

CAD Framework for Simulation of Railway Dynamics

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ABSTRACT — Mathematical modeling of railway vehicles is essential for the analysis of safety and ride comfort for faster and comfortable journey. One major part of this model is the dynamics of the system, which primarily consists of rail-wheel interaction and the multibody dynamics of the carbody or wagon, which again are tightly coupled. Various researchers have developed mathematical models to represent these concepts, some of which have matured into simulation software, dedicated for railway dynamics. There are also similar software developed by commercial organizations. However, for a researcher who is about to get into railway dynamics, the learning curve is steep and hence requires attention. For example, ability to visualize one's kinematic and dynamic formulation of the mathematical model will help him/her to validate the formulations and also provide insights for improvements. This could be in the form of animation of the wheels on rails or the motion of the carbody, modeled as complicated spring-mass-damper system, subjected to various forces and moments. Through this paper, an attempt is made to develop an addin/plugin inside Autodesk Inventor to implement formulations for effective visualization in a 3D CAD software, so that the researcher has better insights.

1 Introduction

Railways has been one of the most commonly used means of transport worldwide, both for passenger and freight movement. With time, the railways has found more importance in research for providing faster and safer movement. This has led to increase in research activity related to the dynamics of railway vehicles. The railway dynamics comprises primarily the rail-wheel interaction and the dynamics of carbody or wagon.

Rail-wheel interaction deals with the determination of contact point between the wheels and the rails and then the forces and moments acting between them, in normal and tangential directions. The dynamics of carbody is analyzed by considering the carbody suspended over primary and secondary suspension system with respect to wheelsets. Different models are considered in the lateral, vertical and longitudinal directions. A detailed explanation on these aspects can be found in [1].

Several commercial software exist that can model and simulate the dynamics of railway vehicles. Some of them include ADAMS Rail, NUCAR, Vampire Dynamics, SIMPACK, etc. However, these software generally include their proprietary software program to solve for the dynamics of the system. Similarly, several research groups have developed software that have been matured into full fledged software such as SigmaSAMS and GENSYS. However, both are available as commercial versions.

Various mathematical models have been proposed by researchers to analyze wheel-rail interaction [2, 3] and the dynamics of carbody as summarized in [1]. In [2], a wheel-rail contact model has been proposed and the results of the analyses are implemented as animation in 3D-DAP, a generic multibody dynamic program. However, most other work mentioned on wheel-rail interaction, such as [3], and carbody dynamics [4] show

only 2D images or graph plots of the analyses results. These may require better understanding of the multibody dynamics to comprehend the results or the response of the system. Therefore, there is a need for a CAD framework which can be used for the visualization of the results of dynamics of railway vehicles, in the form of animation.

For a person starting research in railway dynamics, a thorough understanding of the concepts and the knowledge of the state-of-the art is essential. Thereafter, he/she would try to improvise a certain methodology or propose alternative solutions to solve various research problem. For example, if a researcher proposes a novel method of detection of contact point between a wheelset and rails, it becomes important for the researcher to observe how the motion occurs for various scenarios and for different inputs. Also, while interacting with a 3D model, certain complicated scenarios might get simplified into 2D scenarios which are easier to understand and solve. A similar instance was in the formulation of an analytical method to detect collision between cylinders. In the literature, very few researchers had proposed formulations. The authors then proposed a novel method [5] which uses the axis-symmetric nature of cylinders and extended the concepts of Denavit-Hartenberg (DH) parameters, which are generally used in robotics. CAD software were used extensively in the formulation stage and later on for the validation of the proposal.

For the 3D visualization environment, one can develop a software application using graphics library such as OpenGL, DirectX 3D, Unity 3D, etc. These require more expertise in the graphics domain, which need not be a case for a researcher in railway dynamics. Alternatively, one can also make use of existing CAD software and customize it suit the needs. Almost all CAD software expose their API (Application Programming Interface) using which the 3D data can be read or modified by an external application or program. Autodesk Inventor is one such CAD software which has been used by the authors in different applications, such as validation of cylinder-cylinder collision [5], kinematic identification of serial robots [6] and simulation of CNC programs [7].

