# Assessment of machine tool dynamic properties

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***Hodnotenie dynamických vlastností obrábacích strojov***

*The paper gives a review of research works focused on cutting process during machine tools working conditions. The main result deals with assessing dynamic compliance (stiffness). The simplified experimental modal analysis of machine tools was carried out. This analysis results in determination the direction of the maximal compliance of a machine structure. The measurements are arranged into a diagram giving overview about the most important properties of the machine tool for operational conditions during machining process. The new measurement method gives the possibility to prevent inaccuracies in production after regular machine inspection.*

***Key words:*** *Machine tools, structure resonance, vibration, machining, modal analysis, transfer functions.*

## Introduction

Experimental modal analysis is quickly developed area of science in last years and becomes as efficient as the finite element method. Experimental approach for solving technical problems is a means to estimate or evaluate modal properties of a mechanical structure. The paper is focused at dynamic properties of machine centres, namely at the resonance frequencies and vibration shapes of a simplified tool-work piece system. All this properties are identified by measurements. The machine tool vibration was excited by impulse force and a response of excited vibration was recorded. The measurement points for vibration were selected at the spindle head and the table.

The Department of Control Systems & Instrumentation focuses partly research activity to machine mechanical structures as a problem of signal processing. We are forced to give answers how to avoid a machine state, given by its rotational speed, when machining process is spoiled by vibration.

The principle governing the measurements, namely selecting of the measurement points for attaching accelerometers, is shown in Figure 1.

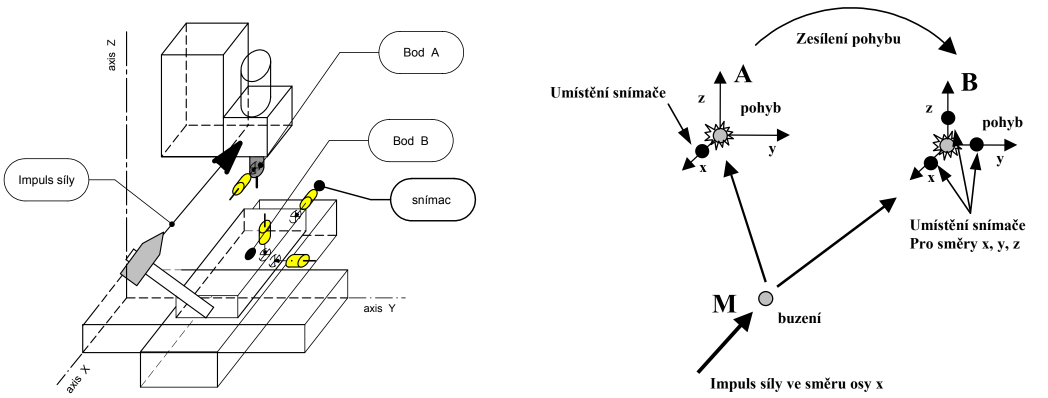


*Fig.1. Principle of selecting measurement points.*

## Simplified modal analysis

A tool for inspection of dynamic properties is a measurement of vibration that is excited by cutting forces acting between the tool and work piece at operating conditions. It is easy to record a response in vibration during machining and almost impossible to measure the mentioned dynamic force. Therefore, the force measurement was replaced by impulse response measurement to the impact force excited by a hammer that tip was fitted by a force sensor. As the goal of these measurements is to evaluate frequency transfer function between the tool (point A) and working piece (point B), the responses in both the point in three directions to the impact force at a reference point were recorded and analysed. The reference point was selected at the machine tool spindle. The frequency response is evaluated by using the following formulas

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$$A_x = \sqrt{\frac{(\mathrm{Re}\{H_{Bx}\})^2 + (\mathrm{Im}\{H_{Bx}\})^2}{(\mathrm{Re}\{H_{Ax}\})^2 + (\mathrm{Im}\{H_{Ax}\})^2}} \qquad \varphi_x = arctg(\frac{\mathrm{Im}\{H_{Bx}\}}{\mathrm{Re}\{H_{Bx}\}}) - arctg(\frac{\mathrm{Im}\{H_{Ax}\}}{\mathrm{Re}\{H_{Ax}\}})$$

