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Chatter analysis of robotic machining process

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Abstract

The need for flexible automation keeps moving downstream in the foundry production process, such as casting parts cleaning and pre-machining. One of the most challenging issues in practice is to know the vibration/chatter characteristic of any given machining process. To reduce the trial and error frustration, this paper presents the underline mechanism and theoretical analysis to provide physical understanding for the onset of chatter problem and principles to prevent that. First, the cutting force model and robot structure model are established for a systematic analysis of chatter mechanism. Completely different from common woes of regenerative chatter in conventional CNC machine paradigm, another type of chatter, namely, mode coupling chatter was identified as the dominant source of vibrations in robotic machining, largely due to the inherent low structure stiffness of industrial robot. In-depth analysis for stability criteria and experimental verifications are then presented followed by the guidelines of process configuration and parameter selections to achieve chatter free machining operation.

Keywords: Robotic machining; Chatter; Mode coupling; Cutting force; Structure model

1. Introduction

In three decades, industrial robot has undergone significant changes from its early days as a repetitive and dedicated tool to a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks. Nevertheless, more than 80% of the application of industrial robot is limited in the fields of welding and material handling. Still very few robots have been applied in high value-added applications such as material removal processes. However, production that was previously done by hand can be done more efficiently by robots that have become increasingly flexible, easy to integrate and easy to use. With the life cycle of products getting shorter, and an increased demand for customization and maintaining the highest quality standards, it is no longer cost-effective to use manual applications or inflexible hard automation solutions.

One of the major hurdles preventing the adoption of robot for machining process is chatter. Tobias and Fishwick [1] and Tlusty and Polacek [2] recognized that the most powerful sources of chatter and self-excitation were the regenerative and mode coupling effects. Regenerative chatter is based on the fact that the tool cuts a surface already cut during the previous revolution, so the cutting force as well as the depth of cut vary. Mode coupling chatter is due to the fact that the system mass vibrates simultaneously in the directions of the degrees of freedom (DOF) of the system, with different amplitudes and with a difference in phases. Regenerative chatter happens earlier than the mode coupling chatter in most machining processes, as explained by Altintas [3].

Although extensive research on chatter has been carried out, none of the existing research has focused on chatter mechanism in robotic machining process. The result is that robotic engineers and technicians are frustrated to deal with elusive and detrimental chatter issues without a good understanding or even a rule of thumb guideline. Very often, to get their process working correctly, one has to spend tremendous time on trial and error for the sheer luck of stumbling a golden setup or has to sacrifice the productivity by settling on conservative cutting parameters much lower than the possible machining capability. This research is trying to bridge the gap by pointing out the underline chatter generation mechanism based on various experimental tests as well as detailed theatrical analysis. In this paper, the characteristics of chatter in robotic machining process are first presented. Secondly, the modeling of chatter process including robot struc-

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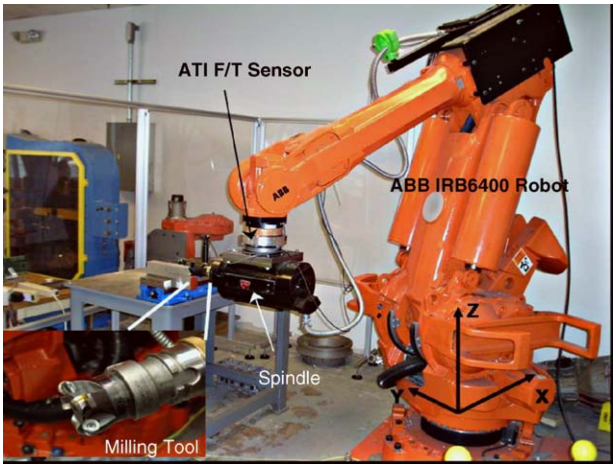

Fig. 1. Setup of robotic end milling.