In this paper, an overview of development of a CAD framework using Autodesk Inventor API is given in Section 2, followed by its usage in geometric modeling of rails and wheelset in Section 3. An illustration of motion of wheelset due to kinematic hunting is implemented in Section 4, followed by the conclusions. Through this paper, the authors propose that a CAD framework is necessary for effective visualization of railway vehicle simulation.

2 3D graphics application

Graphics applications in 3D (3-dimensional) space have been developed for various usages. At the core of these applications is a 3D geometric kernel which stores the data of the objects in the 3D space. Some of the kernels that are used in commercial CAD software are ACIS, Parasolid, ShapeManager, etc. Generally, the shape of the objects is saved in the form of BREP (Boundary Representation), where information about vertices, edges, faces, loops, etc. are utilized. There have also been several attempts at creating open-source geometric kernels such as OpenCASCADE, which could also be used in research implementation.

Though simpler graphics applications can be developed using free and open-source libraries such as OpenGL, implementing BREP and other requirements of a geometric kernel involves greater efforts. Hence, it is suggested that a full fledged CAD software can be used as a base to implement one's work. Autodesk Inventor is a 3D CAD software whose educational version is available for free (for non-commercial purpose) and hence a suitable development platform. In this section, an overview of its API is provided so that a researcher can develop a plugin/addin on top of the software to implement his/her research work.

2.1 Autodesk Inventor API

Like many CAD software, Autodesk Inventor exposes its API (Application Programming Interface) so that the data of the parts and assembly can be read and modified from an external program or application developed in various programming languages such as C++, Visual C#, etc. Since majority of the mechanical CAD software

work on Microsoft Windows OS (Operating System) and the development is easier in Visual C# than in C++, the former programming language is used in this paper.

A plugin or addin can be developed using Visual C# either as internal addin, that loads inside Inventor, or as external addin, that is a separate application that can interact with Inventor through COM (Component Object Model) architecture. External applications are easier to develop and prototype. Once satisfied, they can be moved inside Inventor for faster execution.

Almost all operations performed using the Graphical User Interface (GUI) of Inventor can also be automated by developing corresponding code. For example, extrusion of a profile along a straight line, illustrated in Fig. 1, can be performed programmatically. Similarly it can be done for revolution of a profile about an axis, shown in Fig. 2.

A brief overview of Autodesk Inventor API and connecting it from an external application is given in [7]. Also, different features such as extrude, sweep and revolve, that are generally used to obtain any 3D shape are explained along with sample code.

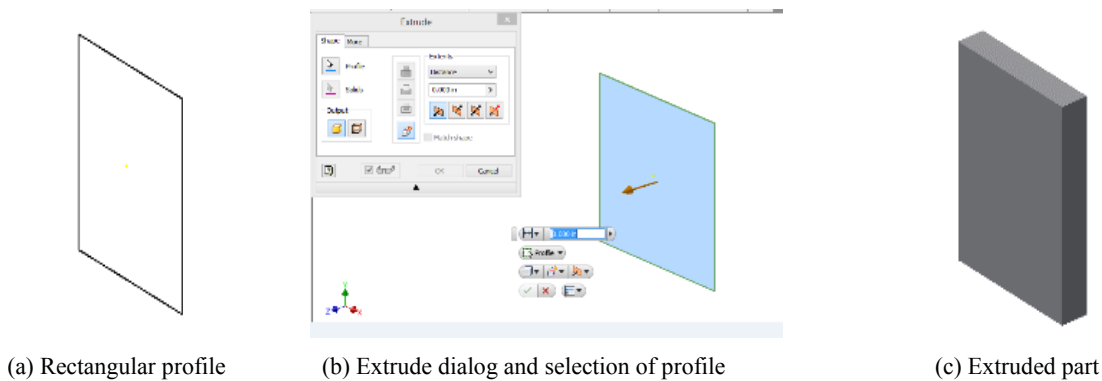


Fig. 1: Extrude feature in Autodesk Inventor using GUI [7]

