Mechanism and Machine Theory 97 (2016) 141–154

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Output-only identification of modal shape coupling in a flexible robot by vector autoregressive modeling

Viet-Hung Vu [a], Zhaoheng Liu [a,*], Marc Thomas [a], Wenchao Li [a], Bruce Hazel [b]

[a] École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, QC H3C 1K3, Canada
[b] Institut de recherche d'Hydro-Québec, 1800 boul. Lionel-Boulet, Varennes, QC J3X 1S1, Canada

ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form 26 October 2015
Accepted 10 November 2015
Available online 7 December 2015

Keywords:
Modal analysis
Output-only identification
Mode shape coupling
Flexible robot
Vector autoregressive model

ABSTRACT

A flexible compact robot was developed for grinding. Its varying dynamic properties during motion must be known. An autoregressive model is applied for modal analysis of the flexible robot first under impact conditions and then under operational excitations. The modes are classified with respect to modal power to show the energy distribution. Energy appears more on the first modes under impact conditions while it is more concentrated near the frequency of rotation while in operation. This analysis makes it possible to characterize the manipulator's dynamic behavior in each direction for further analysis and control. It is found that the joints' flexibility affects the mode shapes in both directions and creates more balanced modal components at the end effector during rotating excitation. A better match in dynamic behavior is found in the vertical direction. The greater error in the horizontal direction, mostly at the highly excited modes may be explained by the sensitivity of the joints' stiffness during operation since the joints operate in the horizontal plane. Operational modal analysis also enables construction of the mode shape at the grinding frequency and the amplitude coupling at the end effector.

1. Introduction

Modal testing has been one of the most reliable techniques for dynamical characterization of mechanisms and structures (Ewins-[1]). Such testing must usually be performed on a setup where controlled excitations can be measured with structures at rest and a low-noise vibratory signal. The trend over the past three decades, however, has been toward operational modal analysis (OMA) (Peeters-[2]), where excitation is not measured. Thanks to advances in signal processing algorithms (Ljung-[3], Reynder-[4], Vu-[5,6]), OMA can be used for non-stop modal analysis to predict the dynamic behavior of structures operating under real-life operating conditions.

In machining research and development, industrial robots have been put to use for certain downstream processes in many industries. Solutions using multi-axis robot manipulators as tool holders have proven to be effective for repairing hydroelectric equipments. Robotics is a large branch of mechanical engineering. In machining applications, manipulators are conventionally considered to be stiff structures. The dynamic behavior of stiff manipulators as machines and mechanisms has been widely covered in the literature on machine dynamics. With advances in recent years regarding materials, fabrication technology and numerical analysis, machining manipulators are now constructed with more flexible links and joints. They are now considered flexible structures capable of attaining higher load-to-weight ratios and operating speeds. For instance, a flexible compact robot named "Scompi" was developed at Hydro-Quebec's research institute primarily for robotic grinding applications (Hazel-[7,8]). As it is compact and flexible, concerns arise regarding its dynamic behavior due to the vibro-impact nature of the grinding process

* Corresponding author.
E-mail address: zhaoheng.liu@etsmtl.ca (Z. Liu).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.11.005
0094-114X/

and self-regenerative excitations (Hazel-[9], Rafieian-[10]). Such excitations are difficult to measure directly during operation. Dynamic analysis of the operating robot must thus rely on time domain OMA. Vector autoregressive modeling was found to be an appropriate mean of analyzing the operational dynamics of the Scompi robot since it supports continuous, accurate automation of analysis in the time domain (Vu-[11]), even in the presence of harmonic excitations from the rotary grinding process (Vu-[12]).

The vibration of flexible robots may be modeled by FEM methods (Zhuo-[13], Tokhi-[14]), assumed-modes methods (Chalhoub-[15]) or lumped-parameter methods (Zhu-[16]). Reviews on modeling flexible robots can be found in (Bascetta-[17]) and (Dwivedy-[18]). Though numerical models can be widely used at the design stage, they have drawbacks when modeling actual operating conditions, especially in vibration and control analysis. Among experimental approaches, (Feldman-[19]) uses the Hilbert transform and (Pisoni-[20]) uses frequency domain FRFs for the identification of the modal parameters considering nonlinear vibrations. Both of these approaches, however, required knowledge about the excitation. It was concluded that the controller influences the dynamic behavior of the robot and introduces inaccuracy in estimating modal parameters. (Yang-[21]) predicted the dynamic response of a single-arm flexible robot with the modal data set at different positions in the workspace. Recently, (Rahman-[22]) presented the correlation of frequency domain OMA and conventional impact testing on a flexible beam representing a robot arm. As with any flexible structure, identifying mode shapes is crucial for evaluating joint and link flexibility. Since actual operating conditions are important for the analysis, OMA must be conducted and modal parameters, including mode shapes, must be identified directly from the operational vibration data.

