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Monitoring of tool collision in drilling by disturbance observer

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ABSTRACT

Disturbance observation is a sensorless process monitoring technique that has not yet been applied to the monitoring of tool collision in the use of machine tools. This paper presents a monitoring algorithm that detects collisions that involve the breakage of drills through observation of the disturbance force change rate. A comprehensive experimental study of diverse operator-induced collisions was conducted to analyze the collision detection potential of the disturbance observer. It was found that collision monitoring by the disturbance observer is more sensitive and responsive than that using a sensorless jerk observer.

1. Introduction

Monitoring of machining operations has been studied by academia for several decades with the aim of enhancing the robustness and stability of industrial manufacturing processes [1–5]. Despite the almost overwhelming scope of monitoring solutions for diverse purposes as presented by scientific literature, industries remain reluctant to implement advanced process monitoring systems [6]. To delve into possible reasons for this reluctance, Teti et al. found that machine operators are often overburdened with the complexity of monitoring systems, which need to be thoroughly understood for them to be properly adapted to individual processes [1]. Hence, more recently, the research focus in condition monitoring has shifted from inventing increasingly complex systems to simplification [1,6,7].

Simplification is required with regard to the monitoring algorithms and the sensor technology [1,7]. The “sensorless” approach focusses on using the information provided by the machine tool control and the feed drives to carry out process monitoring instead of installing expensive and complicated external sensor systems (e.g. [8,9]). In 2011, Kakinuma et al. showed that chatter vibrations can be detected in end-milling through sensorless monitoring of the spindle torque. Kakinuma used the spindle current reference and angular velocity to estimate the disturbance torque [10,11]. Hence, the so-called “disturbance observer” may be considered to be a multi-sensor monitoring method that fuses the sensor data indirectly, because a priori knowledge about the torque coefficient K_t and the inertia J of the spindle is applied to calculate the disturbance torque T_{dis} from the raw signal [2,10].

Current research is being conducted with the goal of widening the application range of the disturbance observer. Recent publications have managed to demonstrate the feasibility of detecting tool contacts as well as cutting edge fractures by disturbance force estimation [12–14]. However, thus far, the disturbance observer has not been applied to tool collision monitoring.

Tool collision monitoring is of great importance for preventing damages, for example, to machine tool spindles. In fact, 60% of severe spindle failures may be traced back to operator-induced collisions between moving parts of a machine tool [15,16]. The spindle components undergoing maximum damage from a collision are rolling-element bearings. Because the contact areas between the rolling elements and the inner and outer races are small, the reaction forces during a collision per unit contact area may exceed the allowable interface pressure, which leads to initiation and propagation of cracks [16].

In 2011, Abele et al. presented an overview of collision protection strategies (see Fig. 1 and [16]). Presently available technical solutions for collision monitoring include measures such

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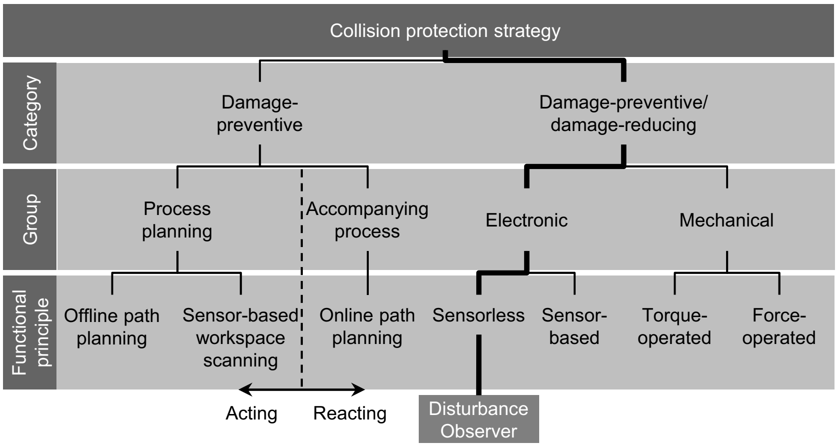

Fig. 1. Overview of collision protection strategies [16] and classification of disturbance observer.

as the use of bearing sensor rings embedded into the spindle motor [17], spindles that are lifted or tilted mechanically in the case of collisions [16], and ultrasonic and capacitive sensors [18].

