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MEASURING MILLING FORCE WITH TWO C9C FORCE TRANSDUCERS

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Abstract: *Cutting forces during milling can be measured using several high-quality, though expensive, devices available on the market. In this study, an attempt was made to measure the cutting forces using two C9C force transducers. The results obtained from these measurements are discussed in this paper.*

Keywords: *milling force measurement, C9C force transducer*

1. INTRODUCTION

Many researchers have analyzed the milling forces with different goals. Most of them used some kind of three-axis dynamometer produced by Kistler.

In [1] the researchers used Kistler 9257B dynamometer for three-component cutting force measurement. They found that cutting force per uncut chip area decreases with the increasing feed per tooth. Most significantly, decrease happens in the tangential direction, but to a lesser extent also in the radial and axial directions. A slight decrease in cutting force was also observed with increasing cutting speed. Researchers assumed that the higher values at lower feed were due to the rake angle at the corner radius (r_ε) of the tool becoming negative as the commanded feed per tooth approached the same order of magnitude as the cutting-edge corner radius.

In [2] the dynamometer Kistler 9255B for three-component cutting force measurement was used. It was determined that tangential and radial cutting force per uncut chip area decreased with the increasing feed per tooth, but the axial cutting force per uncut chip area showed increase at the lumped shear model. The paper's authors divided the cutting mechanism into shearing and ploughing and confirmed that the tangential and axial shearing components indicated slight decrease with the increase of the feed, and the radial component is constant; the tangential, radial and axial ploughing components all increased with the increase of the feed. Thus, together they should increase with the increase of the feed. It was claimed that the ploughing component was better at taking into consideration dynamic effects, and this way their dual model was more precise than the lumped shear model.

Paper [3] analyzed the effect of robot dynamics on the machining forces in robotic milling. A quartz-based three-force-component dynamometer (Kistler 9257B) was used, and the position of the robot end effector was recorded by a laser displacement sensor (Keyence LK-G37; 0.3μm resolution) in the absence and presence of the applied known load to calculate the Cartesian stiffness of the system. The dry milling experiments consisted of linear tool paths with constant radial and axial depths of cut at different feed rates. All tests were run at a constant spindle speed of 1000 rpm. They compared the peek values of the measured and simulated forces as well as compared the differences between the highest and lowest peeks - which occur due to vibrations - and stated that their model was significantly more precise than the older ones.

In [4] wet milling experiments of 34CrNi3Mo steel were conducted, on the EV850L machining center. They used intelligent induction handle BT40_MAGE20 _NL105, comparing modelled and measured bending moment, torsional moment and compressional force on the tool, and obtained similar characteristics.

In [5] the authors developed a FE model to take into account the material behavior at different plastic strains, strain rates and temperatures. The micro-milling forces were determined based on the FE predicted forces and the calculated uncut chip thickness. The predicted forces were validated with experimentally measured results at different spindle angular velocities and feed rates. Kistler dynamometer 9258C2 were used to measure the three orthogonal force components on an ultraprecision 5-axis CNC milling machine (KERN Evo). The results revealed great agreement between predicted and experimentally measured micro-milling forces.

In [6] the actual cutting force was measured by a force dynamometer at a sampling rate of 2kHz in order to develop a controller which stabilizes the work under uncertain conditions. In [7] the instantaneous milling forces were measured by a dynamometer (model: Kistler 9265B). The sampling frequency was set to 2 kHz. They investigated the instance when starts boldly raising the wear curve, i.e. when the tool should be resharpened, or the inserts be changed.

Kistler`s three-axis dynamometers are highly practical and good measuring instruments, but they are also extremely expensive. However, this paper presents results obtained by a much cheaper measuring method.

2. EXPERIMENT SETUP AND THE RESULTS

2.1 Experiment Setup

Authors used a universal milling machine (MUG 62) as a machine tool and a vice as a clamping device. To measure the milling forces two HBK made C9C force transducers were implemented. Force transducers were placed between the jaw of the vice and the workpiece (Figure 4 and Figure 5). Since in this way the force can be measured only in one direction, three different setups were needed to measure force respectively in X (F_x), in Y (F_y) and in Z direction (F_z).

Figure 4 shows the setup for measuring F_x, Figure 5 displays the setup for measuring F_y, while Figure 6 depicts the setup for measuring F_z.

