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A BRIEF REVIEW AND COMPARISON OF SELECTED EXPERIMENTAL METHODS FOR MEASURING NATURAL FREQUENCIES OF CIRCULAR SAW BLADES

Different methods for the empirical determination of the natural frequencies of circular saw blades are presented. Stationary methods, such as the harmonic and impulse tests, are discussed and the results of related comparison are given. The comparison of the methods revealed their degree of practical usefulness and their accuracy in determining natural frequencies. A combination of specific methods is proposed, which should allow optimal results.

Keywords: circular saw blade, measurement methods, natural frequencies

Introduction

Knowledge of the critical rotational speeds of the circular saw blade in use might help the user avoid unstable cutting conditions, which could cause 'snaking' of the saw blade in the workpiece, and, as a result, inaccuracy in sawing. The fundamentals of critical rotational speed theory have been described in studies by Stakhiev [1970], Šteuček [1971], Mote and Nieh [1973] and Strzelecki [1974]. The minimum critical rotational speed is a function of the natural frequencies of the circular saw blade [Strzelecki 1974; Schajer 1986, 1991; Nishio and Marui 1996; Stakhiev 1998]. Nevertheless, the majority of saw blade manufacturers mark their tools with the maximum allowed rotational speed for each saw, and the usual way to determine the maximum rotational speed of a saw is based on the value of the maximum rim speed. According to the literature, sawing speed should not exceed a value of 100 m/s [Li et al. 2000]. This kind of approach may sometimes give misleading information to users, since the actual permissible rotational speeds of some circular saw blades are below those recommended [Stakhiev 2004; Orlowski et al. 2007].

The critical rotational speed theory of circular saw blades has been the subject of many scientific publications. The natural frequencies or critical

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rotational speeds of circular saw blades (clamped saws) have mainly been determined experimentally, e.g. Stakhiev [1970, 1998, 2000], Strzelecki [1974], Javorek and Sokołowski [2000], Veselý et al. [2012], and Kaczmarek et al. [2014].

Recently, Mohammadpanah and Hutton [2015a, b] reported on the analytically and empirically determined instability of guided splined circular saw blades, which rotated with speeds higher than their critical rotational speeds due to flutter (the phenomenon of self-excited vibration). Sawing kinematics with guided splined saws is widely used in the North American wood industry [Mohammadpanah and Hutton 2015b].

The optimal rotational speeds of circular saw blades might be defined empirically, even in sawmill conditions on the circular sawing machine equipped with an individual tool, if the methods presented in research by Orlowski and Hyvärinen M. [2007], and Sandak et al. [2007] are applied. It ought to be emphasized that in the above mentioned approach the behaviour of the circular saw blade is examined and the ranges of the lowest values of the blade's lateral displacements are sought, which correspond to the largest value of dynamic stiffness. Nevertheless, in both cases, there is a need for a stepless driving system for the spindle (arbor) of the circular sawing machine. On the other hand, Finite Element Methods (FEM) have been applied to determine the natural frequencies of circular saw blades, and the results of these analyses have been reported by Gogu [1988], Nicoletti et al. [1996], Cristóvão et al. [2012], Droba et al. [2015], and Svoreň et al. [2015]. Tensioning circular saw blades is a way to increase the critical rotational speed [Schajer and Mote 1983; Schajer 1984, 1992; Schajer and Kishimoto 1996; Chabrier and Martin 1999; Stakhiev 1999, 2000; Cristóvão et al. 2012; Heisel et al. 2015]. Such a saw blade treatment may make it difficult to accurately model the examined circular saw blade. Furthermore, the use of FEM models for complex designs of circular saw blades without their empirical validation could complicate matters.

Theoretical background

The range of the permissible rotational speed of a circular saw blade is defined by the critical rotational speed of the tool. It is usually the maximum speed in which the circular saw blade can work with the required stability. The critical rotational speed could be determined with a knowledge of the values of the natural frequencies of the circular saw blade.

For circular saw blades, there exists a theory which states that the resonance phenomenon of circular plates is a result of the superposition of two component waves in which the first is travelling forwards and the second is travelling backwards [Stakhiev 1970; Schajer 1986; Nishio and Marui 1996]. The equations for determining these frequencies have been published in several studies e.g. [Stakhiev 1970; Schajer 1986; Nishio and Marui 1996, Droba et al.

