Dynamic forces in unstable cut in turning

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Abstrakt

Teorie samobuzeného kmitání (chatteru) při obrábění, která byla formulována v 50. letech, předpokládá osamělou řeznou sílu. Předpoklad jedné řezné síly při nestabilním řezání je používán dodnes. V tomto článku bude čtenáři předložena hypotéza uvažující více řezných sil působících v nestabilním řezu při soustružení. Je zde představen nový model síly. Výpočet meze stability, stejně tak i přesnost predikce stabilních řezných podmínek, je ukázán na tomto modelu. Platnost hypotézy je ještě potřeba dokázat. Přípravy ověřovacích experimentů probíhají již přibližně rok a samotné experimenty začnou v tomto roce (2014). Hypotéza je založena na rozboru výsledků dříve provedených měření dynamických sil jak českých, tak zahraničních autorů.

Klíčová slova

Chatter, komplexní dynamická řezná síla

1. Significance of dynamic forces in machining

In general, dynamic forces are understood as forces variable in time. They include for example forces exciting natural vibrations or forced vibrations. The machining theory primarily focuses just on static forces acting on the cutting process. In this research paper, static forces are understood as forces existing in **stable cutting**, which is always the objective in practice. However, there are cases of **unstable cutting**, where the cutting process itself modulates the originally static components of the cutting force (or cutting forces) in feedback loop to forces periodically variable in time, and therefore dynamic. Chatter arises. Only the dynamic component of cutting force affects unstable cutting. Unstable cutting occurs in all metal-cutting technologies, from lathe-turning, milling to grinding. It occurs both in roughing and in finishing. Instability of cutting processes is manifested in particular by waviness of the machined surface due to vibrations between the cutting tool and the workpiece. This produces unpleasant noise. Amplitudes of vibrations often reach high levels. Cutting edges are thus at a risk of damage. As it is not a desirable phenomenon in practice, it is necessary to know the means for suppressing it. The theory of machining stability (or chatter) is very well elaborated, including practical tools that can be used to eliminate the existing chatter. For the beginnings refer to [1] and [2]. For later studies see for example [3], [10], [11] and many others. Good knowledge of the stability limit enables technologists to optimize (increase) cutting performance. The stability diagram depicted in the upper part of Fig. 1 will be used for illustration. Stable depth of cut is shown on the vertical axis. Revolutions of the cutting tool (milling machines) or of the spindle with a workpiece (lathes) are shown on the horizontal axis. The grey field represents unstable cutting conditions under which chatter arises. The amplitude of the chatter increases during the cutting process. The white field represents stable cutting conditions, depth of cut and workpiece revolutions or tool revolutions, or more specifically cutting speed. After it arises, chatter dampens in this field. The boundary between these two areas is called chatter stability limit, which is defined by constant chatter amplitude.

It is evident from the graph that stable depth of cut changes considerably with revolutions. In places where gaps between lobes are large, i.e. in the area of higher revolutions, it is possible to choose higher stable depth of cut, without chatter arising. See e.g. field A. The arrow in field A shows the so-called stable revolutions. These can be used for milling. The left part of the graph applies to turning. The gaps between lobes are already narrow. Consequently, instead of identifying stable revolutions, variation of cutting speed (revolutions) is used as one way how to suppress chatter. The area of the lowest revolutions in the stability diagram is of special significance for difficult-to-cut materials. As can be seen in the graph, lobes recede upwards and the stable area widens. It is a consequence of the so-called process damping, which, under certain conditions, acts on the cutting process. Increasing the stability limit at low cutting speeds allows us to use high, stable depths of cut, and leads to an increase in cutting performance of difficult-to-cut materials. This effect is otherwise difficult to achieve. An additional benefit is a significant extension of cutting tool lifetime due to a decrease in cutting speed as well as the possibility of using HSS PM tools with an advantage. This applies to both turning and milling. A more detailed explanation is beyond the scope of this paper. Therefore, we refer to the literature in [5], [6], [7], [8] and [9]. The curve of chatter frequency can be seen in the bottom part of the graph. The frequency also changes with revolutions. Based on the step changes, stable revolutions can be identified. As can be seen, stable revolutions make up a certain series. A technologist has the possibility of choosing optimal stable cutting speeds (revolutions) for various materials and tools. The diagram for specific cases can be obtained by a calculation based on measured transfer function in the place of the tool (for milling) or of the workpiece (for turning). The procedure for calculating the diagram is explained for example in paper [22].

