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Chatter stability in robotic milling

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ABSTRACT

Industrial robots are desired to be used in milling light but large aerospace parts due to easier set-up and portability than large machine tools. However, robots are significantly less stiff than the machine tools, hence they cannot be used in all machining applications. This paper presents dynamics of robotic milling. The structural dynamics of an articulated manipulator with a spindle and a tool are modeled. The dynamic milling forces are applied on the robot structure which has strong cross coupling terms. The stability of the resulting system is analyzed using semi-discrete time and frequency domain methods. The predicted stability charts are experimentally validated in milling of Aluminum and Titanium parts. It is shown that the pose-dependent modes of the robot structure are all at low frequencies, and they are damped out by the machining process at high spindle speeds. Only the pose independent spindle modes cause chatter in high-speed milling, hence high material removal rates can be achieved by selecting analytically predicted stable depth of cuts and spindle speeds in robotic milling of Aluminum parts. In low speed milling of Titanium parts however, the pose dependent low frequency robot modes chatter.

1. Introduction

It is desired to use industrial robots in machining large aerospace parts due their lower cost, easier set-up and transportation in comparison to large machine tools. However, robots are considerably less rigid than machine tools, hence their static and dynamic deflections can easily violate the dimensional and surface finish tolerances of costly aerospace parts.

The main focus of past research was mainly on the low static stiffness of the robots which leads to unacceptable dimensional tolerance violations when they are used in machining high strength alloys [1,2]. The Cartesian stiffness matrix is highly pose-dependent [3,4]. Resulting static deformations can be compensated to some extent by using the Virtual Joint Method in combination with a cutting force model [5]. Even if high static deflections are accepted in roughing or compensated in finishing, the productivity is limited by self-excited vibrations, leading to shorter tool life, poor surface finish, or even damage to the spindle mounted on the robot. Extensive research has been carried out to predict chatter as reviewed by Altintas et al. [6], and the chatter suppression methods were reviewed by Munoa et al. [7]. However only a few studies have focused on chatter mechanism in robotic machining.

Chatter is caused by the most flexible, dominant structural modes of the machine-workpiece system. Several authors report that the structural modes of robots are highly flexible and pose-dependent [8,9], with natural frequencies which are considerably lower than those of machining centers [10]. Mejri et al. [11] showed that the pose-dependent dynamics of an articulated robot need to be considered in the stability prediction for milling applications. Law et al. [12] evaluated the pose-dependent stability of a serial-parallel kinematic machine to plan dynamically stable machining trajectories. Mousavi et al. [13] used a multi-body dynamic model of an articulated robot to plan stable trajectories by exploiting the redundancies in the kinematic chain. The asymmetrical tool tip dynamics of a hexapod robot has been studied by Tunc and Stoddart [14], introducing a feed direction effect on the stability. Wang et al. [15] observed chatter at low spindle speed in a robotic boring operation and predicted the stability by introducing a novel chip thickness model.

Two major sources of chatter have been identified in milling: The regenerative effect and self-excited mode coupling. Regeneration is induced by the repeated cutting on the same work surface, resulting in a modulation of chip thickness, which excites the machine structure [16,17]. The mode coupling effect may occur if the natural modes are closely matched in principal directions. Without any regeneration, the structure vibrates simultaneously in the different directions at the same frequency and a phase shift [18]. However in practice the regeneration occurs earlier than the mode coupling in most machining processes

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[17,19]. Pan et al. [20] observed low frequency chatter in robotic milling process and concluded that mode coupling is the dominant source of instability, since the low natural frequencies cannot cause regeneration at higher spindle speeds. They assumed the cutting force to be proportional to depth of cut and time invariant process gain.

The dynamics of milling are modeled by delayed differential equations (DDEs) with time periodic parameters, and their stability diagrams can be predicted by frequency or time domain models. Altintas and Budak proposed zero order [21] and multifrequency solutions [22] based on the truncated Fourier series expansions of the periodic terms. The zero order approximation (ZOA) is satisfactorily accurate in most milling processes. However in highly intermittent milling where the speed is very high and radial immersion is very low, additional stability lobes related to period doubling (flip bifurcation) exist [23]. These can be solved using multi-frequency [24] or semi-discrete time domain models [25]. The semi-discretization method transforms the DDE into a series of autonomous ordinary differential equations by using the modal parameters of the system dynamics [26,27]. The ZOA only predicts quasi periodic chatter in frequency domain (Hopf bifurcation), but computationally efficient due to its direct analytical solution of depth of cut and speed and the use of measured FRFs directly. Most studies neglect the cross FRFs because serial machine tools usually have negligible cross coupling in orthogonal directions, but the solution method does not change even if the cross FRFs (also called structural mode coupling) may exist [28–30].

In this paper, the chatter stability of robotic milling is modeled and experimentally validated. A heavy-duty robot with several modes is considered including cross coupling terms. The dynamic milling forces are applied on the articulated manipulator equipped with a spindle and end mill. The stability of the system is predicted using semi-discrete time and frequency domain models. The difference between chatter in high-speed milling of Aluminum alloys and low-speed milling of high strength alloys are demonstrated.

