Bicycle frame load estimation using semi-analytical multi-body simulation methods

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Type of the Paper: Conference Paper

Abstract:

The design and dimensioning of bicycles have always been a challenging task. It is necessary to solve the conflict between a high level of safety against component failure and the demand for a lightweight and cost-efficient design. The operating loads to which the system components are subjected play a decisive role in this task. However, the determination of these loads is a crucial challenge. Besides the widespread use of multi-body simulation in other vehicle industries, in the design of bicycles, the potential has so far remained largely untapped. The main problems arise in modeling the complex driving tracks and the need for a driver model that accurately represents the complex human behavior.

Using a semi-analytical modeling approach, the system excitation is directly applied in the form of measured loads. This opens the possibility of representing the rider, track, and tire behavior in their full complexity within the numerical simulation, without making simplifications in the modeling process. However, replacing constraints between the bicycle and the environment with forces leads to an unconstrained system where imbalances can lead to instabilities in the form of uncontrolled accelerations, making the results unusable.

This paper presents and evaluates the accuracies of four simulation methods that allow a semi-analytical simulation of bicycles. These are defined by two variations of a locating-floating bearing of the wheel hubs, constraining at a static reference point and the constraining of the frame to a reference point guided along the original frame trajectory. The input of the semi-analytical simulation is based on synthetic measurement data, conducted in a fully analytical simulation with a passive driver model. In contrast to the previous applications of this approach, it was shown that for bicycles, highly accurate results can be calculated without taking the trajectory of the bicycle into account.

Keywords: Multi-body Simulation, Operating Loads, Semi-analytical Approach, Hybrid Simulation Approach, Bicycle Loads, Bicycle Simulation
Introduction

The transport industry is currently experiencing a revolution, as a result, sales of bicycles are at a high level (German Bicycle Industry Association, 2023). The design and dimensioning of bicycles have always been a challenging task in the development process. While prototype tests established in bicycle development can ensure a minimum level of safety for strength verification, they are unable to represent the complexity and diversity of the loads occurring during operation (Köhler et al., 2012). Ensuring the safety of bicycles is particularly important because the failure of a critical component leaves the rider virtually unprotected in case of a fall. With the advent of more and more innovative bicycle kinematics such as full suspension bikes or structures such as cargo bikes, it is becoming increasingly difficult to design safe bicycles just based on experience and applicable testing standards.

In other vehicle industries the widespread use of multi-body simulation (MBS) allows for early statements of the loading and stress conditions in the development process. With the increased capabilities of computers and established tire and road models, a common approach is the use of fully analytical MBS methods to replicate loads of real-world driving. The results form the basis for finite-element analyses with which the component stress can be determined (Johannesson and Speckert, 2014). However, the potential of this process remains largely untapped in bicycle development. The reasons for this lie in the development of an analytical environment model that can accurately represent the actions of the rider and the wheel-road contact, even in demanding riding situations. There is extensive research for passive and active driver models in the area of vehicle dynamics evaluation and also investigations in track wheel contact (Bruni et al., 2020). However, these can only be transferred to a limited extent to highly complex driving scenarios with the aim of quantitatively representing the operating loads numerically. This leads to an inadequate design foundation, which is especially true for the sports sector since both the complexity of the load scenarios and the loads themselves are high.

An alternative modeling approach offers great potential for solving these problems. Instead of the classical "fully analytical" environment model, measurement data can be used at the system boundaries to excite the vehicle model (Tebbe et al., 2006). By using this "semi-analytical approach" (SAA), the analytical rider and track models are replaced by measured excitations at the system boundaries. Thus rider, track, and tire behavior are fully accounted for in their complexity within the simulation, without making simplifications in the modeling process. The measurement data allows for a comprehensive representation, ensuring a more accurate analysis and evaluation of the bicycle’s performance. But when the measured loads are applied to unconstrained systems, it can lead to instabilities in the form of uncontrolled accelerations that do not occur in reality (Speckert et al., 2009; Tebbe et al., 2006). Accordingly, the simulation results become unusable due to motion induced forces. The reason for these unintended movements is the lack of constraints on the vehicle system. Replacing constraint of the track-wheel contact with measured forces at the wheel hub leads to a system where no constraints between the system and the environment reduce the degree of freedom (DOF), therefore leaving the system unconstrained. Even small load imbalances in the excitation can cause the system to accelerate uncontrolled.