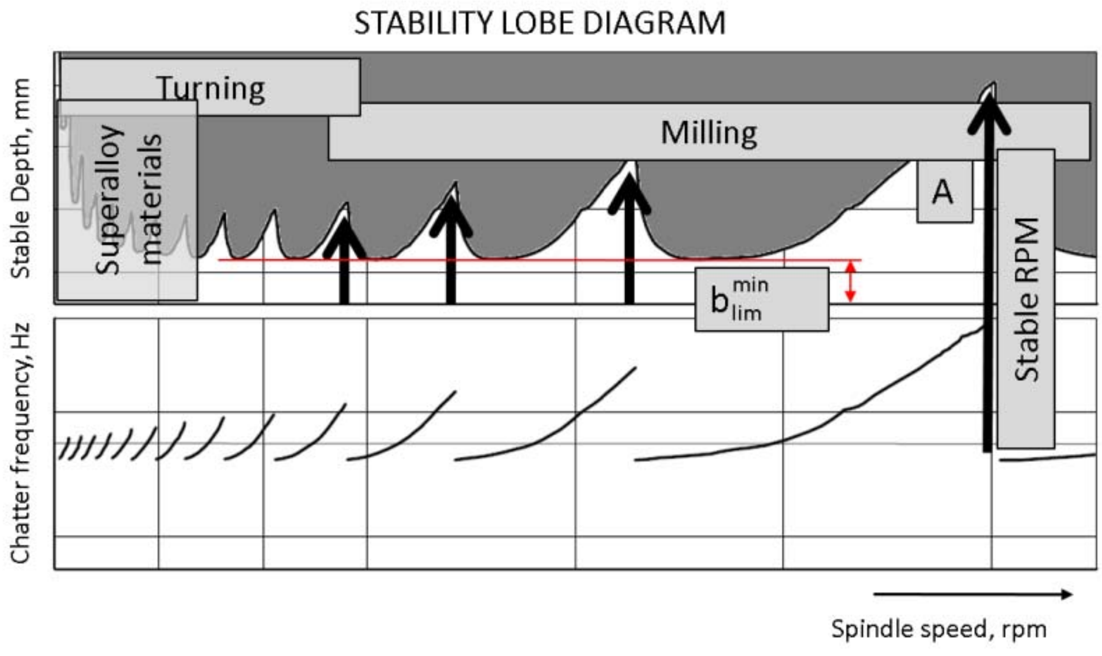

Fig. 1. *Stability lobe diagram. Prediction of stable cutting conditions.*

The values of "stable revolutions" markedly depend on eigenfrequencies of the decisive vibrating system, on the machine-tool-workpiece system in general, and also on some technological parameters, which have not been considered in the calculation so far.

The depicted stability diagram can be a good lead for a technologist in predicting stable cutting conditions as well as in optimizing cutting performance under given conditions.

Sufficient accuracy of the diagram is, however, an important prerequisite. The stability limit in turning operations has, under certain cutting conditions, a specific characteristic in the low cutting speed region and it differs from stability diagrams obtained by calculation. The following chapter will examine this topic in more detail.