The present work defines and applies a methodology for detecting operator-induced collisions in drilling by means of a disturbance observer that does not require external sensors. In terms of Abele's scheme (see Fig. 1), the disturbance observer may be considered to be damage-preventive or, rather, damage-reducing, since the collision between the tool and the workpiece actually occurs before intervention by the monitoring method. Hence, collision monitoring is carried out using the disturbance observer to delimit the damage to the tool and prevent collisions between, say, the tool chuck and the workpiece.

This paper is organized as follows. Section 2 introduces the methodical background of this study. Section 3 outlines the characteristics of collision monitoring by the disturbance observer with regard to distinct collision scenarios caused by diverse operator errors. Finally, Section 4 discusses the results and outlines possible improvements and future work.

Table 1
Table of acronyms.

Acronym	Unit	Description
a	m/s^2	Acceleration
d_d	mm	Diameter of drill
F	–	Collision signal exaggeration
F_{col}	N	Collision force
F_{cut}	N	Cutting force
F_{dis}	N	Disturbance force
F_{fric}	N	Friction force
f_{g_1}	Hz	Cut-off frequency of second order filter
f_{g_2}	Hz	Cut-off frequency of first order filter
f_I	Hz	Sampling frequency of current reference
f_x	Hz	Sampling frequency of x-axis driven stage
g_1	rad/s	Angular velocity of second order filter
g_2	rad/s	Angular velocity of first order filter
I_a^{ref}	A	Current reference
$\hat{j}$	m/s^3	Jerk
K_t	N/A	Thrust force coefficient
K_{tn}	N/A	Nominal thrust force coefficient
l_d	mm	Length of drill
M	kg	Mass of feed drive
M_n	kg	Nominal mass of feed drive
n	min^{-1}	Revolutions per minute of the spindle
pos	m	Position of feed drive
$\hat{S}_{dis}$	N/s	Disturbance force change rate (snatch)
t	s	Time
Δt_{dead}	ms	Dead time
v_x	mm/min	x-axis feed rate
v_z	mm/min	z-axis feed rate

2. Methods

According to Teti et al., the design of a process monitoring algorithm must define both signal processing and the decision making by which the monitoring purpose is achieved [1]. Signal processing is outlined in Section 2.1, and the definition of semi-dynamic thresholds to decide whether a collision occurred is presented in Section 2.2. A table of acronyms may be found in (Table 1).

2.1. Signal processing

A straightforward approach frequently applied to collision detection is the monitoring of the acceleration and deceleration change rates, called jerk (e.g. [19]). The concept of jerk monitoring is based on the fact that the machine tool may exert only a limited jerk to accelerate or decelerate the feed drives. In the case of a major collision, however, the machine axes experience a jerk that exceeds this limited "acceleration jerk". Hence, based on a static jerk threshold collision events causing a much larger jerk may be discerned from an ordinary feeding jerk. The threshold for jerk monitoring must be chosen on the basis of the jerk acting in the rapid feeding mode of the respective axis to avoid misdetection during regular feeding operation.

The jerk may be determined externally, e.g., by acceleration sensors. A sensorless approach to estimate the jerk would be to consider either the current reference I_a^{ref} or the position signal of the screw-driven stage. However, in the case of a collision, the position signal pos responds immediately to the disturbance whereas the current reference increases with a delay [18]. Hence, the position signal is more suitable than the current reference for monitoring collisions without the application of external sensors.

Firstly, a conventional jerk observer shall be defined, see upper block diagram in Fig. 3. Later the properties of the jerk observer will be compared to the properties of the disturbance observer, which is defined by the lower block diagram in Fig. 3. In the continuous domain, the jerk $\hat{j}$ acting on the axes may be estimated by the third temporal derivative of the position signal pos.

$$\hat{j} = \frac{d^3 pos}{dt^3} \qquad (1)$$

Since the position is measured discretely at a sampling frequency f_{pos}, filtering is required to suppress high-frequency noise originating from the quasi-differentiation of the position signal. In particular, at least a second-order low-pass filter must be applied to smooth the acceleration signal. In this study, we used a