The engineering challenge is to stabilize or constrain the simulation without affecting the system behavior and, consequently, the simulation results. The simulation can be considered successful when the determined system loads in the SAA correspond to the real driving scenario. Various stabilization approaches can be pursued for this purpose. Some methods are explored in literature for moving systems without common constraints to the environment (Blanchette et al., 2021; Joubert et al., 2020; Speckert et al., 2009; Tebbe et al., 2006). These approaches can be implemented in the form of artificial constraints at static or dynamic reference points in the system. Active control strategies can also be implemented, where combinations of P, I, and D Controls are used to calculate forces that counteract the unintended movement. Another challenge is the consideration of the inertia forces inside the system itself. In the mentioned applications critical loads on the components were caused by inertia loads inside the system itself in the form of inertia forces. Most of the methods suggest that these must also be taken into account in the application of the SAA. This is achieved by measuring the pose of the system as a function of time and by either directly constraining the system to the measured trajectory or by using it as a reference point for feedback control stabilization.

Previous publications have considered vehicles in which the mechanical structure itself was the prime source of critical loads, such as cars or motorized tricycles. In bicycle systems, however, the inertia forces of the system itself play a minor role compared to the inertia forces of the driver and active forces like pedaling induced by the driver. The driver’s weight can easily surpass ten times that of the bicycle, thus resulting in significantly higher inertia forces. Therefore, exciting the model based on the loads originating from outside the system at the connection points to the wheels and the driver can be sufficient for the SAA of the loads during operation. The data required would thus be reduced by the center of gravity trajectories, only requiring the loads at the system boundaries. This is a great advantage, as the measurement of six-dimensional position data is demanding and cost-intensive, especially since driving routes can be located in rough terrain. As a result, stabilization approaches that were previously ruled out for systems with high inertia forces become interesting again. To that end, the scope of this paper is to evaluate the potential of the SAA for the application on bicycle simulation. In particular, stabilization approaches with artificial constraints were examined and re-evaluated with the background of the new system properties.
1 Methodology

To enable the use of MBS, it is necessary to determine a simple measurement and simulation method capable of calculating accurate component loads without distorting them in the simulation process itself. The bicycle model used in this study corresponds to a full-suspension mountain bike frame, presented in detail in subsection 1.1. Measurement data for the excitation and validation of the SAA is generated in terms of a fully analytical simulation with a passive driver model. In this way, any errors or deviations that occur can be directly attributed to the methodology and are not falsified by deviations in the modeling or measurement of the input data. The modeling of the simulation to obtain the synthetic measurement data is described in subsection 1.2. In order to test the suitability of SAA in general and different stabilization methods in particular, various simulation setups are implemented in an MBS environment and evaluated, see subsection 1.3. In order to prove the hypothesis of the admissible inertia neglect for bicycles, a setup in which the bicycle is guided along a measured trajectory is also considered. In order to compare the performance of the individual SAA with the reference runs, time-force curves are compared. Furthermore, two characteristic values are defined to evaluate the suitability of the simulations, see subsection 1.4.

1.1 Bike Model

The utilized bicycle model is shown in Figure 1. It consists of eight rigid bodies, a frame- and a fork suspension. The component properties, such as geometric connection points, mass, mass inertia tensor, and center of gravity, were experimentally determined and validated in research conducted by (Ingenlath, 2019). The total mass of the bicycle structure as shown in the Figure is $m_{\text{bicycle}} = 15 \text{ kg}$. The model incorporates linearized force element characteristics, which were also derived from the measurements presented in (Ingenlath, 2019). In order to validate the performance of the different SAA-sets, several points throughout the system are used to compare the recreated loads by the SAA with respect to the loads occurring in the reference drive, see Figure 1. Two of the validation points are in the connection between frame and fork. The fork bearing is modeled with two constraint points at the top and bottom. The bottom constraint is limiting axial ($y$-direction) and radial movement ($x$-direction), the top is only constraining radial movement. In this way, only forces in the connection of frame and fork need to be examined. Furthermore, the bearing between the frame and the chainstay is analyzed as well as the connection between the seat stay and lever. The forces are measured in local coordinate systems, displayed in Figure 1. The exact same model is used in the reference drive as well as in the SAA-sets.

Figure 1: Representation of the bicycle model, consisting of eight rigid bodies and spring-damper suspensions in the frame and the fork. In addition, the validation points including the respective coordinate systems are shown.