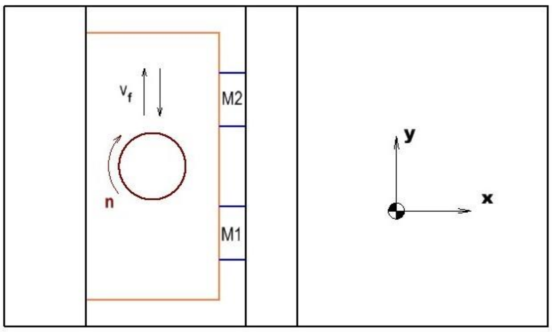

Figure 4. Top view of the vice setup for measuring force in X direction

The workpiece is a rectangle drawn in orange; the tool is a circle drawn with brown color. M1 and M2 represent the force transducers. The rotation direction of the tool is denoted with n, whereas the moving direction of the machine table (i.e. the moving direction of the workpiece during the machining) is represented with v_f. The workpiece material was S235JRG2 steel. All cuttings were made in dry condition (without cooling). Two, four, five and six flute endmills were used. The depth of cut (a_p) was 0,5mm, 1mm and 2 mm, while the feed was v_f=14mm/min. The width of cut (a_e) was in every case equal to the tool diameter. The number of the rotation per minute was 400 min^{-1} for D=5mm, 248 min^{-1} for tool diameters D=9mm and D=10mm, and 120min^{-1} for diameter D=22mm. After clamping the workpiece, the force transducer M1 showed 12350 N, and force transducer M2 showed 8713 N. These values were set as reference zero.

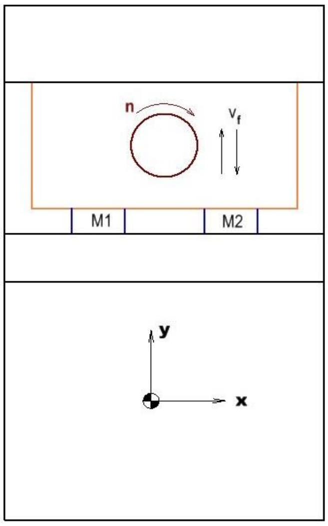

Figure 5 Top view of the vice setup for measuring force in Y direction

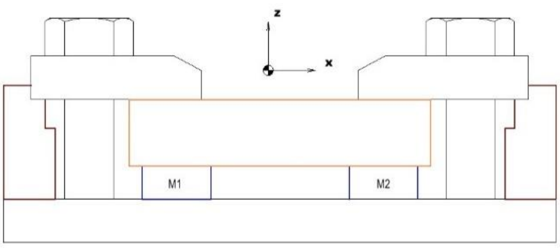

Figure 6 Front view of the workpiece holding with clamp straps

During the measurement of F_z two clamp straps were used instead of a vice.

2.2 The results

As a first step, F_x was measured, both in the case of up milling and down milling.

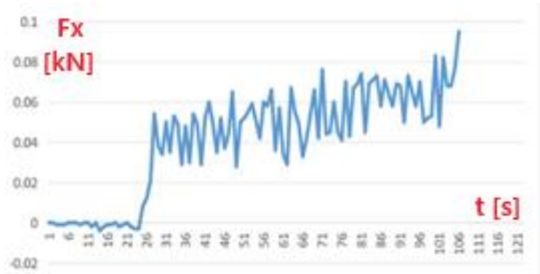

Figure 7 F_x component of the cutting force, with v_f down direction (D5; z2; a_e5; a_p0,5)

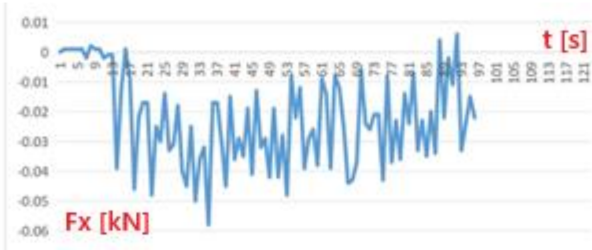

Figure 8 F_x component of the cutting force, with v_f up direction (D5; z2; a_e5; a_p0,5)

Figure 7 presents the case where, at the beginning of the cut, the direction of the tool tooth motion and the workpiece motion were identical. In this case the tangential force of the mill pushed the workpiece onto the measuring elements. (in +X direction in Figure 4). In contrast, Figure 8 displays the case where, at the beginning of the cut, the direction of the tool motion and the workpiece motion were opposite. In this case the tangential force pulls down the workpiece from the measuring elements. (in -X direction in Figure 4)

