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Experimental sensor system implementation for selected micromilling-related parameters

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Abstract
The paper describes micromilling machine and implemented sensor system for microcutting operations. Sensor system can be used for cutting forces, accelerations, acoustic pressure and tool displacements measurement. Cutting forces and accelerations signals were used for cutting depth, hardness of workpiece and excitation frequency of rotating tool monitoring. Other signals obtained during experiment will be used in further work. Conclusions arising from performed experiment and further research plans are presented.

Introduction

Milling can be considered as micromilling when tool diameter is less than 0.5 mm. Micromilling differs from milling in macro scale in several aspects that are result of process miniaturization. Feed per tool blade can be comparable to cutting edge radius which can cause plastical machining end elastic deformation. Moreover, machine spindle or micromilling tool runout can be comparable to feed per tool blade which can imply machining with only one tool blade.

Investigation of micromilling operations can be complicated due to process miniaturization. Small tool diameter does not give possibility of direct tool frequency response function estimation [1, 2, 3, 4, 5, 6]. Measurement of cutting forces can be problematic due to dynamometer own vibrations [7, 8, 9, 10] and very low cutting forces value (less than 1 N).

Some signals connected with proper signal processing can indicate hardness of material, depth of cut or tool rotational speed. Amplitude of cutting forcers has relation with workpiece hardness and depth of cut [11]. Frequency analysis [10, 12] (e.g. fast Fourier transform) of signals gives possibility to verify usefulness of these signals for tool rotational speed monitoring. Frequency analysis also can detect if tool is cutting with one or two blades.

Micromilling machine and test stand

Experiment was performed on prototype three-axial micromilling machine SNTM-CM-ZUT-1 [11, 13, 14] which was build in Mechatronics Centre of West Pomeranian University of Technology. Micromilling machine is equipped with three-axial *Kistler 9256C1* dynamometer that was used for cutting forces measurement. Dynamometer was connected to *Kistler 5070* charge amplifier. *PCB Piezotronics 352B10* accelerometers were used for workpiece and spindle displacement measurement. *G. R. A. S. 46AE* microphone was used for acoustic pressure measurement. *Polytec PSV-400* Scanning Vibrometer was used for tool displacement measurement and tool angular position measurement. National Instruments *CompactRio* with *NI 9234* modules was used for all measured signals acquisition. Sampling frequency during signal acquisition was set to 51 200 Hz. Off-line signal processing was performed by *National Instruments LabView* and *MATLAB* software. Tool was optically observed during experiment with *Keyence VHX-600ESO* microscope. Schematic view of micromilling machine with sensors is shown on figure 1.

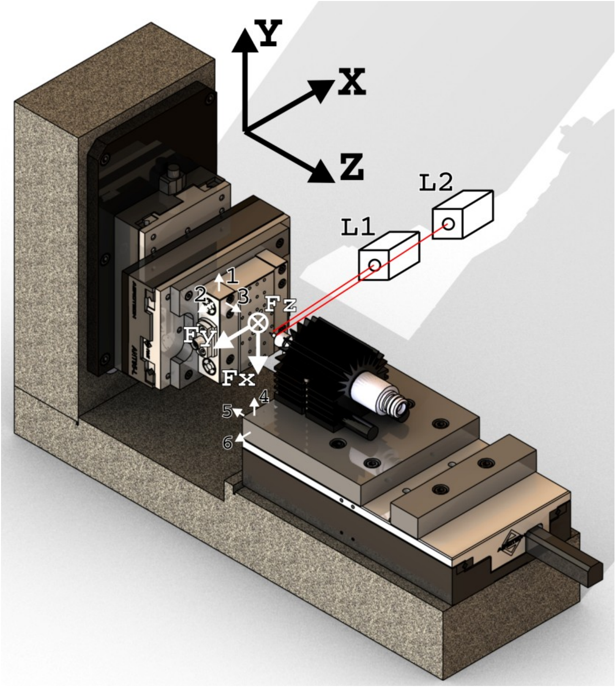


Fig. 1. Scheme of micromilling machine: 1–6 – accelerometers, L1, L2 – laser vibrometer heads

Figure 2a shows laser vibrometer and micromilling machine. Workpiece with accelerometers and tool mounted in machine is shown on figure 2b.