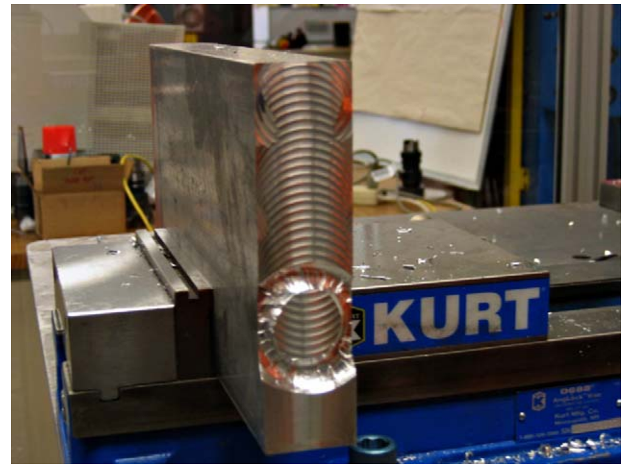

Fig. 2. Chatter marks left on the workpiece.

ture model and machining force model are established. Thirdly, the detailed analysis of chatter mechanism applying both regenerative and mode coupling theory is introduced and compared. Then further experimental results are provided to verify the theoretical analysis. Stability criteria and insightful guidelines for avoiding chatter in robotic machining process are presented followed by Section 6.

2. Characteristics of chatter in robotic machining process

Severe low frequency chatter has been observed ever since when robot was first applied in machining process, nevertheless, no theoretical explanation and analysis are available in the existing literature to date. The conventional wisdom is that this is due to the obvious fact that the robot is much less stiffer than CNC machine, but no answer is provided for the further explanation. The reason for this blank may be the lack of enough sensory information, in particular, the process force information. In addition to the surface damage on the workpiece due to chatter marks, the occurrence of severe chatter results in many adverse effects, which may include a poor dimensional accuracy of the workpiece, a reduction of tool life, and a damage to the machine, etc. Certain conservative cutting parameters, which were proposed by other researchers, intended to avoid chatter at the expense of the loss of productivity.

In the present work, a robotic milling work cell is setup with ABB IRB6400 industrial manipulator. The spindle is mounted on robot wrist while the workpiece is fixed on the steel table. An ATI six-DOF Force/Torque sensor is set up between the robot wrist and spindle as shown in Fig. 1. After compensating the gravity of spindle and tool, three-DOF machining force could be measured accurately. When chatter occurs, the amplitude of cutting force increases dramatically and the chatter frequency is observed from the Fast Fourier Transform of force data. The experimental conditions for robotic end milling are summarized in Table 1.

In most situations, the cutting process is stable; the work cell could conduct 4–5 mm depth-of-cut (DOC) until reaching the spindle power limit. Nevertheless, while feed in $-Z$ direction, severe low frequency (10 Hz) chatter occurs when the DOC is only 2 mm. The characteristics of this low frequency chatter are:

1. The frequency of chatter is the robot base natural frequency at 10 Hz. It does not change with the variation of cutting parameters such as spindle speed, width-of-cut (WOC), feed speed and the location of workpiece.
2. When chatter occurs, the entire robot structure start to vibrate. The magnitude of vibration is so large that obvious chatter marks are left on the workpiece surface (Fig. 2).
3. In the cutting setup of Fig. 1 and Table 1, using the exact same cutting parameters (DOC, rpm, WOC, feed speed), chatter starts to occur when feed in $-Z$ direction, DOC = 2 mm, while the process is stable when feed in $+Z$, $\pm X$ direction, even with the DOC = 4 mm. The cutting forces in unstable (feed in $-Z$ direction) and stable (feed in $+Z$ direction) conditions are plotted in Figs. 3 and 4.
4. The cutting process has different chatter limit at different locations in the robot workspace. Machining experiments are

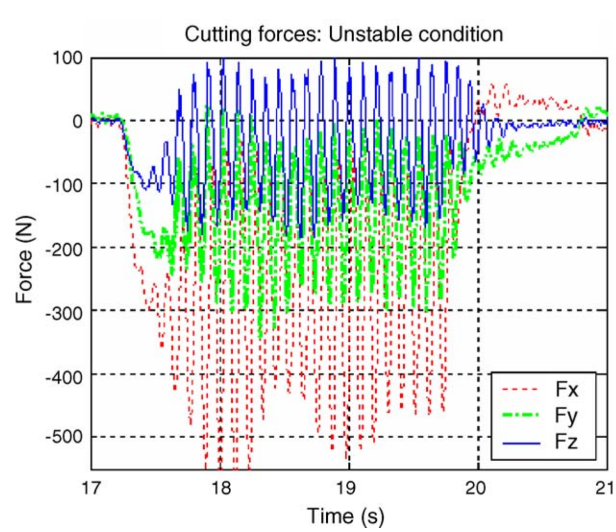

Fig. 3. Force plot while low frequency chatter happens, cutting condition listed in Table 1.