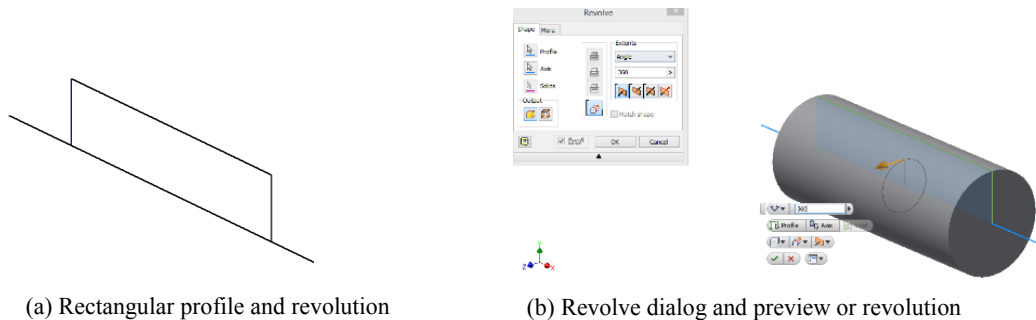


Fig. 2: Revolve feature in Autodesk Inventor using GUI [7]

3 Geometrical modeling of rails and wheelset

The guidance of the railway vehicles is determined by the complex interaction between the wheels and the rails, which requires that the contact between wheel and rail is determined accurately and then formulate the contact forces calculations. More details on the guidance of wheelset can be found in [8]. A typical rail profile's top surface is shown in Fig. 3(a) and that of the wheel surface is shown in Fig. 3(b). Ideally, the contact between the wheels and rails should be a point. However, due to the load in the vertical direction and tangential velocity along longitudinal and lateral directions, a contact patch is developed. Along this contact patch, normal and tangential forces are transmitted to the wheels from the rails which have to be incorporated in the multibody dynamic analysis of the carbody.

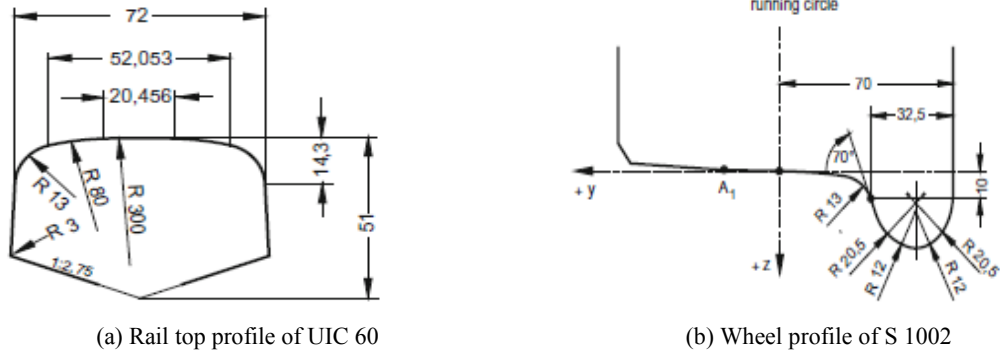


Fig. 3: Standard rail and wheel profile [8]

Therefore, the determination of the coordinates of the contact is of great importance for the further analysis of vehicle dynamics. In addition, the profiles of the rail surface and wheel tread usually wear out and their shape have to be modified in the simulation software. Several researchers, such as Pombo et al [2], have considered rail surface and wheel tread as parametric surfaces. The rail is modeled as a surface where u_r is the parameter in the lateral direction (along the rail) and $f_r(u_r)$ is the parametric curve, represented as a piecewise cubic spline, for the top of the rail surface. The other parameter is the length along the rail. This is shown in Fig. 3(a). Similarly, the curve on the wheel surface is represented using the parameter u_w and another parameter for the revolution of the profile about the axis of the wheel. This is illustrated in Fig. 4(b). In the proposed CAD framework, an addin was developed using Visual C# to model rails and wheelset as explained next.

