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M. Burger, M. Speckert, K. Dreßler

Optimal control methods for the calculation of invariant excitation signals for multibody systems

Berichte des Fraunhofer ITWM, Nr. 194 (2010)

ISSN 1434-9973

Bericht 194 (2010)

Die Veröffentlichungen in der Berichtsreihe des Fraunhofer ITWM können bezogen werden über:

Fraunhofer-Institut für Techno- und
Wirtschaftsmathematik ITWM
Fraunhofer-Platz 1

67663 Kaiserslautern
Germany

Telefon: +49(0)631/31600-0
Telefax: +49(0)631/31600-1099
E-Mail: info@itwm.fraunhofer.de
Internet: www.itwm.fraunhofer.de

Vorwort

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In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe werden sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

The 1st Joint International Conference on Multibody System Dynamics
May 25–27, 2010, Lappeenranta, Finland

Optimal Control Methods for the Calculation of Invariant Excitation Signals for Multibody Systems

Michael Burger*, **Michael Speckert***, **Klaus Dreßler***

*Department Mathematical Methods for Dynamics and Durability
Fraunhofer ITWM
Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany
e-mail: michael.burger@itwm.fraunhofer.de, michael.speckert@itwm.fraunhofer.de,
klaus.dressler@itwm.fraunhofer.de

ABSTRACT

Input signals are needed for the numerical simulation of vehicle multibody systems. With these input data, the equations of motion can be integrated numerically and some output quantities can be calculated from the simulation results. In this work we consider the corresponding inverse problem: We assume that some reference output signals are available, typically gained by measurement and focus on the task to derive the input signals that produce the desired reference output in a suitable sense. If the input data is invariant, i.e., independent of the specific system, it can be transferred and used to excite other system variants. This problem can be formulated as optimal control problem. We discuss solution approaches from optimal control theory, their applicability to this special problem class and give some simulation results.

Keywords: optimal control, optimization, mbs simulation, invariant excitation.

1 INTRODUCTION

Numerical system simulation plays an important role in vehicle engineering. Virtual prototyping of mechanical systems can accelerate the development process enormously and reduces costs.

For the numerical simulation of mechanical multibody system (MBS) input signals are necessary. Convenient examples of such input data are wheel forces, cylinder displacements of a virtual test-rig or a digital road profile used for driving simulation of a vehicle. This input data is called *invariant*, if it is independent of the specific system under consideration. The main benefit of invariant input signals is the possibility to transfer und use them as excitation for different model-variants, which may only exist as virtual model. In this way, time- and cost-intensive experiments can be avoided.

However output quantities which are typically measured in an experiment, e.g., wheel forces or relative displacements, are often not invariant but highly dependent on the specific vehicle variant that was used for the measurement. Therefore, they cannot be transferred and used as excitation signal for other vehicle-model variants. Thus, the general task is to derive and calculate invariant input signals on the basis of easily measured (but system-dependent) quantities. Mathematically, this leads to an optimal control problem, see section 2.2 for a general formulation.

In this paper we present some approaches for dealing with this problem. State-of-the art in industrial applications is the so called *iterative learning control (ILC)* method. The iterative learning control is a pure black-box method, only the input/output behaviour of the considered system is needed. This makes it also applicable to situations, for which it is hard or even impossible to get an equation, which describes the system properly, such as servo-hydraulic test-rigs in the laboratory. It is based on an identification and linearization of the system in the frequency domain. See [9] for a detailed description and applications. But the method lacks of precise mathematical justification, i.e. , there are no general statements about important properties like accuracy, stability and convergence. Additionally, the identified linear system often does not give an appropriate description of the considered, in general non-linear, system. Of course, this can be seen as a consequence of the minimal system knowledge requirement.

In contrast to the case of a servo-hydraulic test rig in the laboratory, for virtual test rigs or more generally speaking for numerical system simulation on a computer, the system is well-known as multibody system model, mathematically described as differential-algebraic equation. In the investigations presented in this work, we only consider multibody system models. Consequently we assume, that a mathematical description of the considered system is available, at least in a structural sense, e.g., in terms of right-hand-side-calls. We discuss some alternative solution approaches for the problem of deriving invariant input signals. These approaches are based on optimal control theory and make use of the information description of the considered system as multibody system model.

