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Development of an innovative plate dynamometer for advanced milling and drilling applications

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A B S T R A C T

Tool geometry optimization, workpiece material characterization, process monitoring and optimization are based on the measurement of cutting forces by using machining dynamometers. Commercial dynamometers cover a wide range of machining applications, nevertheless there is a lack of measuring devices suitable for investigating milling and drilling applications with relatively small cutters and high spindle speeds. In this work, the development and testing of an innovative plate dynamometer designed for this purpose is discussed. The new measuring system was based on three high-sensitive triaxial piezoelectric force sensors arranged in a novel triangular configuration. Component design was optimized by using FE numerical approaches, according to the general guidelines derived from mathematical modeling of sensor dynamics. The prototype of the proposed device was manufactured and experimentally tested against two high-end commercial plate dynamometers by performing static calibration, modal analysis and cutting tests. Experimental results proved the excellent characteristics of the new device and its effectiveness for investigating advanced machining applications.

1. Introduction

Cutting force measurements are essential for understanding the physics of the cutting process [1] and for developing reliable cutting force models [2], as well as for workpiece material characterization, machinability tests and tool comparison [3], tool geometry optimization [4], cutting parameters optimization [5]. Also, cutting force measurements can be successfully applied for tool condition monitoring [6, 7] and detection of chatter vibrations [8].

State of the art regarding cutting force measuring in milling is presented in Table 1. The existing methods and devices can be classified according to different criteria: the location of the sensing element and the physical principle used for cutting force estimate. Other important features to be taken into account for a rough classification are the force measuring range (which is also related to sensitivity), the type and number of independent force components measured by the device.

Regarding sensor location, the measuring device can be installed in the feed drives of the linear axes or in the spindle – spindle housing subsystem. Alternatively, it could be embedded into the rotating spindle adapter – toolholder, or it could be integrated into the machine tool table – workpiece fixture.

It should be also recalled that cutting forces are always estimated by using indirect methods, i.e. by measuring the effects of cutting forces such as local deformations, displacements or accelerations of mechanical elements composing the machining system. For this purpose, several physical principles were exploited, such as the conversion of electro-mechanical power, the variation of electrical resistance of a stretched conductor, the piezoelectric effect and many others.

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Table 1
State of the art of cutting force measurement in milling (* = with dynamics compensation; ** = nominal natural frequency, ideal clamping conditions, no workpiece or light workpiece; NS = not specified).

Sensor location	Sensor description	F_x, F_y		Axial force F_z		Cutting torque M_z		Ref.
		Range (kN)	Band-width (kHz)	Range (kN)	Band-width (kHz)	Range (Nm)	Band-width (kHz)	
Linear drives, spindle, spindle housing	Cutting forces derived from servo-motor currents of feed drives measured by amperometers (research device)	> 1	0.13	/	/	/	/	[9]
	Cutting forces measured from command voltages of electro-magnetic bearings of milling machine spindle (research device)	5	< 2	/	/	/	/	[10]
	Cutting forces derived from spindle vibrations measured by displacement capacitance sensors (research device)	> 5	0.5(1*)	/	/	/	/	[11]
	Cutting forces derived from spindle acceleration measured by triaxial accelerometer integrated in the toolholder (research device)	> 1	1(2*)	> 1	1(2*)	/	/	[12]
	Cutting forces derived from strain gauges attached to spindle bearings or other spindle elements	> 2	0.2	/	/	/	/	[13]
	Force sensors (Kistler 9135 (axial) and Kistler 9145 (shear) rings) integrated in the spindle	3	0.5(1.5*)	36	0.5(1.5*)	/	/	[14,15]
Spindle adapter, tool-holder	Torque rotating dynamometer based on strain gauges (research device)	/	/	/	/	> 100	0.7(< 2*)	[16]
	Rotating mechatronic toolholder, based on piezo-resistive strain gauges or piezoelectric elements (research device)	/	/	2	NS	> 50	NS	[17]
	Piezoelectric rotating dynamometer Kistler 9123C (10,000 rpm max)	0.5 – 5	0.5(2**)	2 – 20	0.5(1**)	20 – 200	1	[8,18]
	Piezoelectric rotating dynamometer Kistler 9125A (25,000 rpm max)	/	/	0.3 – 3	(< 5**)	10 – 50	2.5	[19]
	Strain gauges mounted under each cutting insert, and telemetry for data transmission (research device)	> 1	NS	/	/	> 100	NS	[20]
	Piezoelectric triaxial rings under each cutting insert and telemetry for data transmission (prototype of commercial sensor)	3	1.7	2	1.7	200	1.7	[21]
Platform (workpiece fixture)	Plate dynamometer based on strain gauges attached on flexible octagonal rings (research device)	5	1**	5	1.5**	/	/	[22]
	Piezoelectric plate dynamometer Kistler 9257	5	< 1(2.3**)	5	< 1(3.5**)	/	/	[21]
	Piezoelectric plate dynamometer Kistler 9272 ("Drilling Dyn.")	5	1(3**)	5	4 (6**)	200	2.2(4**)	This paper
	Piezoelectric plate dynamometer Kistler 9256C1 ("Mini Dyn.")	0.25	> 2(5**)	0.25	> 3(5**)	/	/	[23–28], This paper
	Proposed piezoelectric plate dynamometer (research device, "Delta Dyn")	> 1	> 2	> 1	> 3	< 35	> 2.5	This paper

For instance, Jeong et al. [9] extracted cutting force information from the current signals of the servo motors governing machine tool axes, while Auchet et al. [10] adopted a similar approach based on control signals of electro-magnetic spindle bearings. These approaches do not alter machine tool architecture and dynamics, nevertheless a poor frequency bandwidth can be obtained in the first case (130 Hz), while advanced and very expensive machine tool elements such as the electro-magnetic bearings are needed in the second case.

Another possibility is to derive the cutting forces from the local deformations of flexible mechanical parts of the machining system by using strain gauges [13,29,22]. Nevertheless, when using strain gauges it is usually necessary to weaken the mechanical structure where they are attached in order to achieve a sufficient sensitivity. As a consequence, the dynamics of the (weakened) mechanical structure do considerably disturb the measured cutting force signals, implying a modest frequency bandwidth.

Cutting forces may be also estimated from spindle or cutter vibrations, by using accelerometers [12] or displacement probes [11]. As before, one major drawback of these solutions is the poor frequency bandwidth.

Generally, the best compromise between stiffness and sensitivity can be achieved by using piezoelectric crystals [30]. Piezoelectric rings can be installed into the spindle housing [14,15], or rotating dynamometers can be clamped between the tool and the spindle [8,19,17]. However, the range of application of these devices is limited to the low-medium spindle speed range. In addition, cutting force signals acquired by these sensors are disturbed by the low-frequency resonances of the spindle-tooling system.

Recently, an innovative rotating dynamometer capable of measuring individual cutting edge forces in face milling was developed by Totis et al. [21]. The device was based on piezoelectric triaxial force cells installed behind each cutting insert, which was inspired by the pioneering work of Adolfsson et al. [20], who applied strain gauges for the