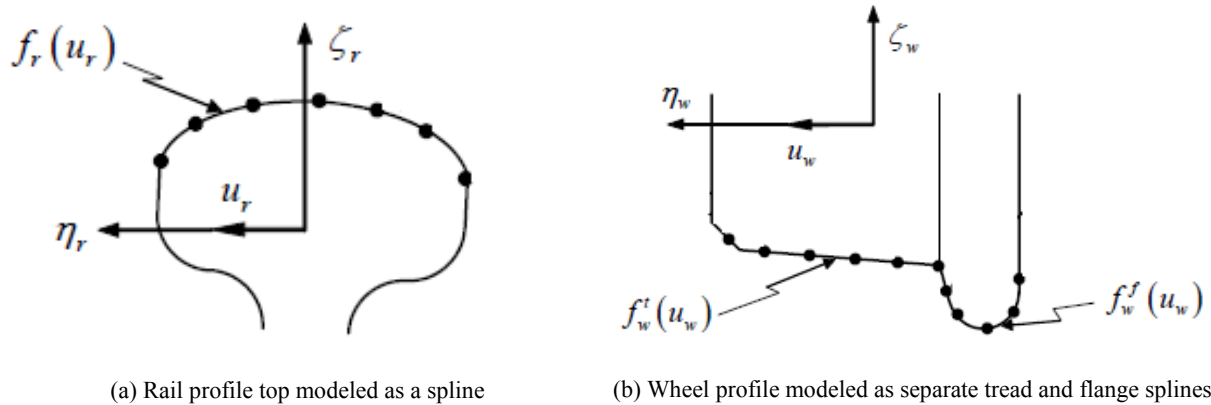


Fig. 4: Parametric modeling of rail and wheel profiles [2]

3.1 Parametric modeling of rails

A rail has a cross-section profile which can be extended along the direction of the rail. Hence, the cross-section profile is important. Different countries follow slightly different profile, with UIC 60 profile being used in Europe. The profile of a cross-section can be modeled as a curve which has one parameter varying. The profile can also be modeled as a piecewise cubic spline curve by considering the points on the profile. For straight rails, the extrusion or the extension is along a straight line, which can also be modeled as a parametric line. Similarly, a parametric curve (a piecewise cubic spline) can also be used to model the curved tracks or a combination of straight and curved tracks. In effect, the rail top surface can now be modeled as a two parameter surface. Any point on the rail surface can be represented using two parameters, one for the profile curve and another along the direction of the rail.

For the geometric modeling of the rails, an addin (Fig. 5) has been developed by the authors. It requires the points on the rail profile as input. Using the default spline feature of Autodesk Inventor, a spline curve (closed) is created programmatically by the addin as shown in Fig. 5 (a). Based on the length of the straight rail, an extrusion of the profile is performed programmatically to get the 3D model of the extruded rail, as illustrated in Fig. 5 (b). Similarly, by creating a spline curve for the curved tracks, the rail profile can be swept along the spline curve to obtain the curved tracks as well, using sweep feature of Autodesk Inventor.

It is important to note that the programming effort required to develop the addin is very less as compared to a standalone application. Moreover, any modifications in the profile or the extrusion can be readily done through the API at ease.