In order to understand vibration of the flexible Scompi robot and study its effect on grinding precision, mode identification and characterization must be conducted for the robot with the grinder installed. In this research, two types of testing are conducted: impact hammer tests and tests of the rotary grinder in operation. Since OMA is of interest, signals from all sensors were processed using a vector autoregressive model. Modal parameters and mode shapes using the two testing schemes are compared to evaluate the correlation and operating conditions. Modal decoupling into two working directions facilitates analysis of the manipulator structure, especially for later evaluation of the vibro-impact contact force at the end effector. The decoupled mode shapes show clearly the flexibility of joints and links in each working plane. The decoupled mode shapes can be further used to identify the actual stiffness and to update the numerical model. It is also found that the decoupled mode shapes in the horizontal direction are more sensitive to actual operating conditions than those in the vertical direction.

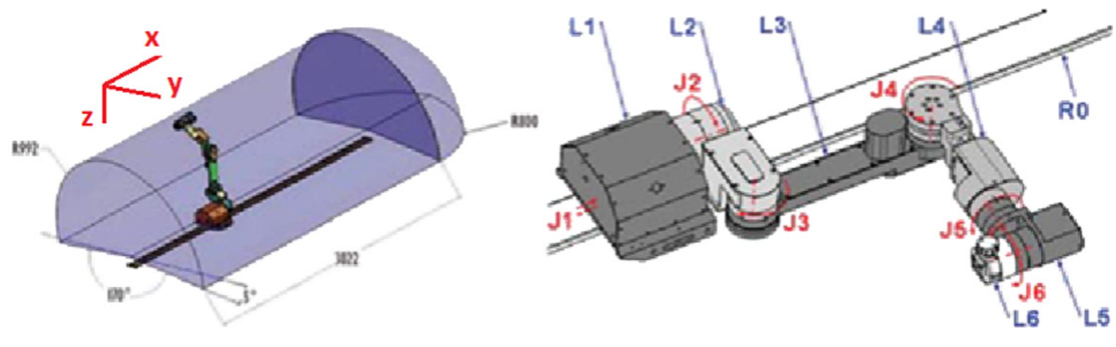
2. Scompi robot characteristics

The Scompi (Super COMPact robot Ireq) is a flexible, compact manipulator developed at IREQ (Hydro Quebec's research institute), for robotic machining in the confined spaces. It is constituted of links and joints to have six degrees of freedom. Fig. 1a shows the working envelope and Fig. 1b shows the construction of the manipulator with its links and joints (Hazel-[7]). Table 1 gives the dimensions of the manipulator.

The 6-DOF robot thus has a wide working space for versatility in performing tasks. Since joints J3 and J4 operate in the same plane and links L3 and L4 are the longest, the main functionality of the manipulator can be based on the in-plane triangle formed by these two links. From a flexibility standpoint, the robot structure can be considered as a construction of multiple flexible joints and two flexible beams, L3 and L4.

In a preliminary study on the robot's dynamic behavior, modal testing (Farzad-[23]) and operational testing (Fatma-[24]) were performed on the manipulator without the grinder installed. The 7.1-kg Bosch HWS-88/230 grinder and 2-kg cup wheel mounted on the end effector are significant weights for the 35-kg manipulator and can change appreciably the modal parameters of the system. It is also important to identify the mode shapes, a prerequisite to evaluating participation of link and joint flexibility.

In this study, an autoregressive model is applied for modal analysis. Characterization of the Scompi robot is presented, emphasizing mode shapes and modal coupling at the end effector. Considering measurement system constraints, both impact



a) Working envelope b) Links and joints

Fig. 1. Scompi robot.