act on the wheel axle. Wheel climb then becomes one of the important derailment scenarios of railroad vehicle systems, particularly in the case of a large wheelset angle of attack (O'Shea and Shabana, 2015).

Approach and Methodology

A fully nonlinear unconstrained multibody system (MBS) wheel climb derailment model is developed to analyze the forces that govern the wheel climb motion when oriented at a large *angle of attack* (AOA). The results of the MBS model in the vicinity of the *climb initiation* are verified using a semi-analytical model that makes use of simplifying assumptions derived from the current interpretation of wheel climb.

Findings

It is shown that, when the wheel makes flange contact with the rail at a large AOA, the lateral and vertical displacements of the wheel become coupled due to motion constraints resulting from the wheel/rail contact. This constraint produces kinematic contributions to the wheel climb motion that are shown to be significant throughout the motion. Additionally, the friction force developed at the point of contact is shown to be three-dimensional and therefore concerns are raised regarding the validity of any planar force balance at the point of contact to capture such motion.

A fully nonlinear unconstrained multibody system (MBS) wheel climb derailment model is used in this project to analyze the forces that govern the wheel climb motion when oriented at a large *angle of attack* (AOA). The results of the MBS model in the vicinity of the *climb initiation* are validated using a semi-analytical model. The main conclusions drawn from this investigation can be summarized as follows:

1. When the wheel makes flange contact with the rail at a large AOA, the lateral and vertical displacements of the wheel become coupled due to motion constraints resulting from the wheel/rail contact.
2. The friction force developed at the point of contact is shown to be three-dimensional.
3. The forces measured at contact point are shown to not represent the forces that drive the derailment.
4. The *Nadal* L/V Limit is shown to not be conservative in the case considered in this project.

Conclusions

There is a strong belief in the rail industry and research community that wheel climb at a large angle of attack is initiated by friction forces. It is believed that when the wheel comes into flange contact with the rail at a large angle of attack, an increase in the lateral force acting on the wheel leads to an increase in the normal reaction force at the flange contact point. Since in this case the contact point on the wheel is moving downward, the large reaction force normal to the flange produces significant upward friction force that results in wheel climb. A fully nonlinear MBS wheel climb model is used in this study in order to investigate the above interpretation of wheel climb derailments. The results obtained using this numerical model are analyzed in order to shed light on the forces that contribute to the wheel climb mechanism. It is shown that the contact between the wheel flange and rail introduces motion constraints that play a significant role in the initiation of the climb, and become more significant as the wheel climbs the rail. In addition to the reaction forces, the contact between the wheel flange and rail produces a friction force that is shown to have non-zero components in three Cartesian directions with respect to the rail and therefore cannot be captured using any planar analysis. It follows that the Nadal L/V Limit, which makes use of a planar force balance, does not correctly capture the friction force at the flange. This project also demonstrates that the forces measured at the flanging rail are not representative of the force that drives the derailment. The above conclusions raise question to the current state of derailment criteria, and in particular the Nadal L/V Limit, which is shown to not predict the derailment presented in this investigation. The criteria may then not be deemed conservative (O'Shea and Shabana, 2015).

These important conclusions are further investigated using a semi-analytical model that is additionally formulated in this project. The semi-analytical model is formulated using assumptions that are derived from the current interpretation of wheel climb in order to analyze the *initiation* of the wheel climb motion. The results of the semi-analytical model are compared with the results of the MBS model in order to validate the assumptions made to develop the semi-analytical model as well as provide insight into the derailment initiation of the MBS model. The two models, although very different in formulation, are in good agreement in the vicinity of the wheel climb initiation. The semi-analytical formulation raises question in regards to use of the "distance to climb" measure used in some derailment criteria, as it is shown that the longitudinal motion is decoupled from the vertical and yaw displacements.

The results of both models confirm the following important conclusions:

1. Nadal’s limit cannot be used as the basis for a conservative derailment criterion.
2. The ratio of the lateral force to the vertical force, L/V, decreases as the wheel continues to climb.
3. Wheel climb can be initiated in the case of zero friction if the wheel is subjected to significant lateral force.

Recommendations

Because of the significance of the problem considered in this project, it is recommended to produce more data from three-dimensional nonlinear wheel climb model considered in this research project. These results can shed light on the definition of the flange angle in the case of profiled wheels.

Publications

The analysis and results obtained in this project are documented in a journal paper published in the journal of Nonlinear Dynamics (O’Shea and Shabana, 2015). The analysis and results presented in this paper question the argument that, in the case of a positive angle of attack and positive pitch angular velocity, the wheel flange contact point on the wheel moves downward thereby creating a significant upward friction force if the lateral force significantly increases, leading to a wheel climb derailment. This interpretation of the wheel climb derailment implies that the initiation of the climb motion is kinetic- (force) based, which requires time history for such a climb initiation since any change in the acceleration does not instantaneously affect the positon coordinates. However, as the result of the wheel flange contact with the rail, the motion of the wheel instantly becomes more restricted, thereby allowing the wheel to move only in specific directions. This restriction is a kinematic motion constraint that is applied instantaneously as the wheel flange comes into contact with the rail, preventing the wheel from penetrating the rail. The kinematic contribution to the climb motion cannot be ignored and is fundamentally different from a kinetic-based climb initiation. Kinematic wheel climb contributions can be dangerous since they are instantaneous and do not require significant applied (external) lateral forces for the initiation. The multibody system (MBS) model used in this project is three dimensional, fully nonlinear, places no constraints on the motion of the wheelset, takes into account the geometry of the wheel and rail profiles, and allows for wheel/rail separation. In the vicinity of the climb initiation, the results obtained using the fully nonlinear unconstrained wheelset model is validated using the results of a simplified semi-analytical model (O’Shea and Shabana, 2015).

O’Shea, J.J., Shabana, A.A., 2015, “Analytical and Numerical Investigation of Wheel Climb at Large Angle of Attack”, *Nonlinear Dynamics*, DOI 10.1007/s11071-015-2347-z.

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