Of course, it is an important aspect how the information and mathematical description of a multibody system model can be revealed. This depends on the way of building and implementing the mbs in first instance, varying from writing the equations of motion by hand to building the model with a commercial MBS software tool like SIMPACK [1], we consider both situations.

The remaining part of this paper is organized as follows: In Sect. 2 we give a mathematical description of the optimal-control problem, we wish to solve and also address the question how information of the mathematical description of multibody system is accessible. In Sect. 3, we describe and discuss to solution methods for that problem and finally, sect. 4 summarizes simulation results for two application examples.

2 MATHEMATICAL PROBLEM FORMULATION AND SETUP

2.1 The Equations of Motion of a Multibody System

A multiobody system generally consists of a finite number of rigid and elastic bodies with masses and moments of inertia that are linked together by joints and force-elements(springs, dampers, driven actuators etc.), which are assumed to be massless. Further, we assume, that the system is excited by a well-defined input signal, e.g., the displacement of some bodies of the system or some forces acting on bodies of the system. The equations of motion describing such a MBS form a second order system of ordinary differential equations(ODE):

$$M(q)\ddot{q} = f(t, q, \dot{q}, u), \tag{1}$$

or, equivalently, as a first order-system

$$\begin{aligned} \dot{q} &= v \\ M(q)\dot{v} &= f(t, q, v, u). \end{aligned} \tag{2}$$

For notational convenience we will often use the short-hand form

$$\dot{x} = f(t, x, u), \tag{3}$$

with $x := (q, v)$ denotes the state vector.

If, however, the system contains kinematically closed loops or constraints, the corresponding equations of motion are given by differential-algebraic equation(DAE) with algebraic equations and variables representing the constraints and constraint-forces.

$$\begin{aligned} \dot{q} &= v \\ M(q)\dot{v} &= f(t, q, v, u) - G(q)^T\lambda \\ 0 &= g(q), \end{aligned} \tag{4}$$

with $G(q) = \frac{\partial g}{\partial q}$. The numerical simulation of the equations (1), (2), (3), (4) has to be performed with a suitable chosen integration scheme, e.g., RADAU5 or SODASRT2 (as implemented in SIMPACK), see [2], [14] for an overview and further information.

The output quantities of the considered system are defined as a given function of the positions and/or velocities q and possibly the input u:

$$y(t) := g_{out}(q(t), \dot{q}(t), u(t)). \tag{5}$$

Now, we assume, that there are some (desired) reference output signals, gained by experiment and measurement, are available as function of time or a sampled time-signal respectively.

2.2 The Optimal Control Problem

We assume, that the MBS including the input interface description defines the input u representing *invariant* input quantities. Then, the problem of deriving (invariant) input signals as described in the introduction leads to the following optimal control problem (OCP):

Find a state variable $x(t) := (q(t), v(t)) \in W^{1,\infty}([0;T])$ and (bounded) input signal $u(t) \in L^{\infty}([0;T])$, such that the cost functional

$$J[x,u] := \|y - y_{ref}\|_{L^2}^2 = \int_{t_0}^{T} \left\|g_{out}(x(t), u(t)) - y_{ref}(t)\right\|^2 dt \tag{6}$$

is minimized, subject to the ODE/DAE (1), (2), (3), (4) respectively and given some (consistent) initial conditions

$$x(t_0) = x_0. \tag{7}$$

For algorithmic reasons, it is sometimes useful to consider the augmented cost functional:

$$J[x,u] := \int_{t_0}^{T} \left\|g_{out}(x(t), u(t)) - y_{ref}(t)\right\|^2 + r \cdot \|u\|^2 dt, \tag{8}$$

where $r\|u\|^2$ is a penalty term with r typically taking values from 10^{-4} to 10^{-8}.

2.3 Access of the Equations of Motions

As already mentioned the way of accessing the mathematical description of a MBS, i.e., the equations of motion, is an important issue. Full information of the considered system is provided, if the equations of motion can be derived and written symbolically by hand. Naturally, this is the most elaborate and time-consuming approach and realistic only for small systems, but it allows to establish exact formulas for derivatives of the right-hand-side: $\frac{\partial f}{\partial x}$. The next advanced possibility is to implement the equations of motion numerically by hand meaning, that values for kinematic and dynamic quantities (such as displacements forces,..) are evaluated numerically by predefined functions in each call of the right-hand-side. However, the most interesting case is building the MBS with a (commercial) MBS software tool. In this work we study this situation on the example of the MBS software tool SIMPACK. The latter provides a CodeExport functionality, which allows to generate, e.g., FORTRAN subroutines. After some involved modifications, these subroutines allow to call the right-hand-side of the equations of motion. We used this feature for the example presented in sect. 4.2.