In Figure 7 on the vertical axis the sum of the reaction force changes (F_x=ΔM1+ΔM2) is in kilonewton (kN), on horizontal axis the time is presented in seconds (s). In Figure 7 the peek value of the F_x force is about +80 N, in Figure 8 the peek value is -50 N (the -60N can be treated as extreme peek). It can be seen that in both cases the amplitude of the F_x force is about 35 N. So, the force that periodically pushes the workpiece in X direction is about 35 N. As a two-flute (z=2) mill was used, this value is in fact the average tangential force on one tooth (F_{czm}). In both figures a slight force increasing trend can be observed, which is due to the thermal expansion, since dry cuts were made.

Figure 9 presents the case when the feed direction of the machine table points in -Y direction (in Figure 5), and the F_f feed force pulls down the workpiece from the measuring elements.

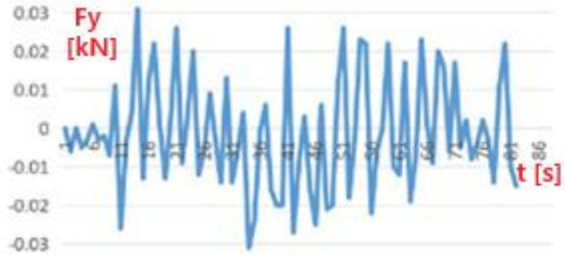

Figure 9. F_y component of the cutting force, with v_f down direction (D9; z2; a_e9; a_p 0,5)

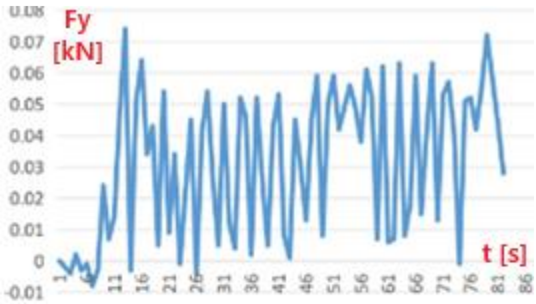

Figure 10. F_y component of the cutting force, with v_f up direction (D9; z2; a_e9; a_p0,5)

Figure 10 displays the case when the feed direction points in +Y direction, i.e., when F_f pushes the workpiece on the measuring elements. In Figure 9 :

$$F_{cm} - F_f \approx 20\ N \tag{1}$$

and in Figure 10 :

$$F_{cm} + F_f \approx 60\ N \tag{2}$$

can be seen. If equations (1) and (2) are added, the following result is obtained:

$$2F_{cm} \approx 80\ N\ \rightarrow\ F_{cm} \approx 40N\ and\ F_f \approx 20N$$

The above mentioned trend showing increase cannot be confirmed in Figure 9, whereas it is present in Figure 10.

Figure 11 and Figure 12 contain the value of F_z. The part of the curves marked in purple represents the axial feed in motion (i.e., the taking of the depth of the cut). In Figure 11 the case when the depth of cut was a_p=0,5mm can be seen. It can be observed that the F_z is about +20 N.

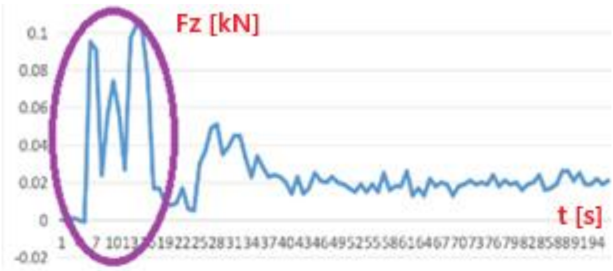

Figure 11. F_z component of the cutting force (D5; n400; z2; a_e5; a_p 0,5)

In Figure 12 the case when the depth of cut was a_p=3,5 mm is indicated. It can be observed that the F_z is about -300 N. These cases indicate when the depth of cut is small, the endmill pushes the workpiece down, yet at a larger depth of cut the tool pulls the workpiece up. This is due to the helix angle of the cutting edges.

