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A new method for reliable rotary tool shank use at speeds above the critical speed range

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Abstract

Dynamic tool characteristics affect both the design and the use of rotary tools applied to high-speed cutting. At present, spindle-driven tools commonly operate at speed values below their critical bending speed. Currently, this is the only way to guarantee reliable tool operation. Consequently, the low natural frequency – in particular for tools with a high length-to-diameter ratio – often results in spindle speeds that utilise neither the cutting materials' nor the machine tools' potential. The paper elucidates a method to design tool shanks and tools to be run above the critical speed, as well as its implementation. The reliable and safe operation of these special tool shanks is based on the physical effects of self-centering and self-balancing, which come into play above the critical speed.

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Introduction

The trend towards high-speed milling (HSC for high-speed cutting) is never ending. If we were to succeed in combining the speed values the speed values typical of HSC run with analogously high feed rates, then we could derive substantial benefits from increased efficiency in comparison with conventional milling. However, as a result of increasing speed, even at speeds below the critical value, the unavoidable effect of imbalance becomes the criterion limiting speed. The phenomenon of resonance has to be avoided; this is, in general, achieved by setting the tool's maximal speed at about 60% of the natural frequency's value. Consequently, it is frequently impossible to achieve the speed and feed rate values commonly used for HSC in many cases due to tool design. A high length-to-diameter ratio (L/d ratio) is desirable in relevant ranges of rotary tool application, which offers another challenge. The natural frequency of rotary tools decreases as a function of an increasing length-to-diameter ratio as physical characteristic. This means that the higher the length-to-diameter ratio, the more difficult high-speed milling becomes and the more probable it is that HS milling will no longer be feasible, insofar as we would not succeed raising the speed value above the tool's natural frequency. It is known that rotors running at speeds above the first critical bending natural frequency tend to self-centering [9].

Theoretical considerations and solution

In the operation of milling cutters, large flexural vibrations occur mainly in proximity of the first critical speed and, as a result, the milling cutter usually breaks in the case of resonance. The reason is the unavoidable, albeit very low, asymmetric mass distribution related to the rotary axis. Consequently, the rotary axis "O" and centre of gravity "S" do not coincide, which results in the eccentricity of the centre of gravity. Furthermore, a distance "a" between the

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geometrical tool centre and the rotary axis is unavoidable. This phenomenon does not only result from manufacturing errors of the tool but, for instance, also from angular and radial displacement in the tool clamping. Apart from high tool precision, low tool masses are also striven for in order to keep the natural frequency as high as possible. A reduction in mass can be obtained by designing tools or tool shanks as hollow shaped parts. This approach has previously become common practice in many applications [2, 4, 6]. The hollow shank design only slightly decreases both the moment of inertia and the stiffness in comparison with commensurable full-volume shanks. An increase in revolutions per minutes makes it possible to elevate the cutting speed to an optimal level for any material. This is particularly applicable to small tool diameters used for aluminum or plastic machining. A significant potential for an increase in productivity can arise from elevated feed rate.

Model of the tool shank dynamics

To pass through the resonance range, it is very important to know the trajectory of the tool's centre of gravity. To calculate the trajectory of the tool's centre of gravity, the formulas (1) and (2) were derived [5] based on the equations of the vibratory motions in x- and y- directions:

$$r_w(t) = a\left(1+\frac{\eta^2}{1-\eta^2}\right) + \varepsilon\frac{\eta^2}{1-\eta^2} = a + (a+\varepsilon)\frac{\eta^2}{1-\eta^2} \quad (1)$$

$$r_s(t) = a\frac{1}{1-\eta^2} + \varepsilon\left(1+\frac{\eta^2}{1-\eta^2}\right) = (a+\varepsilon)\frac{1}{1-\eta^2} \quad (2)$$