3 APPROACHES FROM OPTIMAL CONTROL THEORY

In this section, we describe shortly the main ideas of two solution methods for the optimal control problem (OCP) as stated in sect. 2.2. The first one is a so called *indirect* method and a *direct* method based on discretization of the optimal control problem. We also consider the indirect method for the special case of a linear system equation and propose a combination of that indirect approach and a direct optimization strategy.

3.1 An Indirect Method

In this section, we restrict ourselves to the case, that equations of motion are given as an ODE and we assume, that there are no constraints on the control u.

From the theory of functional analysis and the calculus of variations one can derive ([15, 4]), that a necessary condition for (x, u) being a minimizer of (OCP) is, that they fulfill the following equations:

$$
\begin{aligned}
\dot{x} &= f(t, x, u), & x(t_0) &= x_0, \\
\dot{p} &= -f_x^T p - \sum_{i=1}^{n_y} 2 g_i \cdot \left(\frac{\partial g_i}{\partial x} \right)^T, & p(T) &= 0, \\
0 &= p^T f_u + 2 \cdot r \sum_{i=1}^{n_u} u_i,
\end{aligned}
\tag{9}
$$

where g_i denotes the $i-$th component of the vector $(g_{out}(x(t)) - y_{ref}(t))$. $p \in \mathbb{R}^{n_x}$ are so called adjoint variables. Recall, that r is a penalty factor. These equations form a system of differential-algebraic equations with two-point boundary conditions, which have to be solved for (x, p, u). Thus, they provide the possibility to calculate the *exact* solution of the optimal control problem - of course only in case of existence. However, those types of equations are numerically hard to solve. Additionally and most important, the right-hand-side of eq. (9) requires with each call the derivatives of the right-hand-side of the MBS: $\frac{\partial f}{\partial x} \cdot \frac{\partial f}{\partial u}$. In case of evaluating those derivatives numerically, e.g. by finite differences, this is a very costly, time-consuming and unstable task. Therefore, it is not advisable to use this approach for general nonlinear systems, possibly only available in a commercial MBS tool.

The situation, however, looks quite different, if we only consider linear, time-invariant systems, i.e., the right-hand-side of the MBS and the output quantities take the form

$$
\begin{aligned}
f(t, x, u) &= A \cdot x + B \cdot u, \\
g_{out}(x(t)) &= C \cdot x
\end{aligned}
\tag{10}
$$

with constant matrices A, B, C of proper dimensions. Now, with a suitable transformation, we can reduce the problem of solving eq. (9) to solving firstly the following algebraic equation of Riccati-type for the matrix K:

$$0 = -KA - A^T K + KBR^{-1}B^T K - C^T QC, \tag{11}$$

and secondly solving the following ODE backwards in time:

$$\dot{g} = -\big(A - BR^{-1}B^T K\big)^T g - C^T Q y_{ref}(t) \qquad g(T) = 0, \tag{12}$$

and finally, the optimal state x is gained by solving

$$\dot{x} = -\big(A - BR^{-1}B^T K\big)x + BR^{-1}B^T g(t) \qquad x(t_0) = x_0. \tag{13}$$

Then, the optimal control input u is given by

$$u(t) = R^{-1}B^T\big(g(t) - Kx(t)\big). \tag{14}$$

The last two differential equations (12), (13) are ordinary, linear, inhomogeneous differential equations with constant matrices, which can be solved with a moderate numerical effort. See [16] for more details on that Riccati-type approach for linear systems.

If the system is linear, but time-invariant, the situation gets more involved: Eq. (11) has to be replaced by a matrix differential equation of Riccati-type (see [16]), their solution can bring up some numerical difficulties. If the equations of motion or given in its most general form as DAE, necessary conditions corresponding to (9) can also be derived, at least if the DAE is of index not higher than two, see [13].