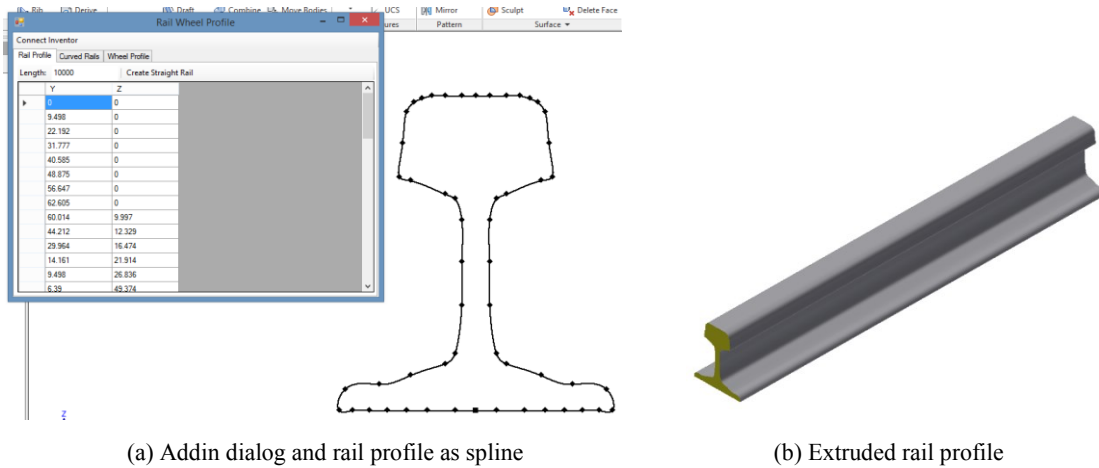


Fig. 5: Inventor addin to create rails

3.2 Parametric modeling of wheelset

A 3D model of a wheel can be developed by revolving a profile about the axis of the wheel. Here, the profile, which is a set of 2D lines and curves can be represented using one parameter for each curve. Any point on the surface can be represented using two parameters. One for the point on the profile and the other, the angle of revolution about the axis to reach that point.

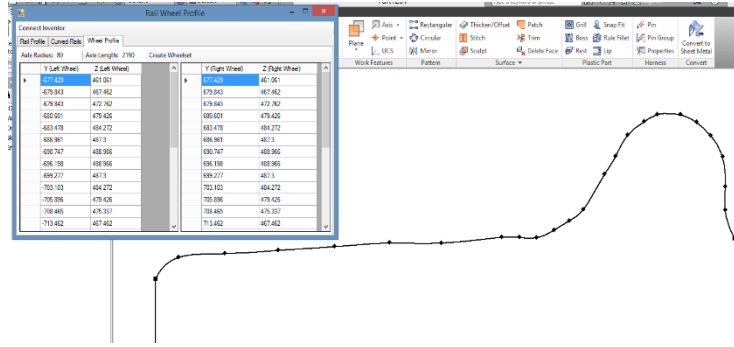
Similar to rail, a wheelset, consisting of two wheels and axle, rigidly joined, is modeled in Autodesk Inventor programmatically. The addin, shown in Fig. 6(a), requires the input of the points on the surface where wheel and rails contact occurs. These are known as wheel tread and wheel flange. The remaining lines are drawn as straight lines for the sake of simplicity. The combined wheelset profile, before revolution is shown in Fig. 6(b). The wheelset model after revolution is shown in Fig. 6(c).

Provision to take separate inputs for both the wheel surfaces is there to model wheels with different wear. Hence, the proposed framework has capability for modeling of wheelset for data from experimental measurement, and just not the initial design.

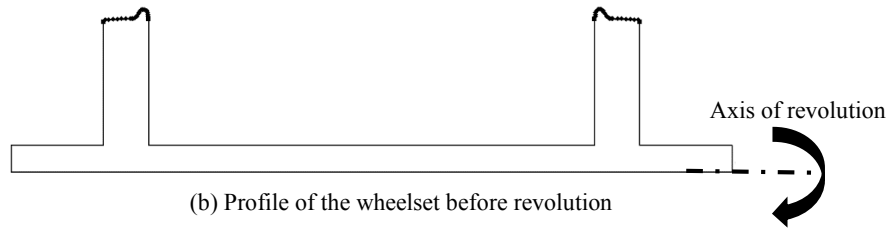
3.3 Assembly of wheelset on rails

The addin after modeling rails and wheels, based on the user input, places the wheelset on the rails, as shown in Fig. 7. Every part in an assembly has an HTM (homogeneous transformation matrix) which can be modified to change its position and orientation, with respect to assembly origin coordinate system. By changing the HTM, one can visualize the motion. These have been implemented in the next section.

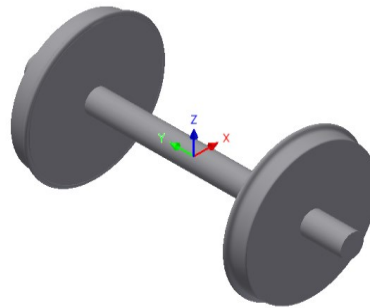
In addition, Autodesk Inventor also has an inbuilt volume interference solver, which can be called from addin. This would help in validating contact detection algorithms that can be proposed and implemented.