2. Milling process - Robot structure interaction

A milling spindle with an end mill is attached to the robot's end effector. The dynamics of the multiple-degree-of-freedom (MDOF) system at the tool tip is described by the differential equation of motion as

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{f}(t), \tag{1}$$

where $\mathbf{M} \in \mathbb{R}^{n\times n}$, $\mathbf{C} \in \mathbb{R}^{n\times n}$ and $\mathbf{K} \in \mathbb{R}^{n\times n}$ denote the system mass, damping and stiffness matrices; $\mathbf{u}(t) \in \mathbb{R}^n$ is the displacement vector, $\mathbf{f}(t) \in \mathbb{R}^n$ is the cutting force vector and n is the number of degrees of freedom. The cutting force represents the shear and friction force applied in the chip formation process and may excite the modes in all three Cartesian directions, see Fig. 1. Generally the system matrices are dependent on the pose of the robot, and may have cross coupling terms due to the kinematic configuration. They can be assumed constant at short tool path intervals.

2.1. Structural dynamic model

The modal parameters of the structure at the tool tip can be identified from FRF measurements at discrete poses of the robot through impact or shaker tests. By taking the Laplace transform of Eq. (1), the dynamics of the system is given as

$$\mathbf{G}(s)\ \mathbf{U}(s) = \mathbf{F}(s), \tag{2}$$

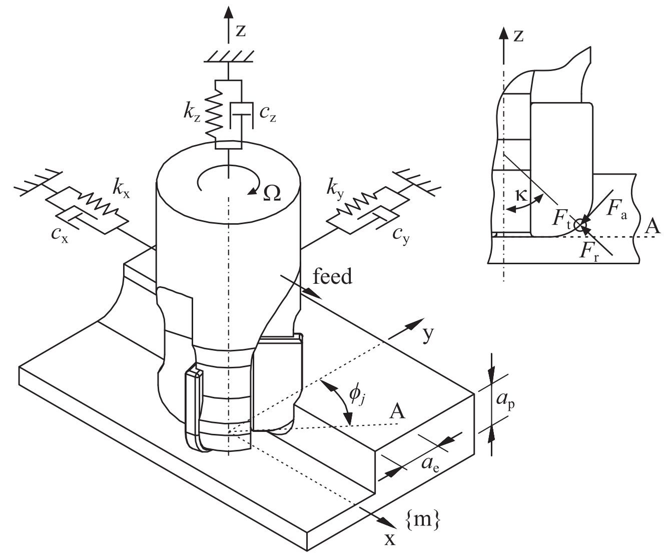

Fig. 1. Dynamic milling model with multiple degrees of freedom.

where $\mathbf{G}(s) = \mathbf{M}s^2 + \mathbf{C}s + \mathbf{K}$. The displacement vector $\mathbf{U}(s)$ can be expressed in common-denominator-model form:

$$\mathbf{U}(s) = \mathbf{H}(s)\ \mathbf{F}(s) \quad \leftarrow \mathbf{H}(s) = (\mathbf{G}(s))^{-1} = \frac{\mathrm{adj}(\mathbf{G}(s))}{|\mathbf{G}(s)|} \tag{3}$$

with $\mathbf{H}(s)$ being the transfer function matrix. The numerator is a $(n \times n)$ matrix containing polynomials of order $2(n-1)$. The common denominator is given by the characteristic equation $|\mathbf{G}(s)|$, a polynomial of order $2n$. In general the measured transfer function $H_{oi}(s)$ between vibration output o with $o = 1, 2, ..., N_o$ and input force i with $i = 1, 2, ..., N_i$ can be modeled as:

$$\mathbf{H}(s) = \frac{1}{A(s)}\begin{bmatrix} B_{11}(s) & \cdots & B_{1N_i}(s) \\ \vdots & \ddots & \vdots \\ B_{N_o1}(s) & \cdots & B_{N_oN_i}(s) \end{bmatrix} \tag{4}$$

with

$$H_{oi}(s) = \frac{B_{oi}(s)}{A(s)}. \tag{5}$$

Eq. (4) represents the multiple-input, multiple-output (MIMO) structural dynamics of the robot at the tool tip. Generally the cross terms, where $o \neq i$, are unequal and the coefficients (m_{oi}, c_{oi}, k_{oi}) of the multivariable system are coupled by the common denominator. For a reliable identification of the modal parameters of the coupled system, all input-output measurements need to be considered simultaneously in a global MDOF approach.

The identification of modal parameters is illustrated on the six-axis heavy-duty robot ABB IRB 6660-205/1.9 with a maximum payload of 205 kg, equipped with a 12 kW high-speed milling spindle and an end mill in a HSK-E40 shrink fit holder. Identification is carried out for one pose with a tool axis perpendicular to the y_0z_0-workplane of the robot by measuring the FRFs in all three Cartesian directions including cross terms at the tool tip with an impact hammer test. The vibrations are collected with a laser Doppler vibrometer Polytec OFV 505/OFV-5000, which can measure low-frequency modes where an accelerometer is not effective. Coherence, amplitude and power spectrum of the impact force are checked, to ensure the data quality. During hammer tests the