Figure 12 F_z component of the cutting force (D5; n400; z2; a_e5; a_p 3,5)

In Figure 13 milling with a 9 mm two-flute endmill, with 0,5 mm depth of cut is shown. The horizontal axis represents time in 20 ms steps, while the vertical axis shows F_x in kN.

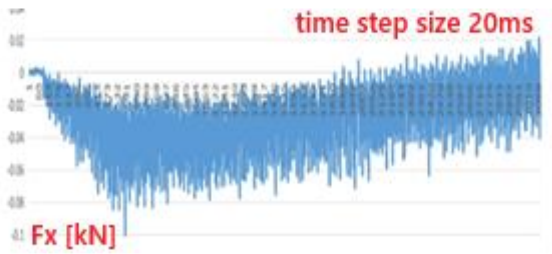

Figure 13. F_x component of the cutting force, with v_f up direction (D=10; **z=2**; a_p=0,5; a_e=10)

In Figure 14 the time step is also 20 ms, and the vertical axis also presents F_x, but this time a 10 mm six-flute endmill was used. The depth of cut was 0,5 mm. In both cases the peek value of the force is about -80 N, but for six-flute endmill the amplitude is about 20 N, while for the two-flute about 60 N. This is logical, as in the fully immersed state (i.e., when a_e=D), one tooth is engaged with the workpiece in the case of a two-flute mill, whereas three teeth are engaged in the case of a six-flute mill. As for the fluctuation, in this way, is three times smaller when one tooth leaves, and another enters the cut.

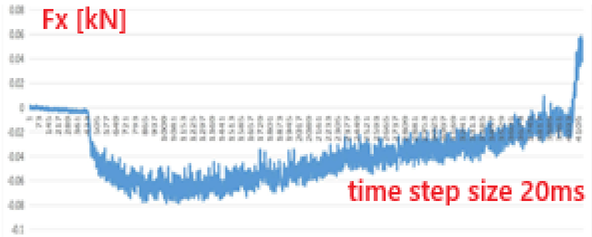

Figure 14 F_x component of the cutting force, with v_f up direction (D9; **z=6**; a_p=0,5; a_e=9;)

The increasing trend mentioned above for both Figure 13 and Figure 14 can be clearly recognised. In Figure 11, it can be observed at the end of the diagram that the force drop during the tool's exit from the workpiece is also approximately 80 N, which is comparable to the force increase during the tool's entry into the workpiece at the beginning of the diagram.

Table 1 Force comparison

	D5 z2 a_p 0,5 f_z 0,017	**D9 z2 a_p 0,5 f_z 0,028**	**D10 z2 a_p 0,5 f_z 0,028**	**D9 z6 a_p 0,5 f_z 0,009**	**D22 z5 a_p 0,5 f_z 0,023**
calculated force values	F_{cm} 32N F_{czm} 32N	F_{cm} 49N F_{czm} 49N	F_{cm} 49N F_{czm} 49N	F_{cm} 56N F_{czm} 19N	F_{cm} 125N F_{czm} 42N
estimated (from diagrams) values	F_j 50N F_a 35N	F_j 60N F_a 40N	F_j 80N F_a 60N	F_j 80N F_a 20N	F_j 150N F_a 70N

Table 1 contains the tool diameter (D) in mm, the number of tooths (z), the depth of cut (a_p) in mm, and the feed per tooth (f_z) in mm/tooth. The presented force values refer to full immerse cutting, i.e., when the width of the cut (a_e) is equal to the tool diameter.

Authors used Kinzle's formula to calculate the average cutting force on one tooth (F_{czm}) and the average cutting force (F_{cm}). The diagrams serve to estimate the force jump (F_j) at entering and leaving, and the force amplitude (F_a) of the F_x force components. It can be noticed that the estimated force amplitude (F_a) is relatively close to the calculated mean force on one tooth (F_{czm}). The estimated force jumps (F_j) are somewhat larger than the calculated mean cutting forces (F_{cm}) on the endmills. Therefore, it can be assumed that they represent the maximal cutting forces (F_{c_max}) on the tool.

3. CONCLUSION

The main goal of these experiments was to test if the milling forces can be measure, and if so, how they can be measured with two force transducers. The results confirm that they can be measured. The main drawback of this method is the time-factor, namely, this way the measurement takes three times longer than with Kistler's devices. However, in cases when it is sufficient to measure one force component, or to present the force changes during milling in a teaching environment, this can be an affordable solution.

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