(a) Addin dialog to take profile points on wheel tread and wheel flange



(b) Profile of the wheelset before revolution



(c) Wheelset after revolution

Fig. 6: Autodesk Inventor addin to model wheelset using revolve feature

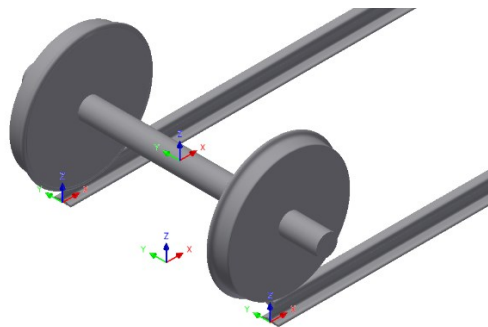


Fig. 7: Wheelset and rails in Autodesk Inventor assembly

4 Kinematic analysis of wheelset motion

A set of carriages are connected and pulled by locomotives. The contact between wheels and rails is a complex phenomenon which involves contact forces in normal and tangential directions. Thereafter the interaction

between the wheelsets and carbodies can be modeled as a complex spring-mass-damper system. The response on the carbodies further affect the motion of the wheelset.

The simplest form of motion that can be implemented and visualized is that of a single wheelset on rails. Thereafter, two wheelsets connected to a bogie can be analysed and further for the whole carbody. As explained earlier, the contact between the wheelset and rails is a complex phenomenon and hence a simple case of kinematic hunting is presented next. In future, contact forces will be considered for the modeling of wheel-rail interaction, and will be evaluated with results obtained in [2].

4.1 Hunting motion of wheelset

Hunting is defined as the periodic lateral motion of the wheelset with respect to its initial equilibrium position. Hunting motion can cause derailment when flange of wheelset comes in contact with rails and hence has to be understood to keep it in limits. In general, the wheel shape is conical with its larger diameter near the inner face of the rail. With this shape, the wheelset tends to automatically self-center during the motion. A simple analysis of this behaviour as reported in [1], is presented below.

Referring to Fig. 8, let the equilibrium condition of the wheel set correspond to zero lateral position ($y=0$). The rolling radii of the right and left wheel can be represented as R_r and R_l , respectively. These two radii are equal for the equilibrium position and are denoted as R_0 . The wheel conicity γ is defined as the slope of the wheel profile where contact with rail happens.

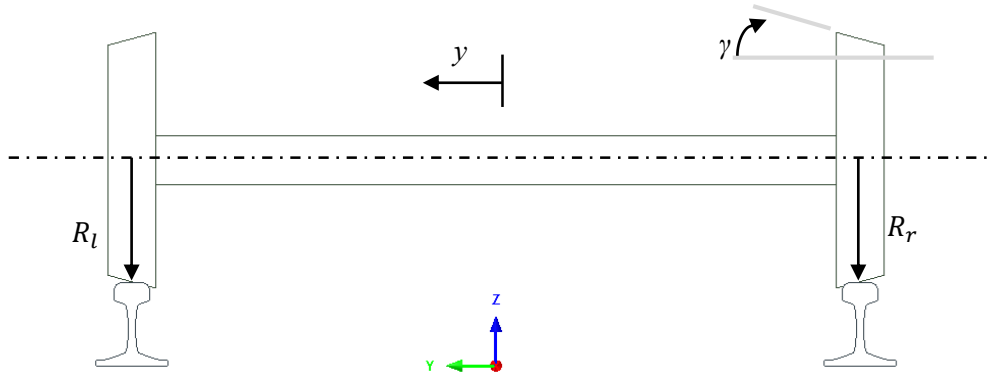


Fig. 8: Wheelset on rails (lateral displacement)

As the wheelset moves laterally, the change ΔR in the two rolling radii can be determined using

$$\Delta R = y\gamma \quad (1)$$

At any instant of time, the wheels' rolling radii is given by

$$R_r = R_0 - y\gamma ; R_l = R_0 + y\gamma \quad (2)$$

If the wheelset is assumed to be rotating at a constant angular velocity ω , the velocities v_r and v_l of the right and left wheels shown in Fig. 9, are given by