$$A_y = \sqrt{\frac{(\mathrm{Re}\{H_{By}\})^2 + (\mathrm{Im}\{H_{By}\})^2}{(\mathrm{Re}\{H_{Ax}\})^2 + (\mathrm{Im}\{H_{Ax}\})^2}} \qquad \varphi_y = arctg(\frac{\mathrm{Im}\{H_{By}\}}{\mathrm{Re}\{H_{By}\}}) - arctg(\frac{\mathrm{Im}\{H_{Ax}\}}{\mathrm{Re}\{H_{Ax}\}})$$

$$A_z = \sqrt{\frac{(\mathrm{Re}\{H_{Bz}\})^2 + (\mathrm{Im}\{H_{Bz}\})^2}{(\mathrm{Re}\{H_{Ax}\})^2 + (\mathrm{Im}\{H_{Ax}\})^2}} \qquad \varphi_z = arctg(\frac{\mathrm{Im}\{H_{Bz}\}}{\mathrm{Re}\{H_{Bz}\}}) - arctg(\frac{\mathrm{Im}\{H_{Ax}\}}{\mathrm{Re}\{H_{Ax}\}})$$

The frequency response in displacement of the point B to the displacement excitation in the point A is denoted by $A_x$ for the direction of *x*, similarly $A_y$ and $A_z$ are denoted the frequency response in the directions of *y* and *z*, respectively. The frequency responses in the A and B points to the impact force in the reference point are designated by $H_{Ax}$ and $H_{Bx}$, respectively. The phase delay of a harmonic vibration in the B point with respects to the A point is designated by $\varphi_x$, $\varphi_y$ and $\varphi_z$. As the frequency response is a complex number, the following formulae have to be employed.

## Operational deflection shapes of the tool – working piece system

Turn our attention to the response in the point B to the sinusoidal waveform excitation acting in the point A of the direction of *x*. The response in the point B can be recorded for all three directions, namely *x*, *y* and *z*. If the exciting signal is a time function $x = e^{j\alpha}$, then the responses in the mentioned three directions can be evaluated in the following forms

$$x = |A_x|\, e^{j(\varphi_x + \alpha)} \qquad y = |A_y|\, e^{j(\varphi_y + \alpha)} \qquad z = |A_z|\, e^{j(\varphi_z + \alpha)}$$

where $\alpha$ is an angle ranging from 0 to 360 degrees. The coordinates x, y and z of a point in the space determine a trajectory in the form of an ellipse. The direction of the ellipse semimajor axis determines the maximum of the displacement amplification in the point B excited by unit displacement of the A point.

The magnitude of the vector, which is identical with the ellipse semimajor axis, and the angles determining the direction are evaluated by the formulas

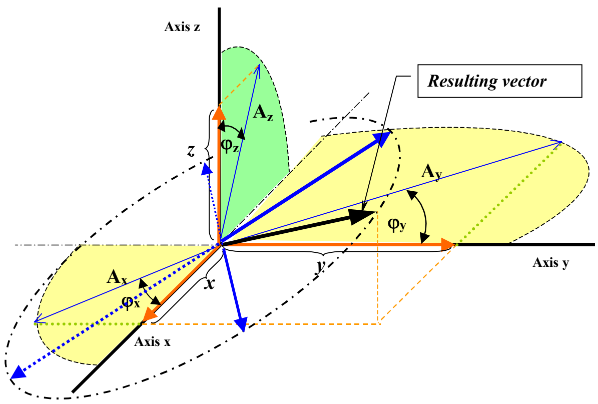


*Fig.2. Response trajectory for sinusoidal exciting.*

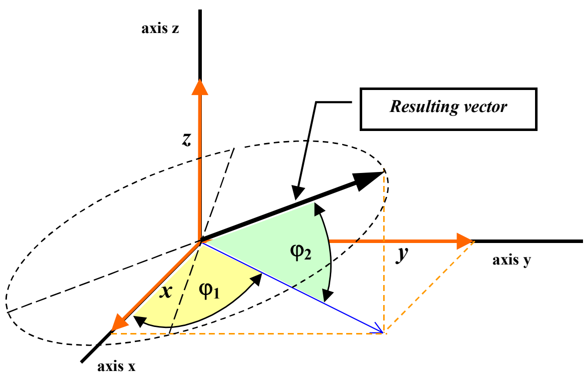


*Fig.3. Angels $\varphi_1$ and $\varphi_2$.*

$$A = \sqrt{x^2 + y^2 + z^2} \qquad \varphi_1 = arctg\left(\frac{y}{x}\right) \qquad \varphi_2 = arctg\left(\frac{z}{\sqrt{x^2 + y^2}}\right)$$