2. A linear model of dynamic cutting force

The cutting force model used by Poláček [1] for calculating stability was very simplified in order to obtain a simple, comprehensible and practically useful formula for quantifying the stability limit. It has the following form:

$$F(t) = K \cdot b \cdot \left[h_m + (Y_o - Y_i) \cdot e^{j\omega t}\right] = F_{stat} + F_{dyn} \tag{1}$$

Here b is width of cut or depth of cut, Y_o denotes amplitude of the waves left by the vibrating tool on the machined surface during the previous revolution, Y_i is amplitude of vibration between the workpiece and the tool. h_m denotes difference in centre lines between surface waves $Y_o(t)$ and $Y_i(t)$. The symbol K is a specific cutting force, ω denotes angular frequency of vibration, F_{stat} is a static component of total Force F(t) and F_{dyn} is a dynamic component of the total force.

The total force F(t) is a component of the cutting force acting in the direction of the normal Y to the machined surface. The tangential component of the force has not been considered in the force model. A linear model was used for the complex dynamic force (phasor):

$$F_{dyn} = K \cdot b \cdot (Y_o - Y_i) = F_{do} + F_{di} \tag{2}$$

while at the stability limit, it applies that:

$$|Y_o| = |Y_i|$$
$$Y_o = Y_i \cdot e^{j\varepsilon} \tag{3}$$

The symbol ε in equation (3) expresses the phase between waves on the workpiece and tool vibrations. Using these equations, a formula can be deduced for quantifying the lowest stability limit for turning operations in the following form:

$$b_{\lim}^{\min} = \frac{1}{2KG_o^{\max}} \tag{4}$$

where:

G_o^{max} ... is the extreme of the negative part of the real component of transfer function, calculated using direction cosines in the direction of the normal [22]. The transfer function expresses dynamic compliance of the vibrating system and can be obtained by measurement. The G_o^{max} value depends on the static stiffness of the machine's vibrating system and on the damping of this system, i.e. on the structural parameters of the whole machine tool structure. If this value is obtained by measurement, its uncertainty is very small. The $b_{\lim}^{\min}$ value according to (4) is the minimum value of the stability limit in the stability diagram. See Fig. 1. The uncertainty of the specific cutting force coefficients K value is much larger. Therefore, it is also recommended that the $b_{\lim}^{\min}$ should be validated when running dynamic machine tests. By doing this, we can determine the real K value under given cutting dynamic conditions that may be influenced e.g. by the geometry of the tool.

Equation (2) can be depicted under conditions (3) in complex plane by phasors. See Fig. 2. The force F_{di} has the phase 180° relative to Y_i. Considering the condition of stability (3), the force F_{do} has the phase ε relative to Y_i. As ε can change within the interval (0 – 360°), the phasor F_{do} rotates around the centre S. Its end point moves along the circle. The centre of the circle lies at the real axis.

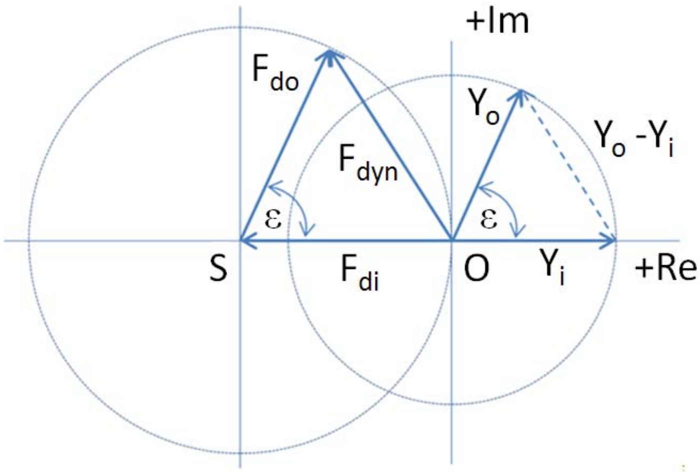

Fig. 2. *Forces F_{dyn}, F_{do}, F_{di} from the Eq. (2) depicted in complex plane for t=0.*

Equation (4) has been used for a number of years for a dynamic test of machine tool structure, the aim of which is to identify weak points of the structure. When using the equation for lobe calculation (milling in Fig. 1) and also when determining the stability limit in turning difficult-to-cut materials in the low cutting speed region, the predicted (calculated) stability limit deviates from the real stability limit. In the next chapter, we will focus only on turning at low cutting speeds, where the deviations are quite considerable.

