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Full length Article

Stability optimization in robotic milling through the control of functional redundancies

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ABSTRACT

Productivity in robotic machining processes can be limited by the low rigidity of the overall structure and vibration instability (chatter). The robot's dynamic behavior, due to changes in its posture along a machining trajectory, varies within its workspace. Chatter in robotic machining therefore depends not only on the cutting parameters but also on the robot configuration. Moreover, the robot can follow a machining trajectory in the operational space with an infinite number of possible trajectories in its configuration space. It is due to the redundancies offered by its kinematic chain. This paper deals with the optimization of robotic machining stability by controlling the robot configurations and the functional redundancies of its kinematic chain. It is shown that stability in robotic machining along a given trajectory can be ensured through the optimization of the robot configurations, without changing the cutting parameters, in order to maintain productivity performance. A multi-body dynamic model of an ABB IRB6660 industrial robot is elaborated using beam elements which can easily be integrated into the machining trajectory planning. The beam element geometry, elasticity and damping parameters are adjusted on the basis of experimental modal identifications. The present study is focused on the dynamic model-based predictions of stable and unstable zones along a robotic machining trajectory with one degree of functional redundancy. Experimental machining tests confirm the stability predictions from the numerical model.

1. Introduction

Recent technical advances in anthropomorphic robots position them as serious competitors to conventional machine tools in terms of precision, load capacity and flexibility. Industrial machining robots are mainly used for pre-machining and for machining or other post-casting applications in the foundry industry with a high productivity requirement. Robotic machining productivity can be limited by the appearance of instability phenomena due to chatter vibrations. Hence, the exploitation of industrial robots in a machining context requires machining stability to be mastered. Most robotic machining research in the literature focuses on robot precision in terms of pose exactitude (end-effector position and orientation) and repeatability. Studies on chatter vibrations during robotic machining operations are much rarer. Pan et al. [14] and Olabi et al. [18] studied chatter in robotic machining by considering the robot dynamic behavior in the low frequency range. They explained that regenerative chatter is mainly induced by mode coupling phenomena. Mejri et al. [11] experimentally studied the stability limits in a serial robot and Tunc et al. [17] in a parallel robot. They both show the importance of the robot's geometric configuration on milling stability.

Chatter is a self-excited type of vibration which occurs in metal cutting. In these conditions, vibrations start and grow quickly. Altintas [2] presents the regeneration of waviness (Fig. 1b) as the most powerful source of chatter and self-excited vibration. The regenerative chatter vibration system can be represented by the block diagram in Fig. 1a.

The dynamic behavior of the robot within the workspace depends on its configuration. Each posture of the robot has its own dynamic behavior and stable cutting conditions [12]. Thus a dynamic model of the robot which correctly takes these variations into account is essential in order to maintain machining operations within a stable margin. Several researchers have reported their studies on the dynamic modeling and identification of robot parameters as well as estimations of robotic machining precision.

Mejri et al. [11] experimentally studied the end-effector position effect on the dynamic behavior of an ABB IRB6660 robot. Tunc et al. [17] investigated the dynamic and positional behavior of a FANUC F200ib hexapod robotic machining platform. They observed modifications in the robot's dynamic behavior depending on changes in its posture. Therefore, the accuracy of the robot dynamics modeling method has a major role in stability prediction in robotic machining.

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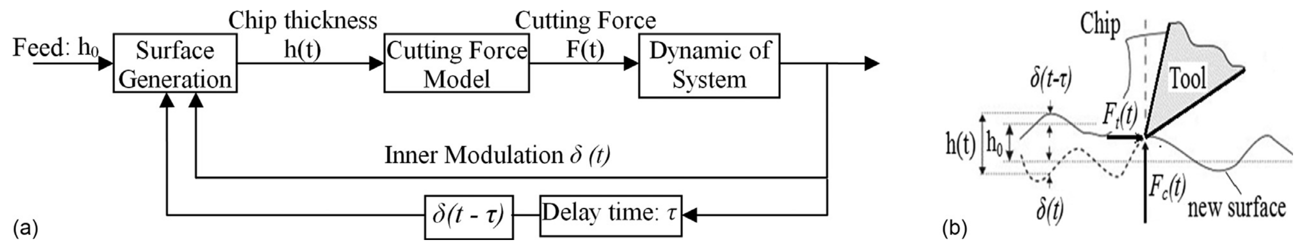

Fig. 1. (a) Block diagram of regenerative chatter vibrations (b) chip thickness variation in regenerative chatter.

Pan et al. [14] considered a lumped mass model of the robot with flexible joints and rigid bodies. Based on this modeling approach, only low frequencies for the robot can be obtained, and these are far from machining frequencies, especially in high-speed machining. Moreover, compared to conventional machine tools, the robot links are not rigid enough to adopt a rigid body assumption. Farid et al. [5] studied the effect of joint flexibility associated with flexible links on the dynamic behavior of robotic manipulators. They demonstrated the interaction of links and joint flexibilities in the dynamic behavior of the system.

Mousavi et al. [12] presented two modeling approaches and compared them according to their respective capabilities to predict machining stability. The developed models take into account respectively only robot joint flexibilities and both joint and body flexibilities. The comparison between these two models demonstrates the necessity of considering body flexibilities for stability analysis in robotic machining. Hence, in the present study, the modeling of the ABB IRB6660 industrial machining robot is carried out by using a flexible bodies and flexible joints approach, in order to predict machining stability under the influence of changes in robot posture.

