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Research paper

On multibody-system equilibrium-point selection during joint-parameter identification: A numerical and experimental analysis

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ABSTRACT

Computational simulations of a multibody dynamic response are an important tool for the analysis and design of various mechanical systems. While the governing dynamic equations of these systems are well known, the identification of model parameters, especially those associated with joints, can prove difficult and time consuming. Traditionally, experimental methods are used to deduce the physical joint parameters by isolating the joint from the rest of the structure and testing it under static or dynamic loads. An alternative to pure experimental joint-parameter identification is the model-based methods, which rely on finding such parameter values that the predicted dynamic response coincides with that of the real system. As the equations of multibody systems are highly nonlinear, linearization techniques are applied to efficiently deduce the system's dynamic parameters using modal analysis. Although significant progress has been made in recent years, none of the studies that propose the linearization technique has addressed the effect of multibody system equilibrium-point selection on the accuracy of the parameter-identification procedure. Therefore, here, a new general model-based parameter-estimation method is proposed that minimizes the difference between the experimentally and numerically obtained dynamic system's natural frequencies. The basic idea of the proposed method relies on the development of an algorithm that identifies the optimal equilibrium point of the linearization for a given multibody system. The equilibrium point is deduced in such a way as to minimize the interplay between the different joint parameters on the system's natural frequencies. Using the proposed approach it is possible to localize the influence of the individual joint's stiffness parameters to one particular natural frequency. The presented case study highlights the efficiency of the developed parameter-estimation procedure and with this the importance of a proper linearization equilibrium-point selection for a reliable and accurate parameter-identification process.

1. Introduction

Due to advancements in the power of computers, computational simulations of a multibody system's dynamic response have become an important tool for the design and analysis of physical systems. Real mechanical systems usually consist of

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many components that are connected together though various joints. The mathematical formulations governing the dynamics of a multibody system are generally known and can be obtained from numeric or symbolic algorithms [1]. Although the governing equations are well defined, the modeling of such systems still represents a challenge due to the uncertainty in the system's parameters, especially those associated with the joints. The identification of a joint's stiffness and damping properties [2–4] is therefore of great importance for the development of validated numerical models.

Traditional experimental methods deduce the physical joint's parameters by isolating the joint from the rest of the structure and testing it under static or dynamic loads [5,6]. The removed joint is installed in the test apparatus using additional joints that can affect the quality of the measurement results. The testing conditions such as loads, pre-loads, temperature, surface mating, position, etc., also determine the joint's physical characteristics [7] and are sometimes hard to reproduce in a laboratory. As modern materials are frequently nonlinear in nature, the test-obtained joint parameters might also not be applicable for the end use of the modeled product. Moreover, it is practically impossible to isolate the joint in certain cases, e.g., in biomechanical systems, where we also have to account for the elastic and nonelastic power that the muscle systems set against the externally induced motion of the joint [8–10].

Alternatives to the pure experimental joint-parameter identification are the model-based methods, which are typically a combination of experimental data and the results obtained from numerical models. The identification problem focuses on finding such parameter values that the predicted dynamic response coincides with that of the real system [11,12]. The cost function is defined in terms of an output error, which leads to a maximum-likelihood estimation. The equations describing the dynamic response of multibody systems are usually highly nonlinear. This is due to the geometrical nonlinearities associated with rigid-body rotations, which makes the problem of parameter identification particularly challenging [13]. The majority of the contributions devoted to this subject have focused on some specific applications, such as robotics [14–17] or biomechanical systems [18–20]. In robotics, motors are usually placed at the joints for control and the joint parameters (stiffness, damping, ...) are obtained by comparing the robot dynamic model with either the measured motion (usually at the end-effector) [16,21] or the motor force/torque [22,23]. Researchers in [24] used springs to model the transmissions between motors and the rigid links in flexible-joint robots. This approach resulted in supplementary degrees of freedom in comparison to rigid body robot modeling. A detailed joint model was used in [23], which included backlash, friction on motor and arm side, damping and nonlinear stiffness. A frequency-domain joint model parameter identification was also utilized, e.g. [24] used only motor-side measurements to obtain the system frequency response functions.

Compared to the area of robotics, relatively little attention has been paid to joint-parameter estimation in the general area of multibody systems [25–27]. The presence of nonlinearities greatly complicates the parameter-identification process since the linear-superposition principle becomes inapplicable and therefore an explicit time integration must be performed to obtain the system's dynamic response. A time-domain procedure for the parameter identification of a nonlinear, multi-degree-of-freedom system was presented in [28]. In [13] the authors proposed a Lie-series technique to estimate the parameters of general multibody systems. In order to achieve a more effective and less time-consuming parameter-optimization process it is often desirable to linearize the equations of motion. The researchers in [29] developed a parameter-identification scheme for linear or linearized systems that are limited to the modeling of torsional vibrations in mechanical systems like rotors and power trains. Researchers have also presented a method that rewrites the equations of motion into a linear form with regards to the parameters that are to be identified [30,31]. The method is broadly used in the field of robotics for calibration and control and is therefore intended for fast, real-time calculations. The robot dynamic model parameters are identified using the standard least squares techniques by comparing the calculated and measured joint torques, positions, velocities and accelerations [32,33].

Although significant progress has been made in recent years, none of the above studies has addressed the effect of multibody-system equilibrium-point selection on the accuracy of the parameter-identification algorithm. Therefore, in our study, a new general model-based parameter-estimation algorithm is proposed that relies on the optimal system's equilibrium-point selection during the joint-parameter identification process. The method is based on minimizing the difference between the experimentally and numerically obtained dynamic system's natural frequencies. The comparison of the natural frequencies is used as they are highly sensitive to any change of the system's parameters and can also be measured with a high degree of accuracy [34]. As the equations of multibody systems are highly nonlinear, the symbolic linearization technique is applied to extract the modal parameters. While there are a number of linearization techniques used to calculate the time responses for a specific set of initial conditions [1,35], only limited work has been done to obtain local linearizations of multibody systems at equilibrium points [36,37]. In our paper the method presented in [37] and upgraded in [35] is utilized because it enables the linearization of a general multibody system at any selected equilibrium point. The basic idea of the proposed parameter-identification procedure relies on the implementation of an algorithm that deduces the optimal equilibrium point for the linearization of a given multibody system. The equilibrium point is chosen in such a way as to minimize the interplay between different joints for the system's natural frequencies. Using the proposed approach it is possible to localize the influence of an individual joint's stiffness parameters to only one selected natural frequency. This results in an accurate and efficient procedure that makes it possible to exploit all the advantages of a on-line parameter estimation.

The efficiency of the proposed parameter-estimation algorithm is demonstrated on a numerical and experimental case study, by estimating the joint-stiffness parameters of a given mechanism. The presented case study highlights the importance of a proper linearization equilibrium-point selection for a reliable and accurate identification of the joint parameters.