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Identification of critical speeds of clamped circular saws*

Određivanje kritičnih frekvencija vrtnje kružnih pila pričvršćenih prirubnicama*

Original scientific paper • Izvorni znanstveni rad
Prispjelo - received: 29. 9. 2005. • Prihvaćeno - accepted: 25. 4. 2006.
*UDK: 630*822.332.6*

ABSTRACT • *This paper presents a simple experimental methodology of determination of critical rotational speeds of circular saw blades. Both producers and users should be interested in getting information on the actual values of critical (permissible) speeds because very often rotational speeds recommended by producers (sometimes also marked on saw blades) are larger than the values obtained experimentally.*

Key words: *circular saw, critical rotational speed, methodology of determination*

SAŽETAK • *U radu se prikazuje jednostavna metodologija utvrđivanja kritičnih frekvencija vrtnje kružnih pila. I proizvođači i korisnici trebali bi biti zainteresirani za informacije o stvarnim vrijednostima kritičnih (dopuštenih) frekvencija vrtnje. Naime, vrlo su često frekvencije vrtnje koje preporučuju proizvođači pila (katkad su naznačene na listovima pila) veće od vrijednosti dobivenih eksperimentalnim putem.*

***Ključne riječi**: kružna pila, kritična frekvencija vrtnje, metodologija utvrđivanja*

1 INTRODUCTION
1. UVOD

Improvement in sawing accuracy and sawn surface quality (roughness), operating noise level, tool life and reduction of kerf losses during cutting with circular saws are inseparably connected with circular saw dynamic features such as: circular saw blade accuracy, workpiece characteristic, static and dynamic properties of the machine tool.

The effect of circular saw dynamics may be considerably amplified if the saw rotational speed is close to the critical rotational speed due to the resonance phenomenon as exemplified by Stakhiev[2] (Stakhiev, 1989; Stakhiev, 2000). The effect of the rotation speed on transverse displacements of the idling circular saw during gradual increase of the rpm is shown in Figure 1.

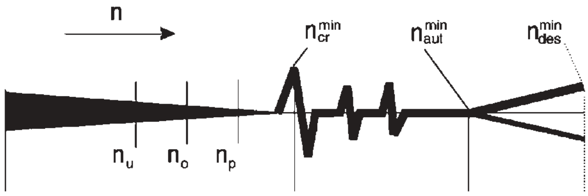

Figure 1 Circular saw blade transverse displacements as a function of rotational speed during idling (saw diameter: 510 mm, clamping diameter: 125 mm), (reprinted from Stakhiev[2], 2000)
Slika 1. Lateralno gibanje lista pile kao funkcija frekvencije vrtnje u praznom hodu (promjer pile 510 mm, promjer prirubnica 125 mm) (Stakhiev[2], 2000)

Speed consists of the following distinguished components:

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* Rad je pripremljen za sastanak Interkatedra 2005 „Woodworking technique"
* The paper was prepared for meeting Interkatedra 2005 „Woodworking technique"
[2] Dr. Yury M. Stakhiev (1934 – 2004) was an acknowledged expert in the field of circular saws and a pioneer in the development of the critical speed theory (Schajer, 2004).

1. universal rotational speed (*univerzalna frekvencija vrtnje*) n_u,
2. optimal rotational speed (*optimalna frekvencija vrtnje*) n_o,
3. permissible rotational speed (*dopuštena frekvencija vrtnje*) n_p,
4. lowest critical rotational speed (*najniža kritična frekvencija vrtnje*) n_{cr}^{min},
5. lowest self-excited rotational speed (*najniža samouzbudna frekvencija vrtnje*) n_{aut}^{min},
6. destructive rotational speed (*destruktivna frekvencija vrtnje*) n_{des}^{min}.