To summarize, the indirect approach described above states necessary conditions on the exact solution of the optimal control problem. It is a suitable solution strategy for linear time-invariant systems. For general non-linear systems, it seems not useful because of the costly and unstable numerical calculations that are needed. However, even in that case the method can bring some benefit, especially, if the system is of moderate size and complexity and whence, the equations of motion can be derived and implemented by hand (or by a tool that generates symbolical equations of motion). Then, information about the derivatives of the right-hand sides are available and problem (9) could be solved numerically. But in most situations the MBS is of large

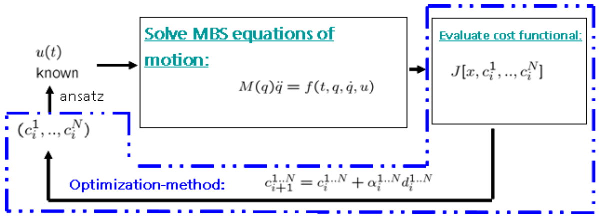


Figure 1. Optimization procedure

size and/or complexity and is only implemented in a commercial software tool. Nevertheless, the indirect approach can be applied to a linearization of the non-linear system. Sometimes an input calculated in this way may be satisfactory, e.g., if the system has only weak non-linearities. But often this is not the case, then, that input can serve as a starting point for an iterative optimization strategy as discussed in the next section.

3.2 A Direct Approach: Discretization of the OCP

The direct approach we discuss in this section is based on a discretization of the OCP ([12]). To this end, we approximate the input u by the function

$$u_{app}(t; c_1, .., c_N) := \sum_{i=1}^{N} c_i \cdot B_i(t) \tag{15}$$

on a time-grid

$$\pi_u := \{t_1, .., t_M\} \subset [0; T]. \tag{16}$$

The functions B_i are any suitable Ansatz-functions, e.g., B-splines. In case of B-splines of order 1 (constant on each subinterval) and 2 (linear on each subinterval), which is sufficient in most situations, the corresponding coefficients c_i can be interpreted as function values:

$$c_i = u_{app}(t_i; ..) \approx u(t_i). \tag{17}$$

After a discretization of the cost-functional (or alternatively by a problem reformulation, see [5])

$$J[x, u] \approx J_{approx} := \sum_{j=1}^{N} h_j \cdot (g_j^2 + r u_j^2), \tag{18}$$

where $g_j := g_{out}(x(t_j), u(t_j)) - y_{ref}(t_j)$ and $u_j = u_{approx}(t_j; ..)$, one has reduced the continuously defined optimal-control problem to a discrete optimization problem (DOCP):

Minimize the discretized cost functional

$$J_{approx}[x, u] \tag{19}$$

with respect to the (finite dimensional) optimization variable

$$\zeta := (c_1, .., c_N). \tag{20}$$

Such an optimization problem can be solved by any suitable iterative algorithm such as Gauss-Newton-methods or SQP-methods ([6]). Take aware, that for each set of values for the optimization variable $(c_1, .., c_N)$, which in turn define uniquely the corresponding approximated input $u_{approx}(t; ..)$ on the complete time interval $[t_0; T]$, the equations of motion have to be solved. Then, the corresponding value of the (approximated) cost can be evaluated and the iterative algorithm can proceed to the next step. Fig. 1 highlights this process schematically.

There are many extension to this basic principle, e.g., one can introduce an additional state-grid (multiple-shooting) or optimize over a moving time horizon. See [3] for an introductive overview.

3.3 Comparison

Both methods have their benefits and drawbacks. The first indirect approach provides a procedure to calculate the exact optimal solution (x, u), whereas the second method only derives an approximation. On the other hand, the first method requires time-consuming and numerical unstable calculations only to setup the equations, which in addition have to be solved numerically. This can be overcome with a acceptable effort only for linear (time-invariant) systems of moderate size and stiffness-properties. The second method requires an iterative optimization algorithm and in each step only the equations of motion of the MBS have to be solved. Therefore, it is not so costly (apart from possibly required sensitivities for the optimization method) and can be applied to general non-linear systems without too much effort. As already mentioned, a synthesis of both, in which the first method provides a starting point for the second method by solving the problem of the linearized system, can be of advantage.

3.4 Implementation and Sensitivities

The indirect approach has been applied successfully to both linear and nonlinear systems of moderate size and complexity, which could be implemented by hand, such as the (simple) tire-substitute model in sect. 4.1. To solve eq. (9) numerically by a suitable boundary-value-problem solver, it is strongly recommended to provide the derivatives of the right-hand side of (9) analytically.

