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Mode coupling chatter suppression for robotic machining using semi-active magnetorheological elastomers absorber

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ABSTRACT

Chatter is one of the major barriers for robotic machining process. As the dominant vibration frequency of the chatter varies under different working conditions, Magnetorheological elastomers (MREs) whose stiffness is adjustable is an ideal device to be used for chatter control. This paper presents a new mode coupling chatter reduction scheme by assembling an MRE absorber on the spindle to absorb vibration with a specific frequency range. Firstly, a MRE absorber was designed and fabricated to suppress the target chatter according to the robot model and then a test was implemented to obtain the frequency shift property of the designed MRE absorber. Subsequently, robotic milling of an aluminium block using ABB IRB6660 robot was tested under various conditions to demonstrate the performance of the MRE absorber under different constant currents. After that, a semi-active controller was established to control the electrical current applied to the MRE absorber to trace the chatter frequency. The experimental results show that the semi-active MRE absorber performs better on the chatter reduction during robotic milling than passive absorbers.

1. Introduction

Modern industrial robots offer flexibility, efficiency, low cost and safety, that have superseded many tiresome, repetitive and especially hazardous manual operations. Nowadays, industrial robots have been widely employed in various industrial applications, including welding, material handling, painting, assembly, machining, etc. [1–3]. In terms of machining applications, due to its high level of accuracy and contact force, CNC machine has been regarded as the backbone for the industrial use for a few decades. Despite this, exploring the potential of industrial robots for machining applications are still of interests. The main advantages of industrial robot compared to CNC machine are flexibility and low cost. However, the relatively low stiffness, which results in mode coupling chatter, is still the main barrier limiting the use of the articulated robot in machining applications [4–6].

Merritt [7] and Tlusty [8] identified two most powerful sources of self-excited vibration (or chatter): regenerative chatter and mode coupling chatter in the machining process. The regenerative chatter occurs during the subsequent processing on the rough surface after the previous cutting path [9]. During milling, the next tooth in cut collides with the wavy surface from the previous cut and generates a new wavy surface. The chip thickness and, hence, the cutting force vary due to the

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phase difference between the wave left by the previous tooth and the wave generated by the current one [9]. On the other hand, the term mode coupling means the vibration exists simultaneously in two or more directions coupled to each other. The mode coupling chatter happens even when the successive passes of the tool do not overlap [10]. Its vibration amplitude has no fixed direction as the tool follows an elliptical path related to the workpiece.

For CNC machine, the conventional wisdom focuses on the regenerative chatter of the machining tools such as boring bar and milling cutter, since the mode coupling chatter seldom happens due to the large stiffness of the CNC machine. However, in robotic machining process, due to the low structure stiffness of the robot, it is observed that the entire robot structure can vibrate during relatively light machining process [11]. The impact of mode coupling chatter on robotic machining is a more complicated issue and thereby improving robotic machining stability has been an interest of research in recent years.

Many researchers have applied the mode coupling theory to explain robotic machining chatter and guide controlling it using either passive or active compensation method. The passive strategy addresses the issue through changing the robot configuration, process behaviours, or system structure, including stiffness, damping, etc. The stiffness of industrial robots varies at different robot configurations and positions due to their serial articulated structure. By selecting the most optimal robot configuration and trajectory, less chatter was observed [12]. Other researchers focused on the suppression of the chatter occurrence by changing the system structure [13]. Recently, active chatter compensation, in particular force control based strategy has also been developed in robotic machining study. The chatter phenomenon arises due to large cutting force, so the cutting force would be adjusted to avoid chatter occurrence through various force sensing technologies and active control strategies [14,15].

However, passive strategies restrict the flexibility of the machining setup and active force control strategy mainly avoids the chatter by limiting the cutting force, which results in low productivity. To the best of our knowledge, there is no research on absorption or disruption of low-frequency mode coupling chatter for robotic machining process. Dynamic vibration absorbers (DVAs) is a conventional solution to suppress vibration/chatter of machines [16]. DAVs have been categorized into three groups: passive DVAs, active DVAs and semi-active DVAs [17], traditional passive DAVs composed of an oscillator, a spring element, and a damping element, they are simple, reliable and cost-effective. However, this kind of passive absorbers is limited to operate at a single excitation frequency due to its uncontrollable damping or stiffness. For robotic machining system, the working condition may change and induce chatter with variant dominant frequency. As a result, active controlled absorbers, which have a time-varying natural frequency through altering its stiffness, are ideal for robotic machining chatter suppression. Nevertheless, the complexity, high-cost and more energy consumption of active control system retard its practical applications [18]. Comparatively, semi-active DVAs, which can achieve comparable active absorption performance, are promising for chatter suppression. Currently, DAVs are tuned by mechanical structure or smart material. Compared to mechanical tuned DVAs [19], Magnetorheological Elastomers (MREs)-based DVAs have the advantages of short response time, simple structure, and easy control, and is a better semi-active absorption technology for many applications [20–22]. Yang et al. [23] presented a study on the MREs-based semi-active vibration absorber. The authors claimed that the proposed device achieved a better performance compared to classic passive dynamic vibration absorbers in terms of frequency-shift property and vibration absorption capacity. In addition, Sun et al. [24] developed a hybrid nonlinear MRE absorber which can vary its natural frequency and has a wider absorption bandwidth under each constant working scenario. The experimental results verified the proposed MRE absorber had a wider effective bandwidth than a linear absorber.

Among all applications of the MREs-based semi-active vibration absorber, its application on chatter suppression for robotic machining has rarely been investigated. The objective of this research is to develop a semi-active vibration control system utilising MREs to achieve a more stable and more productive machining process. This paper is organised into five sections. Following this introduction, Section 2 presents the chatter analyses based on robot and process model. Section 3 presents the design and test of the MRE absorber. Section 4 demonstrates the effectiveness of the MRE absorber on chatter suppression, followed by a conclusion in Section 5.

2. Identification of chatter frequency based on robot model

Generally, the frequency-shift property of MRE absorber determines the frequency range that chatter/vibration it can absorb. Thus, the first step is to investigate the frequency feature of chatter in robotic machining before designing MRE absorber. The results obtained in this section will be used to guide the design of the MRE absorber in the next section.

2.1. Robot model

In this study, an ABB IRB 6660 machining robot was used for milling test. Compared to the conventional CNC machine, the industrial robot features a serial articulated structure. Traditionally, Denavit-Hartenberg (DH) model [25–27] is employed to analyze the robot forward and inverse kinematics. This model considers rigid links and flexible joints (revolute joints) that is sufficient for low-frequency vibration analysis. The DH model and parameters of ABB IRB 6660 were demonstrated in Fig. 1.

Regarding DH-convention the forward kinematics can be derived from the Eq. (1):

$$A_i(q_i) = T_{r_z}(\theta_i)T_t(a_i, 0, d_i)T_{r_z}(\alpha^i) \tag{1}$$