1.2 Reference Data

The reference drive, which is used to generate the synthetic input and to validate loads, is implemented as a full analytical MBS. In this way, errors originating from differences in the modeling of real-world components are eliminated. Consequently, any differences between the results obtained from the SAA and those of the reference run can be attributed to the simulation method itself. The simulations are performed with a passive rider model with a mass of $m_{\text{driver}} = 80 \text{ kg}$. The rider is connected to the bicycle model via handlebars, seat, and pedals. The rider is modeled with nine bodies that are movable relative to each other, see Figure 2a. The position and speed-dependent properties of the legs and arms are represented by force elements. The definition of the body properties and the force elements of the rider are taken from (Ingenlath, 2019). The wheel-track contact is executed via a one-sided constraint with spring and damper properties in the contact point. The wheel properties are also taken from (Ingenlath, 2019). The
track model describes a periodically increasing excitation in frequency and amplitude, generating forces in the x- and y-directions. This is followed by a descent, at the end of which high accelerations in y direction occur, see Figure 2b.

(a) Representation of the passive driver model. The connection points between the system and the environment, where the measurement data for the SAA excitation is recorded, are marked.

(b) Representation of the test track: Following a transient phase, a periodic excitation with increasing amplitude and frequency is applied, resulting in vertical and horizontal excitation. This is followed by a downhill ride that leads to high vertical accelerations.

To compute the excitation and validation loads, the system, consisting of a human and a bike, travels along the track at an initial velocity of \( v_{\text{start}} = 5 \text{ m/s} \). The drive is calculated over a period of \( t_{\text{drive}} = 5 \text{ s} \) with a sample rate of \( f = 1200 \text{ Hz} \). The measured loads at the system boundary, which are further used in order to excite the semi-analytical simulations are defined as follows: Forces in the front (\( F_F \)) and rear hub (\( F_R \)), seat forces (\( F_S \)), forces between the fork and the handlebar (\( F_H \)) and forces between the bottom bracket and the frame (\( F_P \)). As the bicycle only moves on a vertical plane and no chain forces are considered in this work, no torques, rolling, and gearing motions need to be considered. Besides the forces, the position and orientation trajectory of the frame center of gravity are extracted from the simulation.

1.3 Semi-analytical Simulation Setup

In addition to the suitability of SAA for bicycle simulation due to the possibility of overcoming complex modeling tasks, the bicycle system as such is particularly suited to the application of SAA of unconstrained systems. The reason for this lies in the possibility of computing accurate results without replicating the system inertia loads, see Introduction. To examine this thesis in more detail, three simulation setups with artificial constraints are introduced, in which the bicycle is hold on place. In addition, a fourth simulation setup is described where the system is moved along the trajectory of the bicycle measured in the reference drive. Since this enables the recreation of inertia forces within the system, conclusions about the need to account for these inertia forces can be drawn. Gravity is not considered in any of the semi-analytical simulations, since the simulation assumes static equilibrium.

Hub constraints

Based on the principles used in test stand models such as in DIN ISO 4210 (DIN Standards Committee, 2023), and also as a general intuitive way of constraining the bicycle system, a locating-floating bearing setup at the wheel hubs is investigated. Since the wheel loads can be considered as reaction loads resulting from the inertia- or active loads of the bicycle driver system, constraining them could generate reaction loads in the SAA model as well. The locating-floating bearing setup results in two simulation models. One setup with the locating bearing in the front hub, referred to as fixed front hub, see Figure 3a. Secondly, a setup with the locating bearing in the rear hub, referred to as fixed rear hub, see Figure 3b. The locating bearing is constraining all translational DOF and a floating bearing allows only horizontal movement. Both bearings allow a rotation of the hub axis, except for longitudinal rotations of the bicycle. As the hubs are constrained, the only excitation loads the setup requires are the loads induced by the driver. Thus, the hub forces are not required. This is beneficial as in real-world applications, the implementation of a wheel load transducer to measure the hub loads is far more complicated than the measurement setup for the driver loads.
Frame constraints

Furthermore, an artificial constraint setup is examined where all six DOF of the frame are constrained to a fixed point, see Figure 4a. This allows for an excitation with all five input loads, measured in the reference run. This setup is referred to as fixed frame. Finally, in the guided frame setup, the frame is constrained with all DOF to a fixed point that is driven along the pose trajectory recorded in the reference drive, see Figure 4b. This setup aims to reproduce some of the inertia loads of the multi-body system with the goal of increasing the accuracy of the results.