The mechanism of saw blade instability was studied by many scientific publications (Mote and Szymani, 1977; Li et al, 2000; Nishio and Marui, 2000; Schajer, 1986; Schajer, 1989; Siklienka and Svoreň, 1997; Stakhiev, 1989; Stakhiev 2000; Stakhiev 2004) where interest was focused on the theory of critical rotational speed of circular saws. Although this theory seems to be well acceptable by the scientific community, its practical implementation is rather limited. Moreover, the critical speed depends on some additional factors such as: internal stresses, tensioning level (Chabrier and Martin, 1999; Mote and Szymani, 1977; Li et al, 2000; Schajer, 1985; Siklienka and Svoreň, 1997; Stakhiev, 1989; Stakhiev 1989) temperature gradient (Mote and Szymani, 1977; Stakhiev, 1989; Siklienka and Svoreň), and saw design, i.e. the presence of slots (Nishio and Marui, 1996; Stakhiev, 1989; Svoreň, 2004).

It is crucial for users to be well acquainted with the critical rotational speed because in case the rotation speed reaches its critical speed range, the clamped saw blade cannot resist transversal forces and becomes unstable. Furthermore, it was confirmed that the maximum (or permissible) rotational speed marked by tool producers on the saw blade was occasionally higher than the computed critical rotational speed of these investigated saws (Stakhiev, 2004). For example, the mark on the saw indicates 1500 rpm, where the calculated speed was only 1173 rpm! As a result, in the speed range between 1173rpm and 1500rpm, the circular saw would easily become unstable (Stakhiev, 2004).

Methodologies of critical speed determination found in the reference literature are too specific to be applied in industry (Nishio and Marui, 1996; Szymani, 1984) and they mainly deal with computer aided designing of solid saws. An alternative way for identifying the value of critical speeds is through an experiment.

The aim of this paper is to present a simple experimental methodology for identifying critical rotational speeds of circular saw blades.

2 THEORETICAL BACKGROUND
2. TEORIJSKE OSNOVE

According to the theory of critical rotational speed, the vibration of each sawblade is a superposition of two traveling waves moving in opposite directions around the sawblade (the forward traveling wave and the backward traveling wave, respectively). The natural frequency f_n, for the nodal diameter number n, of the running circular saw blade is influenced by the rotational speed of the saw blade. Thus, the frequency f_n is a function of the plate (blade) rotation speed N and it may be expressed as $f_{nf}(N)$. So, the frequencies of the forward and backward traveling waves may be expressed as follows (Mote and Szymani, 1977; Nishio and Marui, 1996; Schajer, 1985; Stakhiev, 1989):

– forward traveling wave (*val koji putuje prema naprijed*):

$$f_{nf}(N) = f_{nf}(N) + \frac{nN}{60} \quad (1)$$

– backward travelling wave (*val koji putuje unatrag*):

$$f_{nb}(N) = f_n(N) - \frac{nN}{60} \quad (2)$$

When the rotational speed of the circular saw increased, the frequency of the backward travelling wave becomes zero at a definite rotational speed, which is called the critical (lowest) rotational speed n_{cr}^{min} (Mote and Szymani, 1977; Stakhiev, 1989). This is the resonance point where a small lateral force causes a large lateral deflection of the saw blade (Stakhiev, 1989; Stakhiev, 2004). There is no critical rotational speed in cases where $n = 0$ and $n = 1$. In most cases the lowest critical speed is for the nodal diameter $n = 2$ (Stakhiev, 1989). Schajer (1986), however, reports that the mode when the lowest critical speed is observed depends also on the collar diameter and sawblade outside diameter ratio.

The lowest critical speed may be calculated by the following equation (Nishio and Marui, 1996; Schajer, 1986; Siklienka and Svoreň,1997; Stakhiev, 1989):

$$n_{cr}^{min} = \frac{60 f_n(0)}{\sqrt{n^2 - K}} \quad (3)$$

where:

- $f_n(0)$ [Hz] is the function of natural frequency of saw blade at rest for the nodal diameter n (i.e. obtained from the impulse excitation test) $f_n(0)$ [Hz] *funkcija je vlastite frekvencije kružne pile koja miruje za broj čvornih promjera n (dobiven iz testa impulsne pobude lista)*
- K is a constant independent of rotational speed. *K konstanta je neovisna o frekvenciji vrtnje.*

Parameter K is a dimensionless value and it is called centrifugal force coefficient (Nishio and Marui, 1996; Schajer, 1986; Siklienka and Svoreň, 1997; Stakhiev, 1989). Theoretical and experimental values of K for solid saw blades can be found in the reference literature (Nishio and Marui, 1996; Stakhiev,1989). Unfortunately, there is a lack of K parameter data for some more complex circular saws (such as saws with larger number of slots).