In order to consider the flexibility of robot links, the finite element method can be used. It provides an accurate estimation of static behavior by the determination of the robot stiffness matrix in the workspace [3]. Variations in robot dynamic behavior can be tracked along a discretized machining trajectory by frequency-domain simulations of the local linearized FEM. Time-domain simulation of nonlinear FEM is impracticable due to the high model complexity and calculation cost [10].

The matrix structural analysis (MSA) method, as a simplified FEM, uses equivalent beam elements for the modeling of mechanical structure components [13]. It is used for model reduction. This method has been applied to predict the dynamic behavior of a machine-tool parts such as spindle rotors using Timoshenko beam elements [7] as well as complete machine-tools using Bernoulli beam elements [9]. This method enables the analysis of the dynamic behavior of a robot in discretized positions along a machining trajectory with an acceptable computing time.

The experimental identification enables the determination of the actual modal parameters of the robot structure in a given position and configuration where the tests are performed [11]. These experimental identifications are time-consuming, but they are usually required as an effective means to calibrate numerical models [6,7].

In addition to cutting parameters, the different robot postures have a decisive role in determining the stability in robotic machining [12]. The robot can follow a machining trajectory with different configurations due to the redundancy offered by its kinematic chain. Hence, the proposed solution to improve robotic machining cell behavior is to manage the kinematic redundancy offered by the structure. It is used to optimize robotic cell behavior with respect to different criteria such as singularity avoidance or rigidity to minimize tool deviation along the machining trajectory [15]. In this work, the optimization criterion retained is chatter stability margins.

In this paper, the first section is dedicated to the development of a dynamic model of the ABB IRB6660 industrial machining robot using the MSA method. The model is controlled by a direct or indirect geometric model to adapt the robot's posture along a machining trajectory. This numerical model is readjusted, based on the experimental modal identification, in the second section. Finally, using the developed model, a machining operation with one functional redundancy is optimized with respect to machining stability.

2. Dynamic model of the ABB IRB6660 machining robot

The ABB IRB6660 robot, with six active joints ($q_1, q_2, \ldots, q_6$) and three passive joints (q_{p1}, q_{p2}, q_{p3}) as shown in Fig. 2a and b, is a robot with six degrees of freedom. It has a hybrid kinematic architecture with combination of a serial part and a parallel part. The parallel part has two active joints (q_2 *and* q_3) and three passive joints integrated into the robot structure. The serial part has three active joints (q_4, q_5 *and* q_6). The robot is equipped with a FICHER MFW 1412/36 spindle with a maximum speed of 36,000 rpm. It is basically designed for pre-machining which requires a high removal rate and productivity.

Dumas et al. [4] proposed a procedure for the joint stiffness identification of a six-revolute industrial serial robot. Their method is based on the measurement of joint angular displacements due to the static load. On the basis of this procedure, joint stiffness values for the ABB IRB6660 robot were obtained experimentally by Subrin et al. [16]. The joint stiffness values from the base to the end effector are constant in the joint space and presented in Table 1.

The dynamic modeling of the robot, for a given configuration $\boldsymbol{x}_0$ in Cartesian space, can be expressed by the following differential equation:

$$\boldsymbol{M}_x(\boldsymbol{x}_0)\ddot{\boldsymbol{\delta}}_x(t) + \boldsymbol{C}_x(\boldsymbol{x}_0)\dot{\boldsymbol{\delta}}_x(t) + \boldsymbol{K}_x(\boldsymbol{x}_0)\boldsymbol{\delta}_x(t) = \boldsymbol{F}(t) \quad (1)$$

where $\boldsymbol{\delta}_x(t) = \boldsymbol{x}(t) - \boldsymbol{x}_0$ is an infinitesimal displacement of the end effector relative to a reference configuration $\boldsymbol{x}_0$. $\boldsymbol{M}_x$, $\boldsymbol{C}_x$ and $\boldsymbol{K}_x$ are respectively robot system mass, damping and stiffness matrices in Cartesian space (Global frame). $\boldsymbol{F}(t)$ is the cutting force vector in milling operations.

The natural frequencies and mode shapes of the system are determined numerically as solutions to the following eigen problem equations:

$$\left(\boldsymbol{K}_x - \omega_{0i}^2 \boldsymbol{M}_x\right)\boldsymbol{p}_i = 0 \quad (2)$$

where ω_{0i} and $\boldsymbol{p}_i$ are respectively the natural frequencies and mode shapes of the system.

A dynamic modeling approach to robot behavior plays a very important role in the accurate estimation of the dynamic properties. Mousavi et al. [12] proposed the flexible joint and body approach to analyze the dynamic properties and then the machining stability of the ABB IRB6660 robot. Thus, a multi-body approach, taking into account joint flexibilities and body flexibilities is used for this investigation. In this paper, body flexibilities are taken into account using the MSA modeling method. The ABB IRB6660 robot model is thus composed of an assembly of 3D beam elements as presented in Fig. 3b.

Dynamic behavior modeling of the robot is based on the following hypotheses:

- The robot base is considered to be rigid since it does not have any impact on the dynamic behavior of the structure (Fig. 3a).
- The robot bodies are modeled by 3D Euler-Bernoulli beam elements without a shearing effect which is considered as being negligible in the present study.