Figure 4: Semi-analytical simulation models with artificial frame constraints

1.4 Evaluation Methods

The evaluation is partially based on a visual comparison of the force-time diagrams at validation points in the bicycle system. In order to make more precise statements and to be able to effectively compare the curves with each other, three characteristic values are introduced. On the one hand, the root-mean-square error (RMSE) between the force-time curve of the fully analytical reference run (Ref) and the semi-analytical approach (SAA) is calculated at the validation points, see Equation (1). To ensure comparability between different datasets the (RMSE)-value is normalized with a range between the maximum and minimum values of the reference data, see (NRMSE) defined in Equation (2). Low values close to zero are considered favorable.

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (SAA_i - \text{Ref}_i)^2}
\]

\[
NRMSE = \frac{RMSE}{\text{Ref}_{max} - \text{Ref}_{min}} \cdot 100
\]
On the other hand, the coefficient of determination \( R^2 \) is used. This coefficient is often used in the evaluation of regressions and shows the correlation between the regression and data points in relation to the x-axis. Applied to the comparison of two force-time curves, the coefficient provides information about the similarity of the course or the correlation of deflections in the loads of the SAA and the reference run (Ref) in relation to the simulation time. Values of this parameter are between zero and one where one corresponds to an exact similarity, see Equation (3).

\[
R^2 = 1 - \frac{\sum (\text{SAA}_i - \text{Ref}_i)^2}{\sum (\text{SAA}_i - \text{SAA}_i)^2}
\] (3)

2 Results

The following section discusses the performance of the four semi-analytical simulation models. The goal is to find a model that is able to reproduce the inner forces in the system based on the excitation loads measured in the reference drive. First, the force-time curves of the SAA results are compared with the loads of the reference drives. Furthermore, the introduced characteristic values RMSE, NRMSE, and \( R^2 \) are used to evaluate the accuracies of the simulations. At the excitation points, the forces in the SAA coincide exactly with the forces from the reference run and are therefore not considered in the evaluation of the agreement of the SAA with the reference data.

Hub constraints

Artificially constraining the bicycle systems using a locating-floating bearing leads in general to similar force-time curves between fixed rear hub and fixed front hub. This is particularly true at the validation points close to the rear hubs. Here, the force curves calculated in both SAA with hubs constraint show good agreement with the loads in the reference run. However, over the entire simulation time, lower absolute forces, in both the x- and y-axis, can be observed for the loads estimated by the SAA simulations. Figure 5 exemplarily shows the force-time curves of the fixed rear hub at the rear two validation points. In Figure 5a, the force comparison between the reference run and SAA is presented, divided into x- and y-axis, for the validation point between frame and chainstay. Figure 5b displays the force comparison at the validation point between the seat stay and lever.
The underestimated forces by both SAA models may be explained due to the lack of active excitation forces at the hubs. The applied driver forces which are directed through the structure and supported at the hub constraints are therefore not capable of reproducing the original hub loads sufficiently. The evaluation based on the characteristic values is shown in Table 1 and Table 2. It can be seen that the accuracies at the rear validation points in fixed front hub are quite similar compared to fixed rear hub. Clear differences between the simulation models can be seen in the front area of the bike. Figure 6 shows the forces in the fork mount for both simulation setups fixed front hub and fixed rear hub. Axial loads (y-axis) in the top fork are not shown in Figure 6a and b, as there is no constraint here and thus no forces arise. Axial movement is the only constraint at the bottom connection between fork and frame. The resulting forces are displayed in Figure 6c and d.

Visible in Figure 6c and d, forces in the axial fork direction (y-axis) can be reproduced relatively well for both SAA simulation models. This is also reflected in the characteristic values, where good agreement in the course of the curve ($R^2$) as well as in the root-mean-square error deviation (RMSE) can be observed, see Table 1 and Table 2. For both models, the accuracy of the axial forces is NRMSE $< 10\%$. However, the radial forces show significant differences between the estimated forces by the SAA and the reference forces. The fixed front hub setup, shows a clear deviation between the reference forces and the calculated forces of the SAA in the fork mount as displayed in Figure 6a and c. The forces in the x-axis show a rather chaotic course, which is reflected in low $R^2$ value, see Table 1. A clear tendency cannot be determined, the forces are partly overestimated and partly underestimated. In comparison the fixed rear hub setup, shown in Figure 6b and d, shows consistently overestimated forces in the x-axis of the
frame-fork connection. Due to the floating bearing in fixed rear hub, horizontal forces induced at the handlebar cannot be supported by the front axle and are transmitted into the frame via a torque. Due to the setup of the constraints, this is reflected in increased forces in the x-axis of both fork frame constraints. The course of both curves shows good agreement for fixed rear hub, which is reflected in R² values close to one, see Table 2.