Experiment setup

In case to verify possibilities of usage presented system for micromilling process observation and diagnostics milling experiments in three different materials was performed. Three different *Kyocera* micromilling tools were used: 2FESM002-004-04 (diameter 0.2 mm), 2FESM005-010-04 (diameter 0.5 mm), 2FESM010-025-04 (diameter 1 mm).

Table 1. Cutting parameters

Tool diameter [mm]	Rotational speed [RPM]	Cutting speed [m/min]	Feed per blade [mm]	Feed rate [mm/min]	Depth of cut [μm]	Frequency [Hz]
0.2	46,000	28.9	0.0014	28.9	10	1533
0.2	46,000	28.9	0.0014	28.9	10	1533
0.2	46,000	28.9	0.0014	28.9	10	1533
0.2	46,000	28.9	0.0014	28.9	20	1533
0.2	46,000	28.9	0.0014	28.9	20	1533
0.2	46,000	28.9	0.0014	28.9	20	1533
0.5	19,000	29.8	0.0034	29.8	10	633
0.5	19,000	29.8	0.0034	29.8	10	633
0.5	19,000	29.8	0.0034	29.8	10	633
0.5	19,000	29.8	0.0034	29.8	20	633
0.5	19,000	29.8	0.0034	29.8	20	633
0.5	19,000	29.8	0.0034	29.8	20	633
1	15,300	48.1	0.0044	48.1	10	510
1	15,300	48.1	0.0044	48.1	10	510
1	15,300	48.1	0.0044	48.1	10	510
1	15,300	48.1	0.0044	48.1	20	510
1	15,300	48.1	0.0044	48.1	20	510
1	15,300	48.1	0.0044	48.1	20	510

Experiment setup and cutting parameters are shown in table 1. Feed rate and rotational speed for tools of diameter 0.5 and 1 mm are suggested manufacturer parameters for carbon steel milling. Tool manufacturer does not provide suggested milling parameters for tools of diameter less than 0.5 mm and for non-ferrous materials.

Experiment results

Information source about micro milling process conditions is measurement of cutting forces signals,

a) 

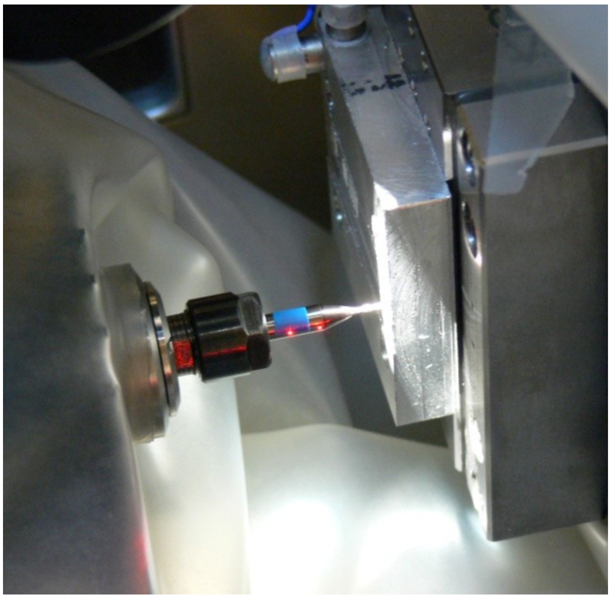
b) 

Fig. 2. View of test stand: a) laser vibrometer and micromilling machine, b) micromilling tool

acceleration signals and acoustic pressure signals. Basing on those signals, there is a possibility to monitor particular parameters important for micro cutting process.

One of the most basic signal that gives exact information of the process is cutting forces signal. Having regard to the limitations described in [7, 8, 9], there is a possibility to get useful information about the process. *X*, *Y* and *Z* components of cutting forces can differ because of various tool-workpiece trajectory, however, the net force should remain unchanged.

Net force can be calculated from equation:

$$F_n = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

where:

- F_x – force component x,
- F_y – force component y,
- F_z – force component z.