3. Complex dynamic forces

In the 1960s, with the support of CIRP, Jiří Tlustý organized first research into dynamic forces acting on the cutting process during turning. The idea for the project was provided by the researchers of the Institute of Machine Tools and Machining in Prague, especially by Miloš Poláček. Several university laboratories in Europe and later in the USA collaborated on the project. See [12] and [13]. The proposed model of dynamic forces assumed only one dynamic cutting force acting on the cutting process in turning. Contrary to the above-mentioned Poláček's model of force, it was assumed that the tangential component of cutting force also contributes to the dynamics of the process. The total cutting force was therefore broken down into two mutually perpendicular components F_N (component perpendicular to the machined surface) and F_T (component tangential to the machined surface). Dynamic forces were expressed by the following equations:

$$F_N = b\cdot\left(K_{do}\cdot Y_o - K_{di}\cdot Y_i\right) = F_{do} - F_{di}$$
$$F_T = b\cdot\left(K_{co}\cdot Y_o - K_{ci}\cdot Y_i\right) = F_{co} - F_{ci} \tag{5}$$

The coefficients K_{di}, K_{do}, K_{ci} and K_{co} are dynamic coefficients of the cutting force components F_N and F_T, corresponding to the dynamic stiffness of the cutting process. It was assumed that the coefficients and thus also forces were complex. The indices “d” and “c” denote “direct” and “cross” directions of the action of dynamic force components F_{di} and F_{do} or F_{ci} and F_{co}. The direction “direct” corresponds to the direction of the normal to the machined surface. The direction “cross” corresponds to the transversal or tangential direction to the normal. The indices “i” and “o” denote “inner” and “outer” modulation of the

components F_{di} and F_{do} or F_{ci} and F_{co} by tool vibrations or by waves on the workpiece surface. Y_o and Y_i have been defined earlier.
The forces in the first equation (5) for F_N are shown in Fig. 3. The force F_{di} has the phase ψ_{di} relative to Y_i and the centre of the circle does not lie on a real axis. Similarly to equation (2), it applies that by changing the phase ε, the end point of the force F_{do} moves along the circle, F_{di} continues permanently in the direction of the circle centre and the end point F_N also moves along the circle. The same properties apply to forces in the second equation (5), which can be depicted analogously.

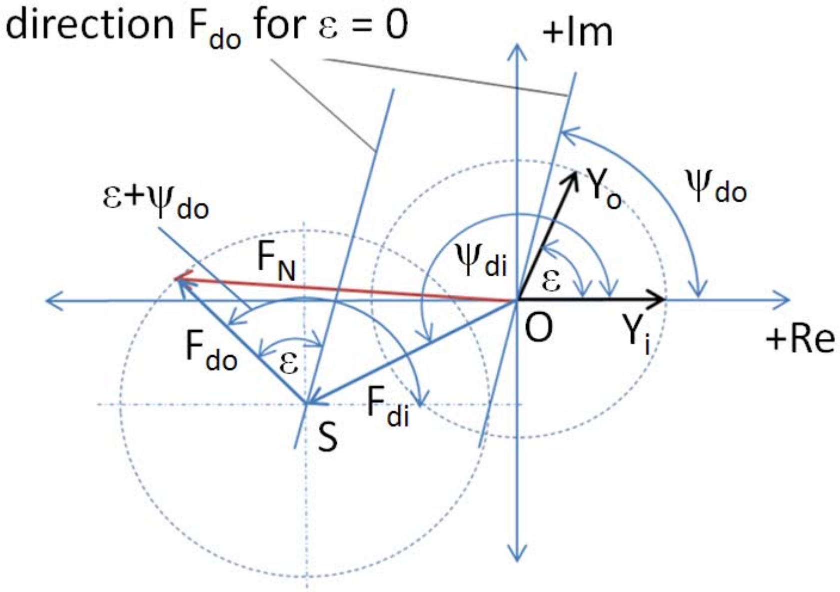

Fig. 3. Equation (5) for the thrust force F_N depicted in the complex plane.