It should be emphasized that in the reference literature (Stakhiev, 1989) data are given of $f_n(0)$ for most

a) b)

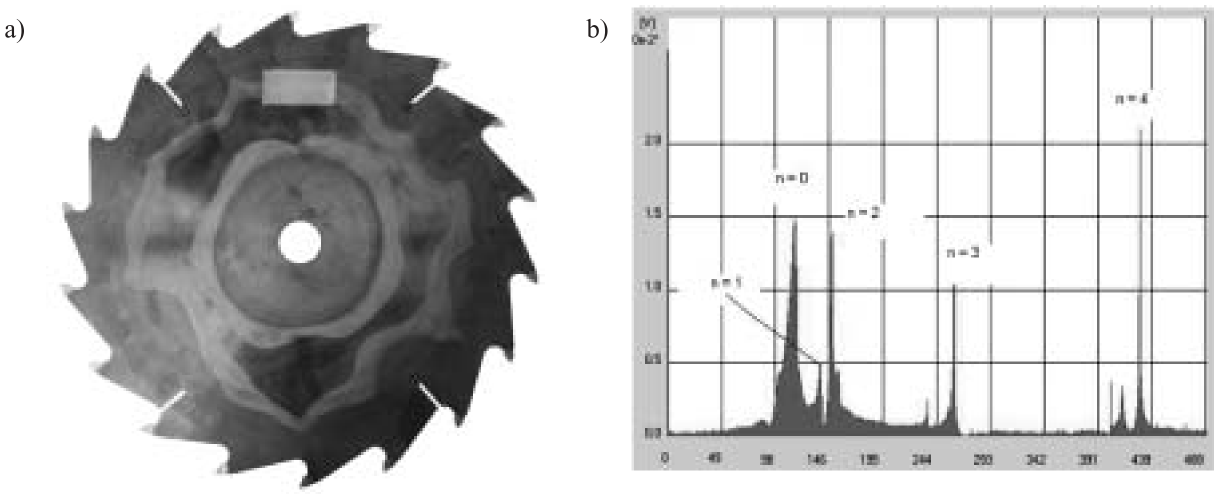

Figure 2 (a) Circular saw general view and (b) Fast Fourier Transform (FFT) of the time data (Saw data: D = 350 mm, d = 30 mm, s = 2,5 mm, z = 18, SL = 4, A/D = 0,35)
Slika 2. (a) Prikaz lista kružne pile i (b) Fast Fourierova transformacija (FFT) podataka o gibanju lista u vremenu (podaci o kružnoj pili: D = 350 mm, d = 30 mm, s = 2,5 mm, z = 18, SL = 4, A/D = 0,35)

commonly used dimensions of circular saws, which are also the subject of the Russian Standards. Thus, critical rotational speeds of solid circular saws may be easily determined.

3 MATERIAL AND METHODS
3. MATERIJAL I METODE

Experimental determination of the critical rotational speed was carried out for a brand new circular saw, delivered by the GASS Company, with the following characteristics: outside diameter D = 350 mm, hole diameter d = 30 mm, saw blade thickness s = 2.5 mm, number of teeth z = 18, number of external slots 4, collar diameter A = 125 mm, clamping ratio A/D = 0.35 (Figure 2a). The transverse displacements of the non-rotating saw were measured with an eddy-current displacement sensor mounted close the saw surface at the radius close to gullets. The saw blade was excited by hitting with a small hammer. Then, the Fourier transform of the obtained signal was computed with "AnalizaDAQ.exe" software application.

Additionally for comparison, natural frequencies were evaluated of the solid saw of the same dimensions as the tested saw, according to the data presented in Stakhiev's paper (Stakhiev, 1989).