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<th>fixed front hub model</th>
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<tr>
<td>x-axis</td>
<td>y-axis</td>
<td>x-axis</td>
</tr>
<tr>
<td>frame – forktop</td>
<td>30.66</td>
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<tr>
<td>frame – forkbottom</td>
<td>52.65</td>
<td>frame – forkbottom</td>
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<td>frame – chainstay</td>
<td>21.28</td>
<td>frame – chainstay</td>
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<tr>
<td>seatstay – lever</td>
<td>15.95</td>
<td>seatstay – lever</td>
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Based on the characteristic values the fixed rear hub model (Table 2) shows slightly better results than fixed front hub model (see Table 1). However, further investigations have shown that this tendency is partly dependent on the test track and the resulting excitation. A general statement, on a preference of the approaches, can therefore not be made. At this point, it should also be noted that the implementation of the axial force excitation in the floating bearing can lead to a slight improvement in performance. However, the advantage of being able to perform the simulation independently of hub forces is lost in this scenario.

Frame constraints

Based on the same reference data, the results of the fixed frame and guided frame model are discussed below. The characteristic values determined at the validation points on the x- and y-axis are, respectively, listed in Table 3 and Table 4. Due to the consistently high accuracies of both simulation setups, a visual representation is omitted. Compared to the hub-constraint models presented so far, the fixed frame setup shows significantly more accurate results, both in absolute deviations (RMSE) and in the course (R²), see Table 3. Although a slightly overestimated force can be observed in the load peaks. Based on the accuracy of these results, it can be confirmed that the neglect of the inertia loads of the bicycle system leads only to minor deviations in the calculated loads. The measurement of the center of gravity trajectory is therefore not mandatory to compute accurate results.

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<th>fixed frame model</th>
<th>guided frame model</th>
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<tr>
<td>x-axis</td>
<td>y-axis</td>
<td>x-axis</td>
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<td>RMSE</td>
<td>NRMSE</td>
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<td>frame – forktop</td>
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<td>frame – forkbottom</td>
<td>52.65</td>
<td>3.07</td>
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<tr>
<td>frame – chainstay</td>
<td>21.28</td>
<td>0.57</td>
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<tr>
<td>seatstay – lever</td>
<td>15.95</td>
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Compared to fixed frame, guided frame only shows negligible improvements in force accuracies. The reason for this is that only the inertia loads of the attachment components like fork, seatstay, and chainstay are reproduced by this setup. The inertia loads of the frame are directly supported by the artificial constraints to the fixed point. Accordingly, these do not contribute to the loads in the contact points between the bodies. Measured against the total weight of the rider-bike system, these components play an almost negligible role, which is reflected in the negligibly better simulation results, see Table 4.

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ISSN: 2667-2812 8 of 10
Table 4: Evaluation of the guided frame model

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Although fixed frame and guided frame are straightforward to implement with rigid bodies, there are some challenges to overcome when it comes to the integration of elastic body properties of the frame. Such extensions of the MBS have a significant impact on the simulation results as shown in (Bolk et al., 2023). Constraining the frame results in constraints of single points on an elastic body. This leads to stress changes as loads are significantly higher at the constraint point and thus, natural deformation is restrained. Furthermore, the center of gravity of the frame, used in this work, is often not on the structure itself. A feasible solution could be, e.g., the implementation of a so-called rb3-element between the whole frame and the reference point. This is element is a common modeling element in finit-element-methods that distributes the load over many points on the structure.

3 Conclusion

The work presents and evaluates the performance of four approaches that allow a semi-analytical simulation of bicycles. It was shown that the approach of a locating-floating bearing setup is limited in its ability to reproduce internal system loads. However, by constraining the frame, very high accuracies in the reproduced loads could be achieved. This was shown in the deviation as well as in the agreement of the course between the semi-analytical simulation loads and the reference loads at different points in the system. The hypothesis that for bicycles the neglection of inertia loads leads only to small deviations could be confirmed. This opens up the possibility of obtaining accurate results and numerically representing the internal system behavior without measuring the system trajectory.

Further research relates to the investigation of actively controlled compensation strategies. These strategies can provide the possibility to integrate elastic bodies, further enhancing the accuracy of numerically recreating loads in bicycle structures. Additionally, closed-loop stabilization approaches could allow an even more accurate representation of frame inertia forces if the center of gravity trajectory is known as well as the expansion and integration of torsional loads. Finally, the results need to be confirmed with real-life measurement inputs.

References


