Development of identification method for minimal set of inertial parameters of multi-body system

Takahiro Homma[1], Hiroshi Yamaura[2]

[1]Department of Mechanical Engineering
Tokyo Institute of Technology
2-12-1 Ookayama Meguro-ku, 152-8852 Tokyo, Japan
honma.t.aa@m.titech.ac.jp

[2]Department of Mechanical Engineering
Tokyo Institute of Technology
2-12-1 Ookayama Meguro-ku, 152-8852 Tokyo, Japan
yamaura.h.aa@m.titech.ac.jp

EXTENDED ABSTRACT

1 Introduction

In motion control and motion simulation, inertial properties (mass, center of gravity, inertia tensor) of object are fundamental and important parameters that serve as input values and have a significant impact on the accuracy of results, therefore correct identification method of inertial properties are strongly demanded. Methods for identifying inertial properties can be classified into two types: theoretical calculation using CAD and other computational methods, and experimental identification with measurement data. Experimental identification is also important as a means of verifying the results of theoretical calculation methods. For this reason, various methods have been developed for the identification of the inertial properties of single-body. In particular, identification methods based on free vibration measurements [1] have been developed in recent years, making it possible to measure inertial characteristics with sufficiently high accuracy and speed for practical use.

In robotics and ergonomics, geometric parameters such as link lengths and the inertial characteristics of individual links are required when dealing with multi-body dynamics models consisting of multiple parts connected by joints. Furthermore, there is a demand to identify the inertial properties of the links in the connected state, due to the identification requirements of the mechanism such as robot in the assembled state and the constraint that the body cannot naturally be detached in the measurement of the human body. While geometric parameters can be easily identified from static measurements, the inertial properties of individual links cannot be identified from link motion and inter-joint torque or external force data, because they are redundant to the multi-body dynamics model. Therefore, the minimum dynamic parameters necessary to represent the multibody dynamics model has been defined and identified. These dynamic parameters are obtained by combining the geometric parameters and the inertial properties of the counterpart elements and are called the minimal set of inertial parameters.

Numerical and analytical methods for calculating the minimal set of inertial parameters have been established [2] and various experimental identification methods have been developed. The conventional identification methods utilize a set of measured link motion and inter-joint torques [3] or a set of measured link motion and floor reaction forces [4]. The former requires a torque sensor for every joint. Thus, it cannot be used in cases where it is difficult to estimate or measure joint torque, such as humans and humanoid robots. The latter can only identify the minimal set of inertial parameters for a plane in the direction of travel from movements such as walking. It has problems such as the difficulty in selecting an effective motion for identifying all minimal set of inertial parameters and the large measurement error and has not yet applied to the identification of individual human bodies.

In the previous method for identifying inertial properties by free vibration measurement [1], the free vibration of an object with small amplitude is measured under the pseudo-peripheral free boundary condition with suspension springs. The effect of the suspension spring is precisely modelled and considered to enable highly accurate identification. By expressing the external force on the suspension spring in three dimensions in terms of a stiffness matrix, if either the force or displacement on the suspension spring is measured, it is possible to calculate the other. The advantage of this method is that the external force can be calculated by measuring the position of the platform suspended by suspension springs, and no actuator or load cell is required. However, this method is the identification method for single-body and cannot simply be applied to the identification of the minimal set of inertial parameters of multi-body system.

Based on this background, this study developed a new method for identifying the minimal set of inertial parameters of multi-body system by expanding and applying the identification method based on free vibration measurements, which is a method for identifying the inertial characteristics of a single-body, and evaluated its performance.

2 Identification method for minimal set of inertial parameters of multi-body system

In our new method, the procedure for identifying the minimal set of inertial parameters of a multi-body system consists of two steps. The multi-body system is modeled as a base link suspended by suspension springs and other links. In the first step, the relative motion between the links is fixed to set a posture and the overall inertial properties in several postures are identified by using identification method for the single-body inertial properties [1]. From these identification results, equations (1) for the position of the center of gravity of each link and the whole multibody system and equation (2) for the moment of inertia can be obtained for several postures corresponding to the number of measurements.

$$\mathbf{MG}_i = m_0\mathbf{g}_0 + \sum_j^n (m_j\mathbf{g}_{ji}). \tag{1}$$

$$\mathbf{J}_i = \mathbf{I}_0 + \sum_j^n (\mathbf{I}_{ji} + m_j [\mathbf{g}_{ji} \times]^T [\mathbf{g}_{ji} \times]). \tag{2}$$

where the subscript 0 indicates the base link, j indicates the jth link, i indicates the ith measurement, M and m are the mass of the whole system and the mass of each link, respectively, $\mathbf{G}$, $\mathbf{g}_0$ and $\mathbf{g}_i$ are the position vector of the center of gravity of the whole system, the base link and link j from the origin of the base link coordinates, $\mathbf{J}_i$ and $\mathbf{I}_0$ are the moments of inertia of the overall and base link around the origin of the base link coordinates and $\mathbf{I}_j$ is the moment of inertia of link j around the link j center of gravity indicated by the base link coordinates.