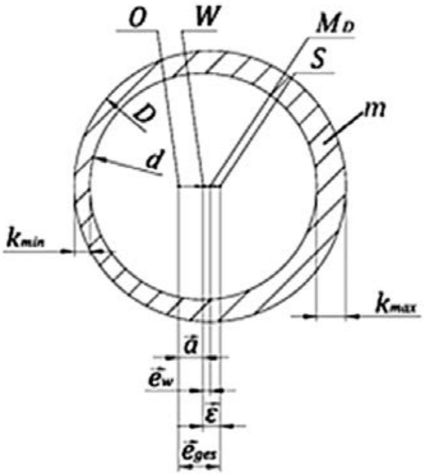
$$r_s(t) = a\frac{1}{1-\eta^2} + \varepsilon\frac{\eta^2}{1-\eta^2} + \varepsilon = a\frac{1}{1-\eta^2} + \varepsilon\left(1+\frac{\eta^2}{1-\eta^2}\right) \quad (3)$$

with $\eta=\Omega/\omega$, ε – distance of imbalance, a – distance between geometric tool centre axis and rotary axis O, $r_w(t)$ – distance between shank centre axis W and O, $r_s(t)$ – distance between centre axis of gravity S and O, Ω - natural frequency, ω - rotary frequency

In this derivation, the influence of external damping was neglected, since it is very low and thus only of minor importance [8]. The term $(a+\varepsilon)$ in the equations (1) and (2) represents the eccentricity of the dynamical system resulting from form errors and dynamic displacement (e_{ges}). It is very relevant in practice, when balancing the hollow shanks. In other words: if one intends to reduce the vibration amplitude during operation, then the imbalance resulting from the total eccentricity (e_{ges}) should be compensated. Altogether it was discovered that extra long hollow shanks clamped on one side show similar dynamical characteristics to those of super-critical, elastic rotors rigidly mounted on two sides, such as the Laval rotor [5, 8]. Thus a self-stabilisation or self-centering effect of the extra long tool shanks introduced is maintained at speeds above the critical one. At values above the critical speed, the rotors' characteristics can be described as "elastic" [8]. Studies of elastic rotors outline a distinct quiet running of the flexurally elastic rotor when run at values above the critical speed [1, 7]. It has been shown that the eccentric tool centre of gravity – which was caused by inaccuracy in machining and tool clamping - drifts to the geometrical centre line, as a function of increasing values above the critical speed. This phenomenon is called the "self-centering effect" [3].

Self-centering

To achieve an efficient self-centering effect for shanks run at values above the critical speed, one has to consider the correlation among the axis of rotation *O*, the shank centre axis *W and* the centre axis of gravity *S*, or the alteration of their mutual relative position as a function of the speed (Figure 1). When running the tool at values below the critical speed ($\eta<1$), the deflection of the centre axis of gravity *S* is greater than the dislocation of the geometrical shank centre axis *W*, since the centre of gravity is pushed outward due to the application of centrifugal forces. If, however, the range of the operating speed is near the natural frequency, then *W and S* are orthogonal to one another related to the axis of rotation *O*. That is, there exists a phase frequency angel $\alpha=90°$. In this case, the deflection of the shank becomes infinite, if there is no damping. However, a strong damping effect can significantly limit the deflection or motion amplitude. When running the tool at speed values above the critical speed ($\eta>1$), then, at increasing speed, the tool's axis of gravity *S* drifts towards the axis of rotation *O and*, finally, upon reaching the phase frequency angle $\alpha=180°$, the geometric shank centre axis *W* lies outside the centre axis of gravity *S*, whereby the distance is equal to the eccentricity. If the rotational speed is beyond super-critical level ($\eta\gg1$), the centre of gravity approaches the state of static equilibrium, whereby the displacement of the shank centre axis W from the axis of rotation *O* is equal to



m – mass of shank, M_D – centre axis of D, *k – wall thickness*

Figure 1. Position of the shank's centre of gravity S related to the geometrical shank centre axis *O* as a function of the speed range, according to [5]