One of the simplest method to exploit obtained data is to calculate root mean square (RMS) value from the net force. RMS value can be calculated from equation:

$$F_{\mathrm{RMS}} = \sqrt{\frac{1}{n}\sum_{i=1}^{N} F_{ni}^2} \tag{2}$$

where:

- N – number of signal samples,
- F_{ni} – net force for i-th signal sample.

RMS values calculated from net forces for different micromilling tools and different workpiece materials are shown in table 2.

For simpler and more convenient presentation of the results from table 2 mean values of net forces can be calculated:

$$\bar{F}_{\mathrm{RMS}} = \frac{\sum_{j=1}^{N} F_{\mathrm{RMS}j}}{N} \tag{3}$$

where: $j = 3$, $N = 3$.

Mean values calculated from equation (3) are presented in table 3.

Table 3. Mean values of net forces from table 2

Material	Tool diameter					
	0.2 mm		0.5 mm		1 mm	
	10 µm	20 µm	10 µm	20 µm	10 µm	20 µm
PA6	0.1439	0.3065	0.1596	0.3342	0.2049	0.6890
Cu	0.3776	0.6098	0.2802	0.7772	0.4659	1.0941
18G2	0.4075	0.8521	0.5949	1.0529	0.5823	1.6091

Cutting depth recognition and material detection

Cutting depth parameter indicates material thickness removed from the workpiece. Maximum value of this parameter is usually given by manufacturers and differs depending on tools dimensions. During micromilling process it is particularly important to maintain defined cutting depth. To distinguish cutting depths used in experiment (10 µm – 20 µm) for three different tools of diameter: 0.2 mm, 0.5 mm and 1 mm, RMS value of net cutting force shown in table 3 can be used.

Mean values of cutting net forces give information about deepness of the micromilling operation. Table 3 shows how $\bar{F}_{\mathrm{RMS}}$ values changes, depending on depth of cut. RMS values of net force are greater for larger depth of cut (20 µm) than for lower depth of cut (10 µm) for tools of all diameters.

RMS values of net force (Tab. 3) gives possibility to distinguish type of milled material basing on its hardness. Three kind of metal workpieces were used in experiment to show possibility of detecting differences in materials hardness. The lowest net force values is for PA6 duralumin. Higher cutting force value is for copper. Milling in 18G2 carbon steel gives the highest cutting force values. This relation occurs for every tool diameter and cutting depth.

Table 2. RMS value of the net force of force components F_x^2, F_y^2, F_z^2

Material	Tool diameter																	
	0.2 mm						0.5 mm						1 mm					
	10 µm			20 µm			10 µm			20 µm			10 µm			20 µm		
	Fn1	Fn2	Fn3	Fn1	Fn2	Fn3	Fn1	Fn2	Fn3	Fn1	Fn2	Fn3	Fn1	Fn2	Fn3	Fn1	Fn2	Fn3
PA6	0.1322	0.142	0.1577	0.2789	0.3085	0.3321	0.1321	0.1695	0.1773	0.2514	0.3146	0.4368	0.1816	0.1979	0.2353	0.4957	0.6929	0.8786
Cu	0.3567	0.3787	0.3975	0.5655	0.5814	0.6827	0.2678	0.2825	0.2903	0.7452	0.7853	0.8011	0.3158	0.452	0.6301	0.9485	1.1145	1.2193
18G2	0.3127	0.4791	0.4308	0.7571	0.8954	0.9038	0.538	0.6015	0.6452	0.9806	1.048	1.1303	0.2198	0.5831	0.9442	1.3656	1.6264	1.8354

Excitation frequency monitoring

Transforming measured signals during micromilling process from time domain to frequency domain allows to calculate the excitation frequency of rotating tool. Every tool used in experiment had two cutting blades and their rotational speed was set to: diameter 0.2 mm – 46,000 RPM, 0.5 mm – 19,000 RPM, 1 mm – 15,300 RPM. Excitation frequency is calculated from the following formula:

$$f_{\text{ex}} = \frac{n}{60} z \tag{4}$$

where:

n – rotational speed [RPM],

z – number of cutting blades.

