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Angular analysis of the cyclic impacting oscillations in a robotic grinding process

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ABSTRACT

In a robotic machining process, a light-weight cutter or grinder is usually held by an articulated robot arm. Material removal is achieved by the rotating cutting tool while the robot end effector ensures that the tool follows a programmed trajectory in order to work on complex curved surfaces or to access hard-to-reach areas. One typical application of such process is maintenance and repair work on hydropower equipment. This paper presents an experimental study of the dynamic characteristics of material removal in robotic grinding, which is unlike conventional grinding due to the lower structural stiffness of the tool-holder robot. The objective of the study is to explore the cyclic nature of this mechanical operation to provide the basis for future development of better process control strategies. Grinding tasks that minimize the number of iterations to converge to the target surface can be better planned based on a good understanding and modeling of the cyclic material removal mechanism. A single degree of freedom dynamic analysis of the process suggests that material removal is performed through high-frequency impacts that mainly last for only a small fraction of the grinding disk rotation period. To detect these discrete cutting events in practice, a grinder is equipped with a rotary encoder. The encoder's signal is acquired through the angular sampling technique. A running cyclic synchronous average is applied to the speed signal to remove its non-cyclic events. The measured instantaneous rotational frequency clearly indicates the impacting nature of the process and captures the transient response excited by these cyclic impacts. The technique also locates the angular positions of cutting impacts in revolution cycles. It is thus possible to draw conclusions about the cyclic nature of dynamic changes in impact-cutting behavior when grinding with a flexible robot. The dynamics of the impacting regime and transient responses to impact-cutting excitations captured synchronously using the angular sampling technique provide feedback that can be used to regulate the material removal process. The experimental results also make it possible to correlate the energy required to remove a chip of metal through impacting with the measured drop in angular speed during grinding.

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Nomenclature

I	moment of inertia (kg m^2)	ω_n	robot's first mode natural frequency (rad/s)
N	nominal rotational frequency (Hz)	ξ	robotic holder damping ratio (%)
P	grinding power (W)	Δ	tool advance per turn (m)
R	wheel radius (m)	E_c	energy per impact (J)
S	measured signal	E_r	rotational kinetic energy (J)
e	eccentricity (m)	F_a	alternating force (N)
f	rotational frequency (Hz)	F_{ext}	external force (N)
h	dynamic cutting depth (m)	F_{m}	average normal force (N)
j	spindle revolution index	K_p	process stiffness (N/m)
m	filter length (revolutions)	S_f	filtered signal
n	number of samples per revolution	c_t	robotic holder damping (N s/m)
ρ	ratio of cut	f_{ml}	mean line rotational frequency (Hz)
δ	tool deflection (m)	f_n	robot's first mode natural frequency (Hz)
Ω	rotational frequency (rpm)	f_{mp}	mapped rotational frequency (Hz)
θ	angular position (deg)	h_0	desired cutting depth (m)
μ	friction coefficient	k_t	robotic holder stiffness (N/m)
ω	rotational frequency (rad/s)	m_t	robotic holder mass (kg)
$\overline{\varpi}$	mean line rotational frequency (rad/s)	m_u	unbalance mass (kg)
		n_c	number of impacts per turn
		v_{fd}	feed speed (mm/s)

1. Introduction

The dynamics of material removal has always been a subject of interest for research and development in machining operations. Extensive modeling and experimental effort has been deployed to explore the physical phenomena involved inside the contact zone between a cutter and workpiece material in order to develop an understanding allowing further improvement of the machining task. Interruption of the cut is an issue of great concern in this area because it introduces nonlinearity into the system dynamics. The importance of nonlinearity depends on the application under study and hence researchers have developed different methodologies to deal with it. The interruption phenomenon is recognized as the basic nonlinearity in machining chatter [1] and a traditional approach is to deal with it in numerical simulations by setting the cutting force to zero when the tool moves out of the cut. Modern cutting operations involve conditions where the degree of such nonlinearity is increased and the tool cuts the material for only small fractions of the spindle period. High-speed machining of contoured surfaces, near-net-shape flexible components and difficult-to-machine materials are examples of such operations [2]. A generalized analytical approach is proposed [2–5] by denoting a parameter $0<\rho<1$ which represents the ratio of time spent cutting to not cutting during a spindle period. The stability of interrupted cutting is then investigated for scenarios both of continuous operation ($\rho \approx 1.0$) and of highly interrupted operation ($\rho \approx 0$).

The application presented in this paper is a recently developed machining technology that provides a striking example of intermittent cutting. A lightweight (approx. 30 kg) 6-DOF robot manipulator holds a grinding tool and uses its multi-body articulated mechanism to extend far and perform grinding as shown in the laboratory setup in Fig. 1.

The SCOMPI robot developed at Hydro-Québec's research institute, IREQ, has been used over the past 15 years for maintenance jobs on such hydroelectric equipment as turbine blades, penstocks and head gates. Details of the technology can be found in Refs. [6,7]. This paper is part of an ongoing research about the study of chatter vibrations in the robotic grinding process performed by SCOMPI. Chatter is the unwanted self-excited vibration due to the interactions between the

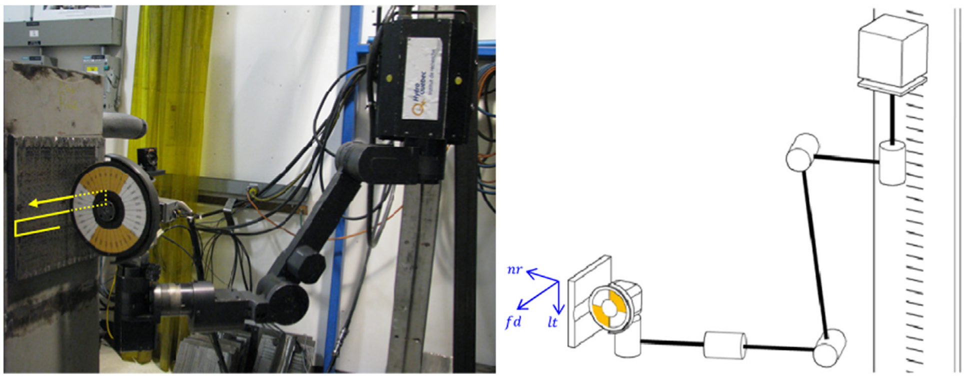

Fig. 1. 6-DOF manipulator SCOMPI (Super COMPact robot IREQ) as the holding mechanism in grinding operations (*fd*: feed, *nr*: normal, *lt*: lateral).