$$v_r = R_r\omega ; v_l = R_l\omega \quad (3)$$

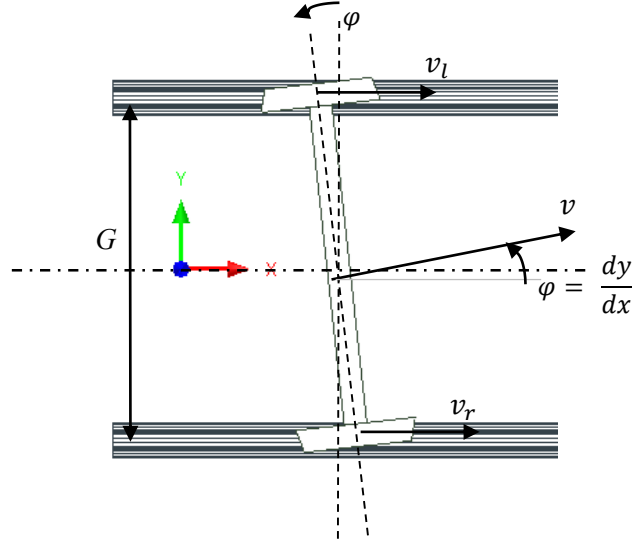


Fig. 9: Wheelset hunting motion (yaw rotation)

The velocity of the center of the wheelset, v , is given by

$$v = (v_r + v_l)/2 = R_0\omega \quad (4)$$

Assuming the yaw angle ϕ to be small ($\tan(\phi) \approx \phi$), the rate of change of lateral motion can be determined as

$$\dot{y} = \frac{dy}{dt} = \frac{dy}{dx} \frac{dx}{dt} = \phi v = \phi R_0\omega \quad (5)$$

The rate of change of yaw angle ϕ , can then be written as

$$\dot{\phi} = (v_r - v_l)/G = -2y\omega\gamma/G \quad (6)$$

where G is the distance between the rails, shown in Fig. 9. Differentiating Equation (5) with respect to time and substituting for $\dot{\phi}$, a second order ordinary differential equation is obtained as

$$\ddot{y} + \left(\frac{2R_0\omega^2\gamma}{G} \right) y = 0 \quad (7)$$

If the coefficient of y in the preceding equation is positive, the solution of the equation above can be written in the following form:

$$y = A \sin(\omega_n t + C) \quad (8)$$

where A and C are constants that can be determined using initial conditions, and ω_n is the system undamped natural frequency given by

$$\omega_n = v \sqrt{\frac{2\gamma}{R_0 G}} \quad (9)$$

The solution of the response is obtained with an assumption that ω_n^2 is positive, represents a sustained oscillation with constant amplitude. The above formulation is known as Klingel's formulation as reported in [1]. Similar solution is possible for the yaw angle (ϕ).

The analysis presented above is based on purely kinematic considerations and does not include the forces that arise due to rail-wheel interaction. The effect of rail-wheel might increase or decrease the hunting behaviour, depending on various factors.

The kinematic equations to mimic the hunting motion were implemented in an addin for Autodesk Inventor as shown in Fig. 10. The addin would connect to Autodesk Inventor and read an assembly which has two straight rails and a wheelset. If the wheelset has a lateral offset, the equation of the response of the lateral motion is set for the motion of the wheelset in the lateral direction. This is achieved by changing the HTM (homogenous transformation matrix) of the origin frame of the wheelset. A set of screenshots for the motion is shown in Fig. 10 (a, b). For the motion, only the lateral displacement (y) has been updated based on the equations and the yaw angle of the wheelset is not modified. For more realistic animation, the yaw angle will be included in the future.