To apply the direct approach described above, we have used the optimal control software package of M. Gerdts [11].

Since a numerical optimization algorithm usually requires the gradient of the objective function with respect to the optimization variables, i.e., in our case: $\frac{dJ_{approx}}{dc_i}$, the task arises to calculate the sensitivities $\frac{\partial q}{\partial c_i}, \frac{\partial v}{\partial c_i}$ in each iteration step of the optimization procedure. An often used solution of this problem is the simultaneous integration of the original system equations and the N additional sensitivity-ODE/DAE-systems, which are gained by differentiating the original ODE/DAE with respect to the parameter c_i; recall, that N denotes the number of the discretization variables. However, in the special class of optimal control problems, we consider here, the number of variables c_i that are necessary to approximate the input function $u(t)$ adequately is typically very large - also in comparison to number of state variables $x = (q, v)$. In that case the calculation of the sensitivities can be achieved more efficiently by use of the adjoint method, see [8, 7]. This approach addresses directly the calculation of sensitivities of derived functions that have integral-form as our cost functional (6), (8). To this end, the integration of *only one* additional, so-called adjoint system is required - independently of the number of sensitivity-parameters. This adjoint system reads as follows for our problem formulation:

$$\dot{p} = -\left(\frac{\partial f}{\partial x}\right)^T p - \sum_{i=1}^{n_y} 2g_i \cdot \left(\frac{\partial g_i}{\partial x}\right)^T, \tag{21}$$

with adjoint variables p. (21) is linear in p and has to be solved backwards in time with special end-conditions. Note, that this is exactly the same equation as in (9), but here, it is *decoupled* from the state $x = (q, v)$. See [8] for a detailed derivation of that approach.

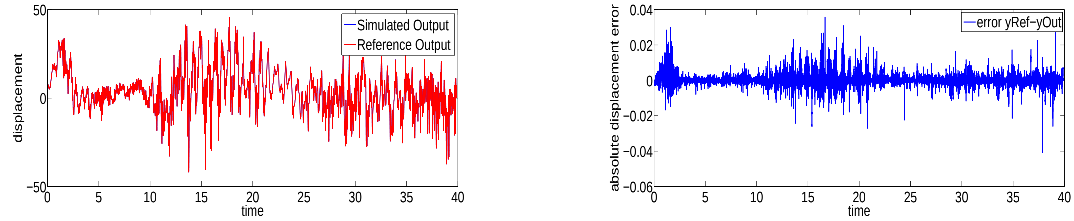
We have used the adjoint method to calculate required sensitivities in combination with OC-DAE1.

4 Application Examples

In this section we give two examples, where the solution approaches for the OCP presented in the previous section have been applied. The first one is taken from automotive industry and in the second one, the considered MBS is an established planar truck-model [10].

4.1 Application example from automotive industry: Invariant Excitation for a SUV

In this application a SUV-model is considered. The overall goal is to derive a virtual road profile as invariant input signal. To this end, the advanced tire-model is replaced by very simple one: a linear two-mass-spring-damper system in all three translational degrees of freedom, which are considered independently of each



(a) Simulated and reference Output (b) Difference between simulated and reference output

Figure 3. Simulation Results

other.

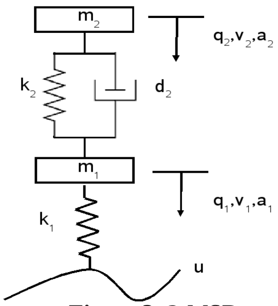


Figure 2. 2-MSD

Then, transferred into our general problem setup, the output quantity is the displacement of the highest mass representing the displacement of the hub, whereas the the input quantity is the displacement of a virtual road point, cf. fig. 2. In literature, such a model is often referred to as quarter vehicle. As reference output a sampled time-series for the rim-displacement is available for all three directions gained from measurement/simulation during an experiment on an off-road test-drive. Be careful, that in this example not the complete SUV-MBS-model is the considered dynamic system, but the tyre-substitute model consisting of a linear mass-spring-damper system. Obviously, the equations of motion are given as a time-invariant linear system of dimension four. Therefore, the indirect method discussed in sect. 3.1 is a good choice and has been applied for this example. Fig. 3 shows some simulation results, exemplarily for one tire substitute for the vertical direction. The left diagram contains a section of the simulated and the desired reference output, whereas the right one shows their difference, the absolute error is of order 10^{-2}, this corresponds to a relative error of order 10^{-4}. The cost functional has been augmented with a penalty factor of 10^{-4}, with a smaller penalty factor, the absolute error can be decreased further, which in turn requires a higher numerical effort.