These results make it possible to identify the minimal set of inertial parameters except for the moment of inertias. But equations between the moment of inertias can be also obtained.

In the second step, in order to identify the minimal set of inertial parameters for the moment of inertias, these equations are used. Then, the moment of inertias can be identified from relatively simple movements, such as the relative motion of links on a certain plane. In experiments, relative motion between the links is measured. This movement is induced using muscle force or the repulsive force from the springs attached between the links. The external forces are the forces received from the suspension springs of the measurement system installed to create the boundary conditions of pseudo peripheral freedom, which can be calculated from the position measurements because they are modelled precisely. The equation of motion for the joint-torque-independent part caused by these internal forces is given by equation (3) based on n-link's equation [5].

$$\mathbf{H} \begin{bmatrix} \ddot{\mathbf{q}}_o \\ \ddot{\mathbf{q}}_c \end{bmatrix} + \mathbf{b} = \mathbf{K} \cdot \mathbf{q}_o. \tag{3}$$

where $\mathbf{H}$ is the inertia matrix, $\mathbf{b}$ is the sum of the Coriolis force, centrifugal force and gravity force, $\mathbf{K}$ is the stiffness matrix related to the forces received from the suspension springs [1], $\mathbf{q}_0$ are the generalized coordinates of the base link corresponding to the foundation of the link system and $\mathbf{q}_c$ is the joint angle vector.

Equation (3) can be transformed using the minimal set of inertial parameters as in equation (4), from which the minimal set of inertial parameters for the moment of inertias are identified. As can be seen from equation (4), the measurement of joint torques is not required.

$$\mathbf{Y} \cdot \boldsymbol{\phi} = \mathbf{K} \cdot \mathbf{q}_o. \tag{4}$$

where $\boldsymbol{\phi}$ is a vector of aligned minimal set of inertial parameters, $\mathbf{Y}$ is called the regressor matrix over $\boldsymbol{\phi}$ and is a function matrix of $\mathbf{q}_0$, $\mathbf{q}_c$, $\dot{\mathbf{q}}_0$, $\dot{\mathbf{q}}_c$, $\ddot{\mathbf{q}}_0$ and $\ddot{\mathbf{q}}_c$.

By constructing an identification theory based on equations (1), (2), (4), it is possible to construct identification method for minimal set of inertial parameters that does not require the measurement of joint torques in a simple motion. In our paper, the results of theoretical validation using two-link measurement objects and a discussion of the identification accuracy is also described.

3 Conclusion

A new method for identifying the minimal set of inertial parameters of a multi-body system has been developed by expanding and applying the identification method based on free vibration measurements, which is the identification method for inertial properties of single-body. While the conventional method of identification by measuring the link motion and floor reaction force has difficulties in extending to three dimensions, this method has shown that all minimal set of inertial parameters can be identified with high accuracy from relatively simple motion measurements, both theoretically and by means of basic experiments.

Acknowledgments

The authors sincerely thank Resonic Japan Co., Ltd. for helping experiment. Our sincere thanks to Emeritus Professor M. Okuma for his support.

References

[1] R. Kloepper and M. Okuma. A Compact Device for Measuring Rigid-Body Properties Based on Five Unscaled Modes, Topics in Modal Analysis I, Volume 7, page 215-224. Springer, 2014.

[2] H. Mayeda, K. Yoshida and K. Osuka. Base parameters of manipulator dynamic models, IEEE trans. on robotics and automation, Vol.6, No.3, 1990.

[3] K. Maeda. Dynamic Models of Robot Arm and Its Identification, Journal of the Robotics Society of Japan, 7 (2) , page 95-100, 1989

[4] V. Bonnet and G. Venture, Fast determination of the planar body segment inertial parameters using affordable sensors, IEEE transactions on neural systems and rehabilitation engineering, Vol.23, No.4, 2015.

[5] Y. Fujimoto, S. Obata and A. Kawamura:, Robust Biped Walking with Active Interaction Control between Foot and Ground, Proc. of the IEEE Int. Conf. on Robotics and Automation, pp.2030–2035, 1998.