It follows from the results of the research into dynamic forces that the coefficients as well as dynamic forces (components) are complex values and real and imaginary coefficient components depend on cutting speed. Using the results to calculate the phase dependences on the cutting speed of the components F_{di} and F_{do} or F_{ci} and F_{co}, we discover that the phases of these forces, relative to the tool vibration Y_i, are different. See Fig. 4. Similar data was published by Rao [15] as well as by Goel [14]. It means that the resultant forces F_N and F_T have a mutual phase too.

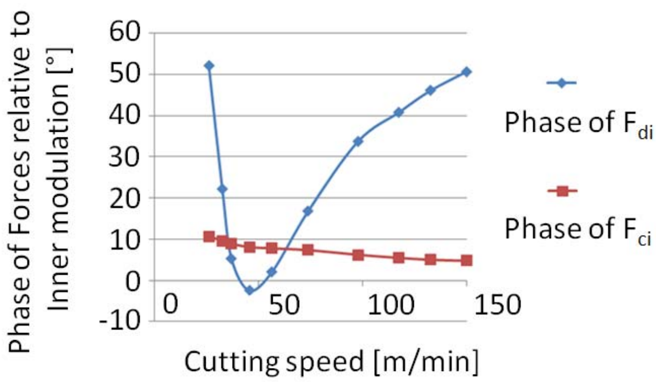

Fig. 4. A change in phases of the direct and tangential force compoments F_{di} and F_{ci}. Compiled after [12].

If we use this data and calculate stability limit relative to cutting speed for the chosen values of the stiffness "k" and damping "ξ" of a vibrating system with one degree of freedom (these values will not be influenced by the form of the stability limit curve), we discover that there is a considerable drop in the stability limit curve. See Fig. 5. This characteristic of the stability limit differs considerably from the results commonly modelled so far, depicted already in Fig. 1. It is necessary to highlight that the model (5) is already capable of expressing this curve in some way, but it still only works with one cutting force in the cutting process or with its two components. This is in contrast to the measurement result, which proved that forces are complex with various phases relative to the vibration of the tool. The dependence of the stability limit according to Fig.5 was verified independently by machining tests, which can be found in a number of studies, e.g. in [14] to [21]. Some chosen examples are shown in Fig. 6.

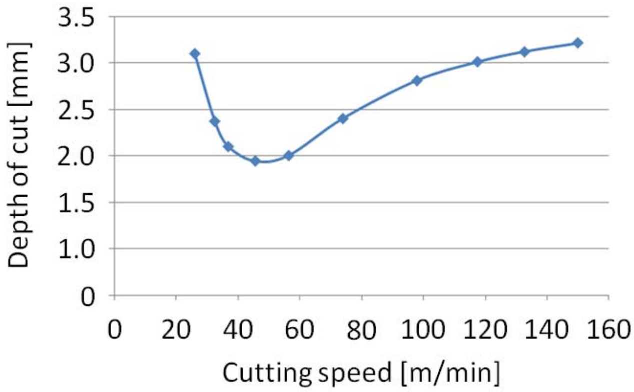

Fig. 5. *Limit of stability for turning, calculated using the data published in [12].*