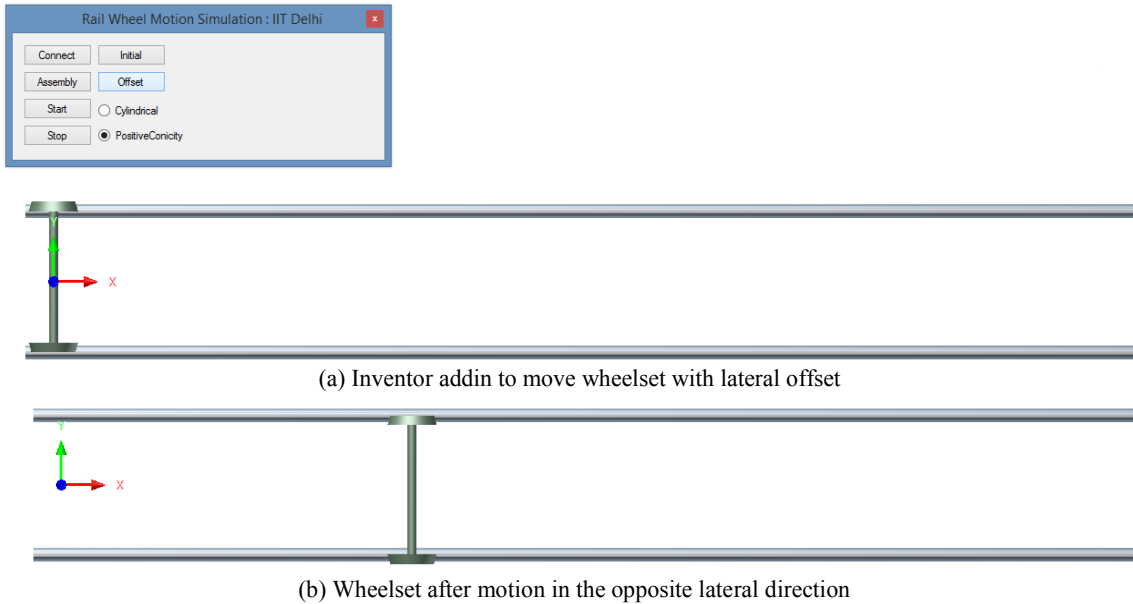


Fig. 10: Autodesk Inventor addin to move wheelset on rails

As the wheel moves, the point of contact between the wheelset and rails can be determined using existing or newer algorithms. Thereafter, Inventor’s API can also be used to validate whether the contact point found is correct or not, using the interference volume. An illustration of interference volume is shown in Fig. 11. In the future, contact detection and contact forces formulations will be implemented in the proposed framework. Thereafter, the effect of these forces and moments on a wheelset can be implemented, as reported in [2].

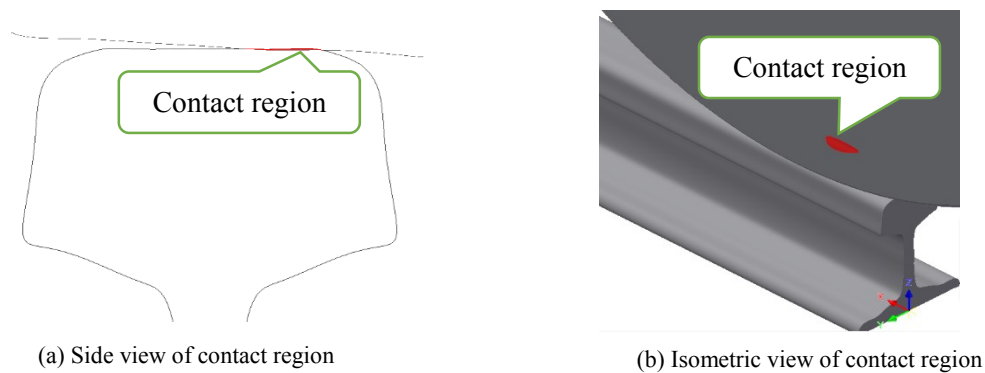


Fig. 11: Intersection volume calculated by Autodesk Inventor

5 Conclusions

Railway dynamics primarily involves wheel-rail interaction and multibody dynamic analysis of carriages, with a tight coupling between them. As these are complicated topics, researchers starting their research might find it difficult to implement and visualize their formulations. Though various full-fledged railway dynamics software are available, most of them being commercial, implementing one's custom formulation in these could be cumbersome. Hence, the authors propose a framework that uses Autodesk Inventor as base for the development of an addin that can be useful in railway research. In this paper, the authors have implemented geometric modeling of rails and wheelset, and kinematic motion of the wheelset on rails using the equations of motions for hunting phenomenon. In future, contact forces will be considered and a dynamic model will be formulated and implemented to mimic the motion of wheelset on rails due to various guidance forces. Further, dynamic analyses of carriages are being planned in the framework, for effective visualization of motion.

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