## Circular diagram for determining the direction of the maximum machine compliance

A ratio between the semiminor and semimajor ellipse axis is a criterion for machine structure directional compliance. The larger ratio, the larger compliance in the given direction can be measured. To assess the dependence of the directional compliance a circular diagram was proposed. The direction of the semimajor ellipse axis is determined by two angles, $\varphi_1$ and $\varphi_2$. The angle $\varphi_1$ is situated in the plane of *x*, *y*, while the angle $\varphi_2$ represent an angle between the plane of *x*, *y* and the direction of the semimajor ellipse angle. There are two vectors associated with a resonance frequency. The length of the thin one ended by a circle (—●)

determines amplification of vibration while the length of the thick one ended by an empty circle (▬O) is proportional to the value of the angle between the *x*, *y* plane and the semimajor axis.

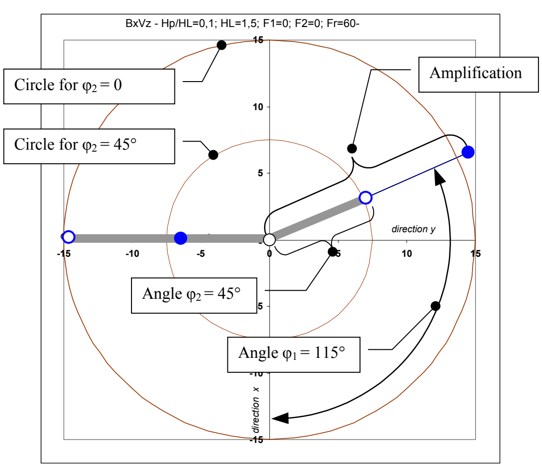


*Fig.4. Circular diagram.*

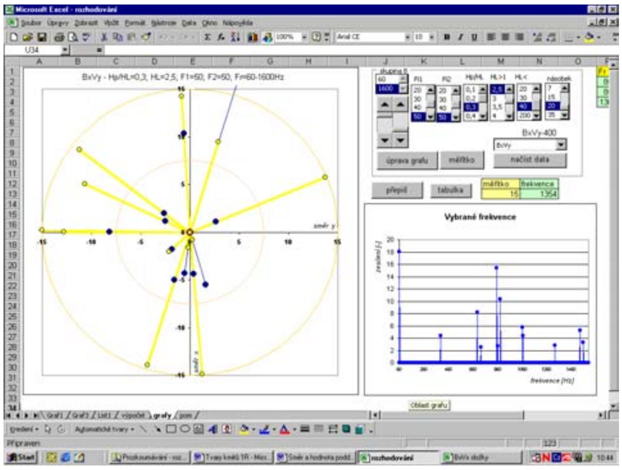

*Fig.5. Excel program.*

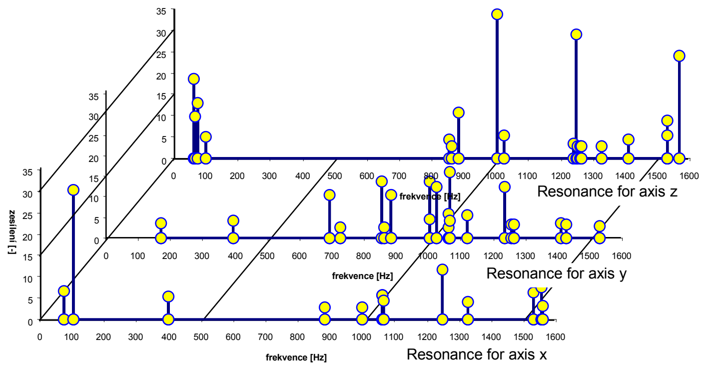


*Fig.6. Resonance frequencies.*

An Excel program that appearance of the main sheet is shown in figure 4 performs all the computations based on the measurement.

All the measurements were performed by PULSE, the BK signal analyser, on a vertical machining centre.

An Excel program that appearance of the main sheet is shown in figure 5 performs all the computations based on the measurement.

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If the frequency responses are arranged into the 3D plots (see Figure 6), the overview about the dependence of the structure compliance on frequency is obtained. This result of analysis can be interesting for solving a problem dealing with the optimalisation of the cutting process.

## Conclusion

The paper is focused on analysis of the machine tool mechanical structure that results in a circle diagram determining the direction in which is machine structure the most compliant. The importance of this research work results from today's requirement for quality machined surface and long lifetime of tools. The new measurement method gives the possibility to prevent inaccuracies in production after regular machine inspection

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