Fast Fourier transform was calculated for 1 s time segment for cutting forces, acceleration signals and microphone signal. Cutting forces signals and acceleration signals for analysis were taken from feed (*X*) direction. Excitation frequency calculated from equation (4) should have highest amplitude on FFT graph.

Figure 3 shows FFT graphs for milling in copper at 46,000 RPM. Excitation frequency (1533 Hz) is highest on cutting forces FFT signal. Both FFT from acceleration and microphone shows frequency that is related with tool rotational speed (767 Hz).

FFT graphs for milling in copper at rotational speed of 19,000 RPM is presented on figure 4. Dominant frequency in cutting forces FFT is 317 Hz which corresponds with tool rotational speed. Excitation frequency (633 Hz) is also visible on FFT graph, however, it has lower value. For acceleration and microphone signal dominant frequency is excitation frequency.

Fast Fourier transform of cutting forces, acceleration and microphone signals for rotational speed of 15,300 RPM are shown on figure 5. Dominant frequency in cutting forces signal and in microphone signals is excitation frequency (510 Hz). On FFT from acceleration signals excitation frequency and frequency related to rotational speed have similar amplitude.

Conclusions

Root mean square value of cutting net force changes with depth of cut and material hardness. For greater depth of cut RMS value of net cutting force is greater than for lower depth of cut. Milling in different material results in change of RMS net cutting force. For material with greater hardness cutting force value increases.

On the graphs in frequency domain both, excitation frequencies and frequencies related with tool rotational speed can be visible. This phenomena can be caused by milling with one blade of cutting tool. There can be noticed some differences in FFT

