Efficient cutting force characteristic measurement based on a single turn in milling operation

D. Bachrathy[1], G. Stepan[2],
Department of Applied Mechanics, Budapest University of Technology and Economics,
Budapest, H-1111, Hungary,
bachrathy@mm.bme.hu

Summary
The knowledge about cutting force characteristics is a key factor in process optimization of cutting processes. It is needed for determining the loads on the cutting edges and the power consumption of the spindle. The derivative of the cutting force function with respect to the chip thickness strongly influences the appearance of the so-called chatter vibration. The cutting force function is usually based on a series of cutting tests for different feed rates. The assumed function is usually fit only onto the averages of the measured cutting force signals, without 'seeing' the real characteristics. In the presented, method the radial and the tangential cutting force is determined for each angular position of the cutting edge and plot as a function of the theoretical chip thickness. This way, the cutting force function can be identified in a wide range of the chip thickness with a single measurement. This method can be applied in higher spindle speed ranges due to the advanced compensation method for a 6-channel Kistler dynamometer.

Keywords
high-speed milling, cutting force, dynamometer, compensation

1. Dynamic Force Compensation

The main idea of our dynamic compensation is to consider the dynamometer as an oscillator for which the frequency response function can be defined by experimental modal analysis. The important difference is, that we define the transfer function $\boldsymbol{H}_F$ between the measured force $\boldsymbol{F}_m$ and the excitation force $\boldsymbol{F}_e$. In a typical Kistler dynamometer plate, 8-channel measurement provides the necessary data to determine the measured force $\boldsymbol{F}_m$ and moment $\boldsymbol{M}_m$ components in the Kistler device's *x-y-z* coordinate system. Determining the trasferfunction for both the force and the moment, lead to a better compenstion. The transfer function $\boldsymbol{H}_{FM}$ for the forces and the moments is defined as:

$$\begin{bmatrix} \boldsymbol{F}_e \\ \boldsymbol{M}_e \end{bmatrix} = \boldsymbol{H}_{FM} \begin{bmatrix} \boldsymbol{F}_m \\ \boldsymbol{M}_m \end{bmatrix}. \tag{1}$$

Note, that all elements are in the frequency domain. During modal analysis, a single channel is used for the detection of the force signal of the modal hammer. In one test point, the excitation force vector and the moment vector can be defined by means of the magnitude of the hammer force F_h, the normal of the excited surface $\boldsymbol{n}$ and the position vector of the excitation $\boldsymbol{r}_{OA}$:

$$\boldsymbol{F}_e = \boldsymbol{n} F_h, \quad \boldsymbol{M}_e = \boldsymbol{r}_{OA} \times \boldsymbol{n} F_h. \tag{2}$$

For accurate FRF measurement, multiple measurement points are arranged as follows:

$$\begin{bmatrix} \boldsymbol{F}_{e,1} \cdots \boldsymbol{F}_{e,k} \\ \boldsymbol{M}_{e,1} \ldots \boldsymbol{M}_{e,k} \end{bmatrix} = \boldsymbol{H}_{FM} \begin{bmatrix} \boldsymbol{F}_{m,1} \cdots \boldsymbol{F}_{m,k} \\ \boldsymbol{M}_{m,1} \ldots \boldsymbol{M}_{m,k} \end{bmatrix}, \tag{3}$$

from which the transfer function $\boldsymbol{H}_{FM}$ is determined by a pseudo invers. Theoretically, this transfer function can now be used to dynamically compensate any measured dynamometer force signal to get the exact excitation force. However, the compensation is only valid in a finite frequency rage, defined by the highest applicable frequency of the modal hammer excitation. Nevertheless, this frequency can be ~8 kHz if an appropriately small sized hammer is used.

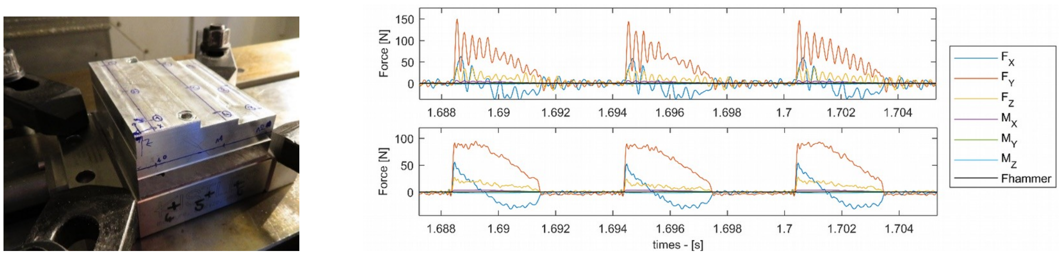

Figure 1 left: Test setup with 9129AA Kistler dynamometer and 14 marked points on the workpiece for modal analysis. Right: Directly measured (top) and the compensated (bottom) x-y force components for n=5000 rpm.

2. Direct Force Characteristics Measurement

The above introduced compensation method enables to directly measure the force function. According to our proposed method the angular position of the tool has to be measured, which can be used to transform the measured *x-y* force components to the edge's local radial and tangential (*r-t*) coordinate system:

$$\begin{bmatrix} F_r \\ F_t \end{bmatrix} = \begin{bmatrix} \cos(\phi(t)) & \sin(\phi(t)) \\ -\sin(\phi(t)) & \cos(\phi(t)) \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix}. \tag{4}$$

Finally, the radial and tangential force components can be plot against the corresponding theoretical chip thickness values $h(t) = f_z \sin(\phi(t))$, where f_z is the feed per tooth. Measurement results for a simple down milling processes with a helical tool for spindle speeds n=5000 rpm are presented for differenc feed per tooth values.

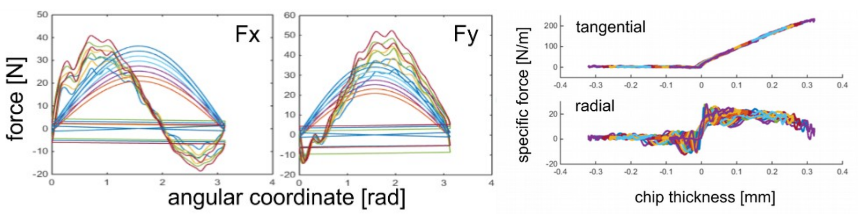

Figure 2 Compensated cutting force in the x-y coordinate system with the nominal chip thickness (left) and the transformed radial and tangential component plotted againts the chip thickness (right). Colors represent different feed-per-tooth values in the range =[0.1,0.325] mm.

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