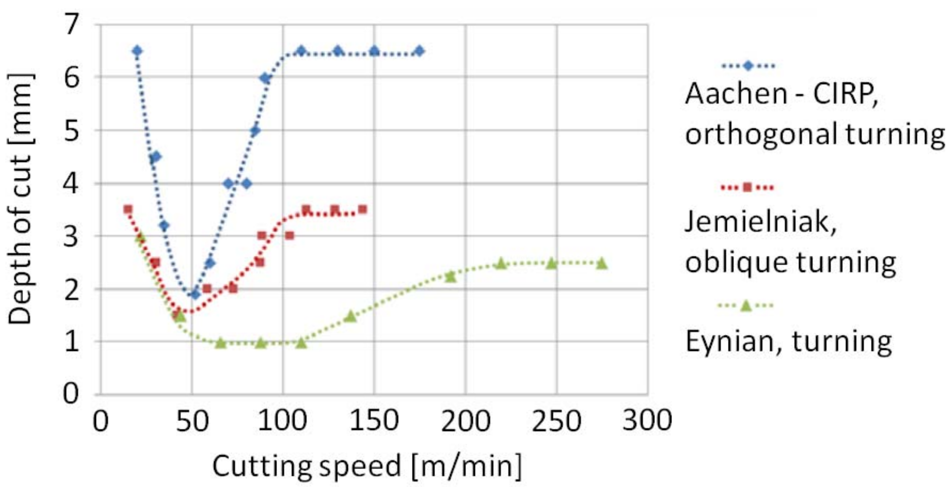

Fig. 6. *Stability curves measured by machining tests. Data compiled after [10], [11], [13] and [17].*

4. New model of dynamic forces

The fact that the dynamic forces F_N, F_T are mutually phase shifted has two consequences. Firstly, the forces are not components of one dynamic force, but must be understood as independently acting forces. Secondly, some other dynamic forces must act on the cutting process. It is especially the damping process force as well as the damping force caused by tool wear. We consider these forces as complex too, i.e. they have a certain phase against F_N or F_T dependent on the cutting speed, which produces a phase shift of F_N or F_T against Y_i as well as the discussed decline in stability. Based on the previous consideration, we assume a new model in the following form:

$$F_N = K_d \cdot b \cdot (Y_o - Y_i) + F_{dDamping} + F_{dWear}$$
$$F_T = K_c \cdot b \cdot (Y_o - Y_i) + F_{cDamping} + F_{cWear} \tag{6}$$

The model (6) now contains further force components $F_{dDamping}$, $F_{cDamping}$ and F_{dWear}, F_{cWear}. While $F_{dDamping}$ and $F_{cDamping}$ are a normal and a tangential component of the damping force of the cutting process (process damping), F_{dWear} and F_{cWear} are damping forces caused by tool wear. The other indices have been defined earlier. The forces F_N and F_T are mutually perpendicular and have generally different magnitudes and phases. We assume that if the forces $F_{Damping}$ and F_{Wear} are correctly identified in both directions, the new model (6) will be a better basis for calculating stability limit for the low cutting speed region than the existing models. Stability limit calculated using the model (6) will be defined both by conditions (3) and other technological parameters that influence the boundary between stability and instability. Such a parameter is for example cutting speed. See Fig. 1. We assume the coefficients K_d and K_c in complex form, so for forces in equations (6), using (3), the following can be written:

$$F_N = b \cdot |K_{do}| \cdot Y_i \cdot e^{j(\psi_{do}+\varepsilon)} - b \cdot |K_{di}| \cdot Y_i \cdot e^{j\psi_{di}} + F_{dD} + F_{dW} =$$
$$= |F_{do}| \cdot e^{j(\psi_{do}+\varepsilon)} - |F_{di}| \cdot e^{j\psi_{di}} + |F_{dD}| \cdot e^{j\varphi_D} + |F_{dW}| \cdot e^{j\varphi_W} \tag{7}$$

$$F_T = b \cdot |K_{co}| \cdot Y_i \cdot e^{j(\psi_{co}+\varepsilon)} - b \cdot |K_{ci}| \cdot Y_i \cdot e^{j\psi_{ci}} + F_{cD} + F_{cW} =$$
$$= |F_{co}| \cdot e^{j(\psi_{co}+\varepsilon)} - |F_{ci}| \cdot e^{j\psi_{ci}} + |F_{cD}| \cdot e^{j\varphi_D} + |F_{cW}| \cdot e^{j\varphi_W} \tag{8}$$

where:

$|K_{do}|, |K_{di}|, |K_{co}|, |K_{ci}|$ ...are absolute values of complex coefficients. We used the shortened designation D or W instead of the indices Damping or Wear in the equations.