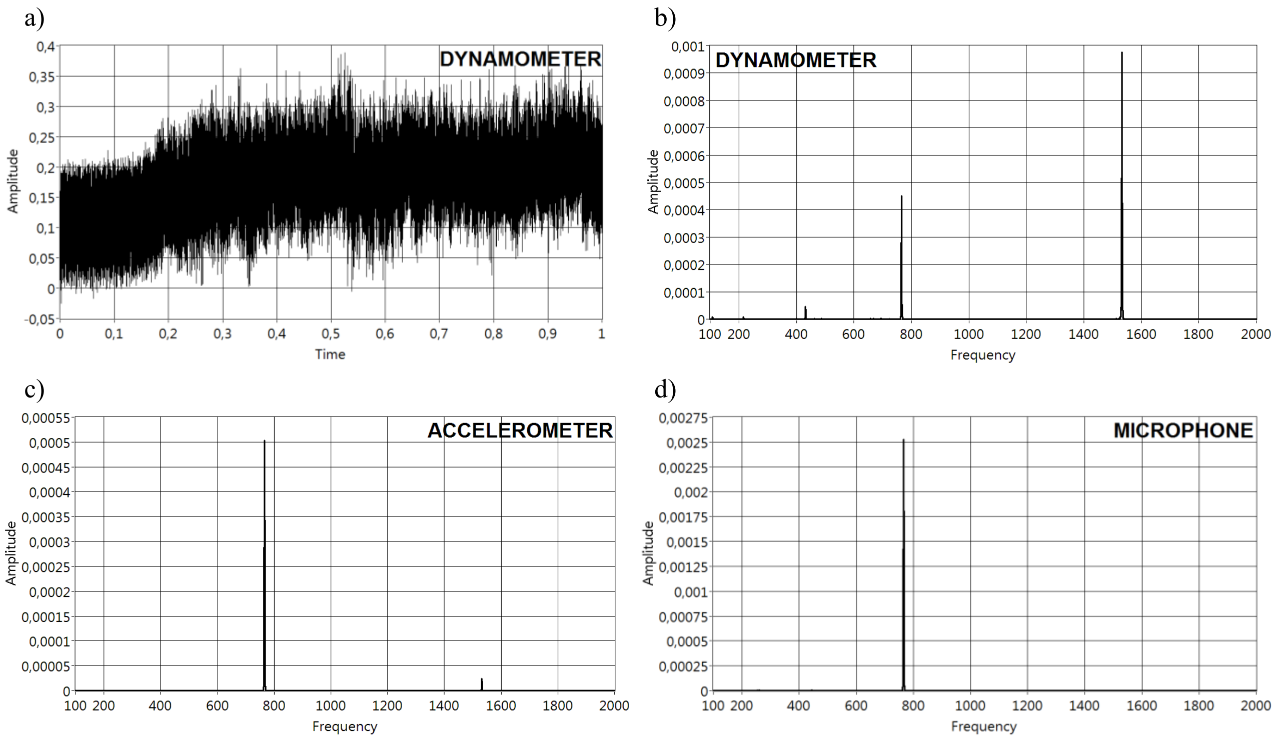


Fig. 3. Raw data and FFT graphs for tool of diameter 0.2 mm, spindle rotational speed 46,000 RPM, excitation frequency 1533 Hz depth of cut 20 μm, material – copper: a) raw cutting forces signal, b) cutting forces FFT, c) acceleration FFT, d) acoustic pressure FFT

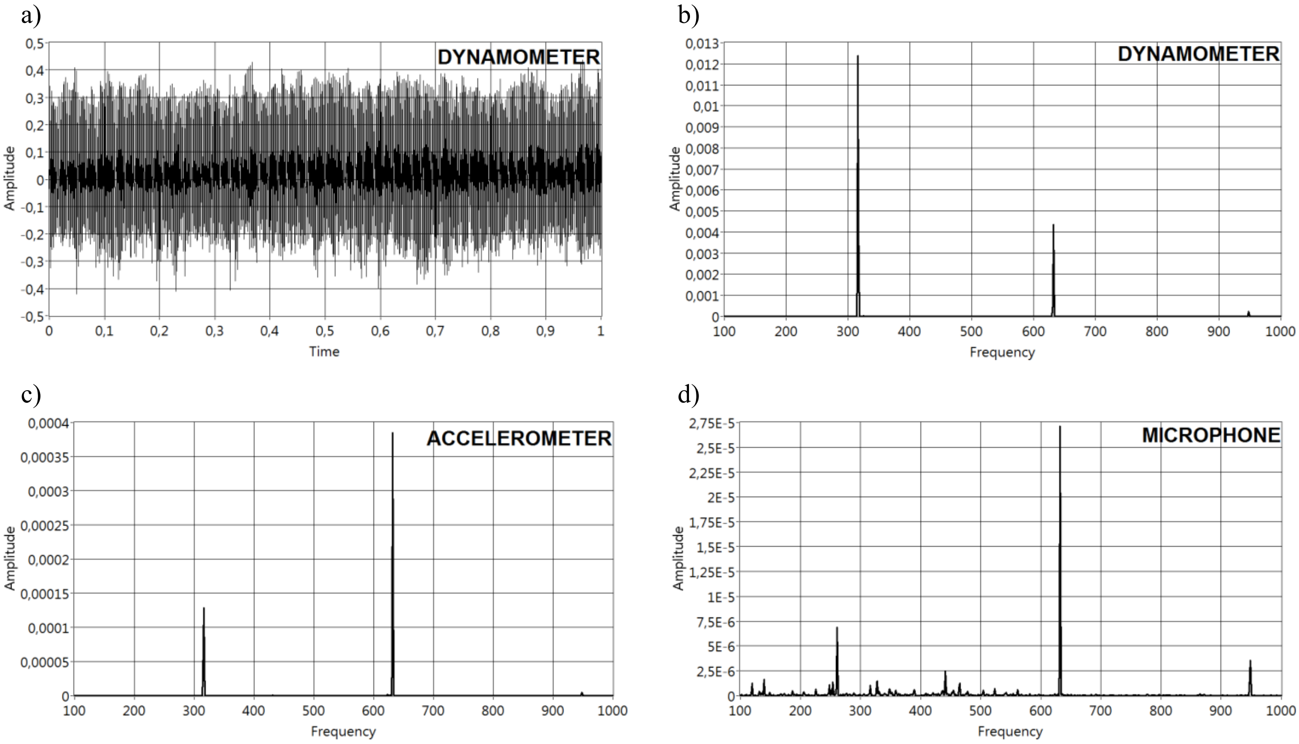


Fig. 4. Raw data and FFT graphs for tool of diameter 0.5 mm, spindle rotational speed 19,000 RPM, excitation frequency 633 Hz depth of cut 20 µm, material – copper: a) raw cutting forces signal, b) cutting forces FFT, c) acceleration FFT, d) acoustic pressure FFT

