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A pose-based structural dynamic model updating method for serial modular robots

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ABSTRACT

A new approach is presented for updating the structural dynamic component models of serial modular robots using experimental data from component tests such that the updated model of the entire robot assembly can provide accurate results in any pose. To accomplish this, a test-analysis component mode synthesis (CMS) model with fixed-free component boundaries is implemented to directly compare measured frequency response functions (FRFs) from vibration experiments of individual modules. The experimental boundary conditions are made to emulate module connection interfaces and can enable individual joint and link modules to be tested in arbitrary poses. By doing so, changes in the joint dynamics can be observed and more FRF data points can be obtained from experiments to be used in the updating process. Because this process yields an over-determined system of equations, a direct search method with nonlinear constraints on the resonances and antiresonances is used to update the FRFs of the analytical component models. The effectiveness of the method is demonstrated with experimental case studies on an adjustable modular linkage system. Overall, the method can enable virtual testing of modular robot systems without the need to perform further testing on entire assemblies.

1. Introduction

Serial modular robots (SMRs) consist of several interconnected joint and link modules which can be disconnected and reassembled to perform a variety of tasks depending on required motion and workspace requirements. The geometry of an individual SMR module usually consists of an actuated joint which drives a connected link. As self-contained units, the motions of individual joint-link modules can be independently controlled. Also, with an increase in the number of modules, the structural dynamic models of SMRs can become quite large thereby increasing the numerical complexity. Therefore, vibration model reduction procedures, such as component mode synthesis (CMS) [1] may prove useful when analyzing SMR assemblies. Furthermore, the reduced component models of SMR modules may contain uncertain parameters, such as joint or connection stiffness and damping. When analytical CMS assembly is performed for SMR modules, if the structural dynamic models of individual components contain errors, the required accuracy of the assembled SMR model may not be within satisfactory limits. Thus, the entire model of the SMR assembly may require updating using experimental data, which is a difficult task if a large number of modules exist within an assembly (hence large number of simultaneous model updating parameters). Conversely, if the individual modules are experimentally tested beforehand, the model updating

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process can become more efficient since the number of simultaneous updating parameters can be reduced drastically. Afterwards, if the updated component models of SMR modules are well-correlated with experiment data, the assembled CMS model can be used to perform further testing in a virtual environment, thereby reducing the need for extensive experimental tests on an entire SMR assembly.

Unlike typical industrial manipulators, whose components are not readily detachable, the attachment points (or connection interfaces) between SMR modules may contribute to the dynamic behavior of the components. Therefore, connection stiffness, mass and damping should be accounted for in the experiment and updated model. Also, the experiment boundary conditions (BCs) should match the module connection interfaces as closely as possible. Additionally, the experiment and CMS BCs must be carefully selected to allow tests in different module poses for pose-based structural dynamic model dependencies. Moreover, the individual modules will experience stiffened dynamic behavior during component tests, as compared to testing an assembled SMR. As a consequence, the experimental mode shapes and natural frequencies of individual modules will occur at higher frequencies than those of an assembled SMR. Hence, the use of experimental FRF data across the entire measurement bandwidth should be more beneficial for model updating of individual components, rather than the use of measured natural frequencies and mode shapes alone. Furthermore, FRFs contain a greater number of data points than modal data for the same number of tests, and can contain information about component modes that cannot be directly measured or out of the bandwidth [2,3] such as joint stiffness or connection dynamics. Also, FRF data can be specified for any number of measurable DOFs, whereas critical mode shape information may be lost if there are too few measurement points.

The existing CMS methods were applied for the vibration analysis of non-modular robots. Imam et al. [4] developed a CMS model for planar mechanisms and observed the changes in natural frequencies with respect to mechanism motion. Shabana and Wehage [5] proposed a floating frame approach for the vibration analysis of serial robots using free-free component BCs to perform CMS. De Smet et al. [6] created a stationary vibration model of an industrial manipulator using Craig–Bampton CMS with fixed link boundaries, and validated their results in two different poses. Jen and Johnson [7] used a CMS model with free-interfaces to study the effects of pose changes and payload variations on the stationary vibration characteristics of a planar manipulator. Xianmin et al. [8] used a free-interface CMS method with residual flexibility attachment modes to model flexible parallel mechanisms in different poses. Park and Mills [9] modeled a manipulator connected to a flexible payload using fixed-interface CMS to reduce the complexity of the dynamic equations of motion. More recently, Gerstmayr et al. [10,11] developed absolute nodal coordinate formulations for their CMS models using the Craig–Bampton [1] method.

In the current literature, there are no CMS methods applied to modular robots. For the majority of CMS procedures, the choice of component modes used in the reduction process is dictated by the boundary conditions (BCs) imposed on each substructure model. So far, the existing robot CMS models involved separating the components directly at the movable joints. These methods make the experimental vibration testing of robot components difficult since the influence of joint dynamic parameters and component connection dynamics cannot be included if free-free component BCs are used. Alternatively, the simplest BCs to implement for SMR joint-link modules would be to fix one end of an active joint and free the end of the link. The use of hybrid fixed-free interfaces could enable joint-link modules to be tested at different joint angles to identify pose-based structural dynamic dependencies. Furthermore, the natural connectivity at the base of a joint module with a preceding link module can be preserved if the experimental BCs closely mimic the connectivity conditions when the modules are assembled. This can allow for an experimental estimation of the unknown joint and connection interface structural dynamic parameters by observing changes in the FRF data. Although CMS methods with "mixed" BCs were studied for robots [12], the interface conditions between adjacent components were either all free, or all fixed. Therefore, a hybrid CMS method is needed which motivates the research in this paper.

The model parameter updating techniques have been successfully developed and applied to typical non-modular robots. Pham et al. [13] developed an updating method to identify the joint stiffness of a serial manipulator with rigid links and flexible joints. Alici and Shirinzadeh [14] created an identification procedure to determine the joint stiffness of a fully flexible 6-DOF serial robot using static tests in 20 different poses. Zhou et al. [15] created an eigenvalue sensitivity method to identify the joint dynamic parameters of a parallel robot using 28 different robot poses. A similar approach was used by Rognant et. al [16] for a parallel robot by minimizing the sum of squares error between the analytical and experimental FRFs. Dumas et al. [17] developed a static joint stiffness identification procedure for 6-DOF industrial manipulators subjected to an external payload force using three robot poses. Only a few publications apply model updating methods for modular robots. The research group of Li et al. [18] devised a joint stiffness updating method using modal data for a 9-DOF (nine revolute joint modules) serial modular robot. However, the solutions obtained in [18] may not be valid for different robot poses since the joint parameters were identified using a single robot pose.

Currently, there are no true component testing and model updating approaches in the literature for individual SMR modules. That is, the majority of available robot updating techniques use experimental data for the entire robot assembly, instead of testing the individual modules separately and performing the model updating stages at the component level. To address these issues related to the component structural dynamic model updating of SMRs, a new methodology is presented in this paper. The objective is to avoid experimentally testing a fully assembled SMR by obtaining accurately updated CMS reduced-order component models of each module such that the updated CMS model of the entire assembled system can provide accurate structural dynamic results in any possible pose. This is achieved by updating the component models of each module using experimental data from individual component tests which mimic their natural interface boundaries with