4.2 A Truck Model

In this example, a planar truck model is considered. The model has nine degrees of freedom and has been used in its unconstrained version, see [10]. The truck is modelled with air springs, i.e., besides the geometrical non-linearities, it includes non-linear force-characteristics. Thus, the equations of motion are given by a non-linear system of ODEs. For comparative reasons and to setup a more realistic situation, the model has been built up in the MBS tool SIMPACK. Similar to the previous example, the displacement of a virtual road point at rear and front wheel is defined as input quantity, cf. fig. 4 The vertical displacement of the chassis body, the loading area and the cabin are chosen as output.

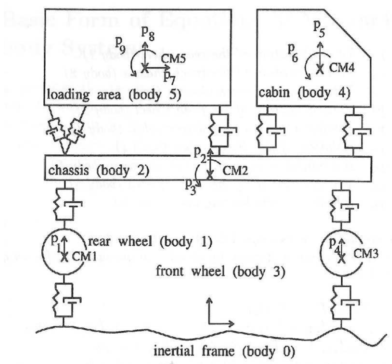


Figure 4. Truck MBS, [10]

For the reference signal, we have taken a signal that has been generated by exciting the truck model by a highly uneven vertical road profile. For the solution of this task, we have advanced in the following way: Within the software tool, we have generated a linearization of the system around its static equilibrium point, i.e., the matrices A, B, C, cf. sect. 3.1. Then, using the indirect Riccati-type method from sect. we have calculated an input signal as starting point for an iterative optimization procedure based on the direct discretization procedure from sect. 3.2. In order to perform the latter, with SIMPACK's CodeExport functionality, FORTRAN routines have been generated, which provide us with right-hand-side calls of the full non-linear system. They have been included and serve as interface to the Optimal Control Soft-

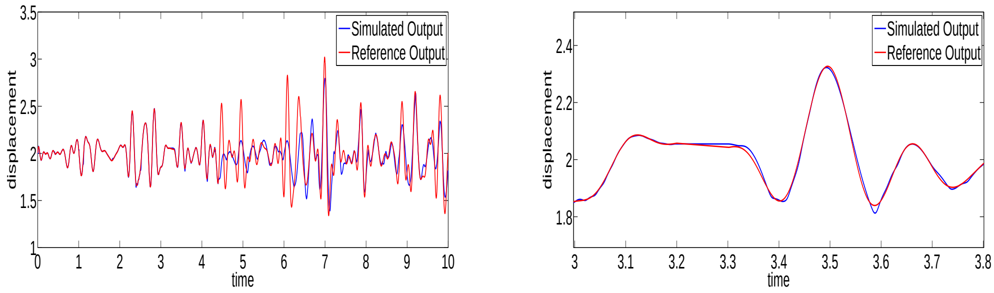


Figure 5. Simulation Results for the truck example

ware OC-DAE1, [11]. Recognize, that in this example the input quantity u, representing the virtual road profile, enters the model at two different time points, namely, at time t at the front wheel and at time $t - td$ at the rear wheel, where td is constant delay - assuming, that the truck is moving with constant speed in x-direction. This leads to an optimal control problem with delays and requires some slight but advanced mathematical modifications in both approaches. However, the general principle remains the same.

Fig. 5 shows the results. The absolute error is of order 10^{-1}, i.e., the relative one of order 10^{-2}. As mentioned the results could be improved by some involved extensions and modifications of this approach such as an additional state grid or moving time horizon. We are currently working on these topics.

5 SUMMARY

In this work, the problem of deriving (invariant) input signals for a MBS is formulated as an optimal control problem. Based on this formulation solution strategies from optimal control theory can be applied. Indirect approaches and a direct discretization method are discussed. The first are a suitable choice for linear systems of moderate size and complexity, whereas the latter is applicable to general full non-linear MBS, which can be modeled in a commercial MBS software tool. For that case, the indirect method can provide a starting point for the iterative optimization process, if it is applied to a linearization of the MBS.

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