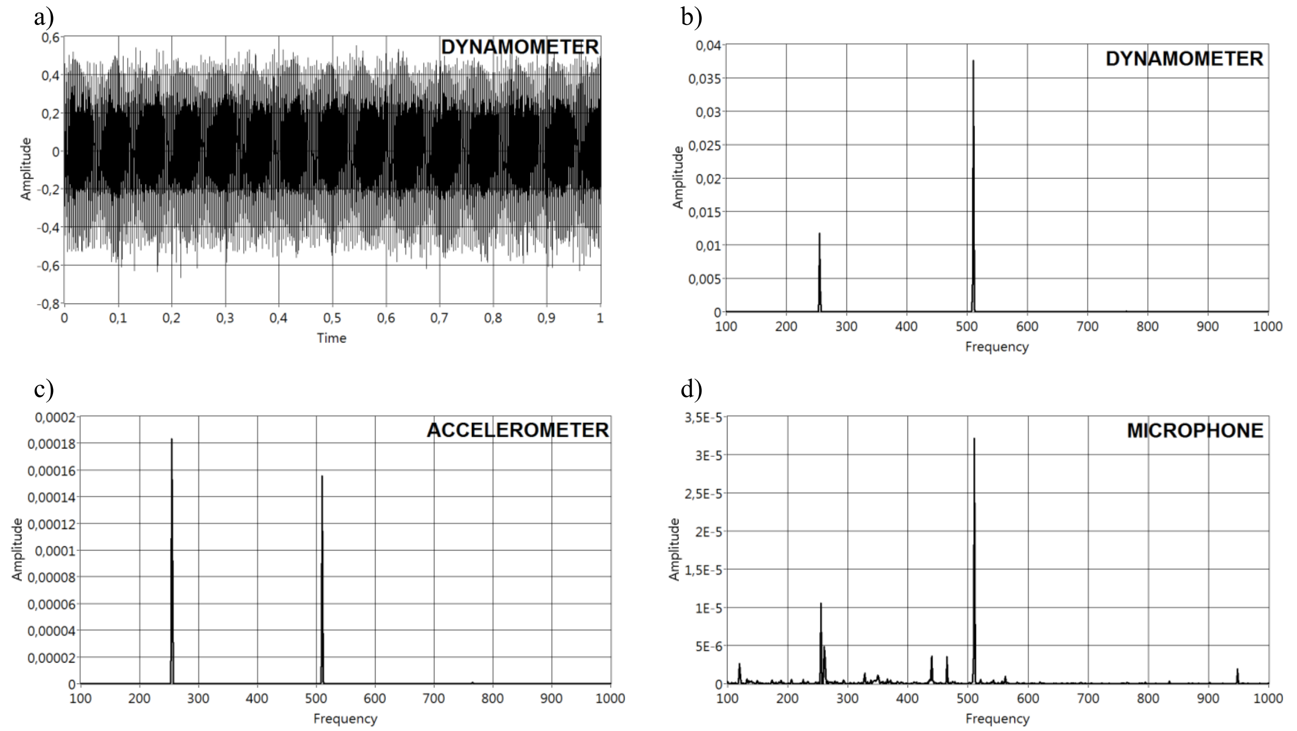


Fig. 5. Raw data and FFT graphs for tool of diameter 1 mm, spindle rotational speed 15,300 RPM, excitation frequency 510 Hz depth of cut 20 µm, material – copper: a) raw cutting forces signal, b) cutting forces FFT, c) acceleration FFT, d) acoustic pressure FFT

amplitude for different signals sources (dynamometer, accelerometers, microphones), although at least for dynamometer and accelerometer the same frequencies should be dominant.

Performed signal analysis gives diagnostic information about micromilling process and can be used for detection of cutting parameters variation. The paper does not present results of tool displacement measurement with laser vibrometer. These results will be presented in further work.

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