4 RESULTS AND DISCUSSION
4. REZULTATI I DISKUSIJA

The critical rotational speeds of the examined saw were determined by the Equation 3 based on the results of computed Fourier transform (Figure 2b) of the obtained time signal for the saw with slots (number of slots SL = 4). Furthermore, for the solid saw (number of slots SL = 0) values of frequencies were taken from the Stakhiev's paper (Stakhiev, 1989). The mentioned speeds were calculated for the nodal diameters n = 2 and n = 3 because of the value of the clamping ratio A/D = 0.35 (Schajer, 1986). The constants K have values equal to K = 2.05 (n = 2 , SL = 4, (Nishio and Marui, 1996)) and K = 2.42 (n = 2 , SL = 0 (Stakhiev, 1989)), and K = 2.80 (n = 3, SL = 4, (Nishio and Marui, 1996)) and K = 3.59 (n = 3, SL = 0, (Stakhiev, 1989)). Additionally, permissible rotational speeds were calculated according to Stakhiev (Stakhiev, 1989; Stakhiev, 2004):

$$n_{\mathrm{p}} = 0.85 \cdot n_{\mathrm{cr}}^{\min} \tag{4}$$

The discussed results are presented in the bar graph (Figure 3).

For both types of circular saw, with and without slots, minimum critical speeds have been observed for nodal diameter n = 3. The obtained minimum permissible rotational speed n_p(min) = 5441 rpm (of the circular saw with slots SL = 4) is slightly lower than the value of rotational speed recommended by saw producers n_r(v_c = 100 m/s) = 5450 rpm (the latter is an example of the usual way to determine maximum rotational saw speed

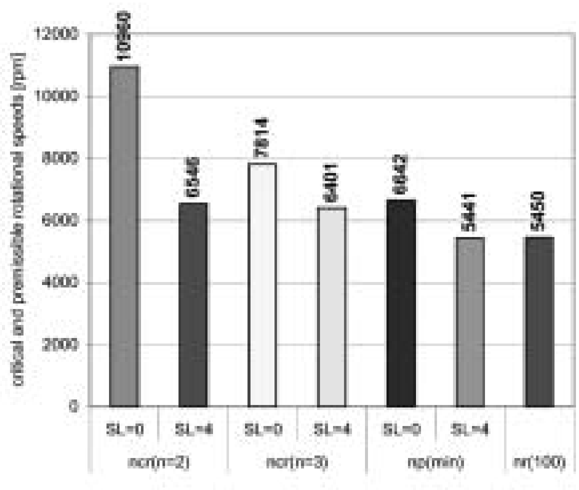

Figure 3 Critical rotational speeds n_{cr}, minimum permissible rotational speeds n_p(min) and rotational speeds recommended by saw producers n_r(v_c = 100 m/s)
Slika 3. Kritične frekvencije vrtnje n_{cr}, minimalno dopuštene frekvencije vrtnje n_p(min.) i frekvencija vrtnje koju preporučuje proizvođač kružne pile n_r(v_c =100 m/s)

based on the value of maximum rim speed). It should be emphasized that inappropriate tensioning, hitting of the saw during cutting and shrinking of the clamping ratio may reduce the critical speed even more. Therefore, working with such a saw at the maximum rotational speed recommended by the producer might affect the product quality or, even worst, it could be dangerous for the user.

5 CONCLUSIONS
5. ZAKLJUČCI

Based on the results of this study following conclusive remarks can be drawn:

1. The presented methodology may be efficiently used by producers and users for identifying permissible rotational speeds of circular saw blades.
2. Values of minimum critical rotational speeds of saws with external slots are lower than values of solid circular saws. Hence, in case of saw design with slots, the reduction in the constant *K* value should be taken into account.
3. The minimum permissible rotational speed n_p(min) = 5441 rpm (of the circular saw with slots SL = 4) is slightly lower than the value of the rotational speed recommended by the saw producers $n_r(v_c$ = 100 m/s) = 5450 rpm.

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Acknowledgement:

Special thanks to *GASS Company, Suwalki* (Poland) for providing the circular saw used in the experiment.

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