5. Experiment

The aim of the experiment is to measure the vectors of the dynamic components F_{di}, F_{do}, F_{ci}, F_{co}, F_{dD}, F_{dW}, F_{cD} and F_{cW} and their dependences on cutting speed. These components will be determined from circles that the end points of the vectors F_N and F_T circumscribe during a step change of the phase as shown in Fig. 3 and Fig. 4. A change of the phase is not possible in naturally induced unstable machining. In order to create waves on the machined surface, simulated tool vibration in a direction perpendicular to the machined surface will be used. In order to determine the forces F_D and F_W, process damping and damping caused by wear, it will be necessary to gradually set up conditions under which these forces will be eliminated, or suppressed to the minimum. Equations (6), or also (7) and (8), will then express different situations in which it will be possible to identify the forces F_D and F_W. The experimental set-up of the equipment is shown in Fig. 7.

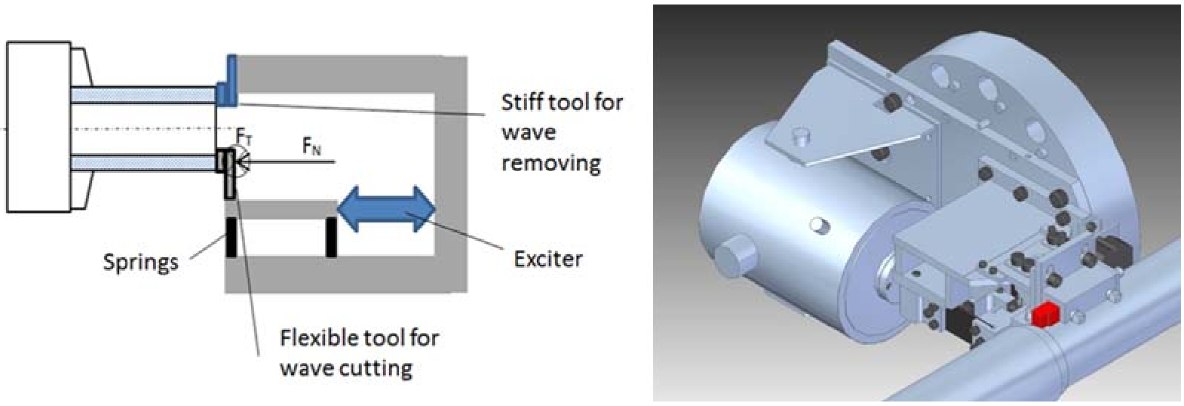

Fig. 7. *Experimental set-up.*

6. Conclusion

In this paper, we provided an outline of our present research. The analysis of the older data showed some new phase relations of the dynamic forces acting during unstable turning operations. These phase relations show us that it is not just one dynamic force that acts on the cutting process in turning, but multiple forces. Based on this, a new model of dynamic forces has been suggested. A development of the model depends on successful experimental identification of all the assumed dynamic forces.

List of symbols

K	specific cutting coefficient	(MPa)
ε	phase between waves on the workpiece and tool vibrations	(rad)
ω	angular frequency	(Hz)
F_T	tangent force	(N)
F_N	normal force	(N)
b	width of cut	(mm)
h_m	difference in centre lines between surface waves $Y_o(t)$ and $Y_i(t)$	(mm)
Y_o	amplitude of the waves on surface during the previous revolution	(mm)
Y_i	amplitude of vibration between the workpiece and the tool	(mm)
G_o^{max}	the extreme of the negative part of the real component of transfer function	(mm/N)
K_{do}, K_{di}, K_{co}, K_{ci}	dynamic coefficients of the cutting force	(MPa)

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