2015]. When the rotational speed of the circular saw (clamped with collars) increases, at a certain rotational speed the frequency of the backward travelling wave becomes zero, which is called the critical (lowest) rotational speed, n_{cr} [Stakhiev 1970]. At this point the phenomenon of resonance occurs, and even a small lateral force can cause a large lateral deflection of the saw blade [Stakhiev 1970, 2004].

Orlowski et al. [2007] presented a simple measurement method for determining natural frequencies in the impact test (the impulse excitation test). This kind of test is useful for examining circular saw blades with more complex shapes (a large number of slots, unknown tensioning method, etc.). In the impulse test, the measurements of saw blade displacements may be taken with the use of an eddy current displacement sensor [Orlowski et al. 2007], a microphone [Cristóvão et al. 2012], an inductive displacement sensor [Kaczmarek et al. 2014] or a laser [Orlowski et al. 2007]. In the latter, the laser spot position seen by video camera changed according to the saw blade deflection; therefore, it was possible to analyse the amplitude of the circular saw vibrations.

The impulse method seems simple but at the same time very effective. However, if the circular saw blade design is more complex in shape, it may be difficult to gain a proper understanding of the natural frequencies from the Fast Fourier Transform (FFT) of the time course of the circular saw displacement signal [Kaczmarek et al. 2014]. Hence, in some cases the results obtained from the impact (impulse) test might be ambiguous. In such cases, the experiment should be supported by the harmonic test, despite it being extremely time-consuming. The harmonic method is based on the classic Chladni patterns method which allows identification of the modal shapes of the resonances of the plates [Šteuček 1971; Strzelecki 1974; Kaczmarek et al. 2014].

The aim of the paper is to present and compare the empirical results of determining the natural frequencies of a circular saw blade of complex design clamped with collars using both the impulse test and the harmonic test.

Materials and methods

Tool

In both experiments, the harmonic test and the impulse test for determining the natural frequencies of a brand-new circular saw blade (ASPI Tech) were examined. A Multix saw blade was examined with the following measurements: outside diameter $D = 350$ mm, hole diameter $d = 30$ mm, saw blade thickness $a = 2.5$ mm, teeth of cutting number z = 18 (not tipped with inserts), number of teeth throwing chips $z' = 16$, collar diameter $A = 90$ mm, clamping ratio $A/D = 0.26$.

Harmonic test

Natural frequencies were empirically determined at the Technical University in Zvolen [Orłowski and Javorek 2009]. The tested saw blade was clamped with collars and sprinkled with semolina, which, for the specific exciting frequencies, created Chladni's patterns corresponding to the modal shapes of resonances (natural frequencies). Then, the values of the natural frequencies were noted and pictures were taken of each of the patterns obtained.

Impulse test

The impulse test was conducted in a laboratory of the Technical University in Zvolen. The saw blade under examination was mounted using collars measuring A = 90 mm in diameter (clamping coefficient A/D = 0.26). Then the non-rotating saw was excited by hitting it with a small hammer. The transverse displacements were measured using a contactless inductive displacement sensor (Balluff BAW M08EI-UAD15B-BP03) mounted close to the saw surface at the radius close to the gullets. The sampling frequency amounted to 3000 Hz, and the number of samples totalled 16384. The signals obtained were recorded in a form which made it possible to change them by FFT into an amplitude spectrum using software such as Labview (v.8) or AnalizaDAQ. In turn, the values of the natural frequencies of the tested circular saw blade were obtained from its amplitude spectrum [Orlowski et al. 2007].

Results and discussion

The natural frequencies of the examined circular saw blade obtained in both the harmonic f_h and impulse f_i tests, together with Chladni's patterns corresponding to the modal shapes (nodal diameters) n = 1-5, are presented in table 1.

Determination of the natural frequencies of the circular saw on the basis of the FFT of the time data obtained in the impulse test are presented in figure 1. At first glance, without a knowledge of the values of the natural frequencies quantified in the harmonic test, determination of these frequencies from the FFT transform (fig. 1b) could prove difficult, and in reality ambiguous. Moreover, some frequencies, from the point of view of Chladni's pattern occurrence, could be disregarded, since their amplitude values in the amplitude spectrum were rather low.

The nodal diameters of the same mode occurred for different values of frequencies. However, Chladni's patterns (tab. 1) changed their position on the circular saw blades. It should be emphasized that the harmonic method provided proof of the phenomena of quasi-twin resonant frequencies (the same modes but different positions) [Kaczmarek et al. 2014]. This kind of phenomenon has not been observed for circular saw blades with simple designs. Furthermore, the FFT spectra for the latter were straightforward and determining the natural frequencies was an easy task [Orlowski et al. 2007].

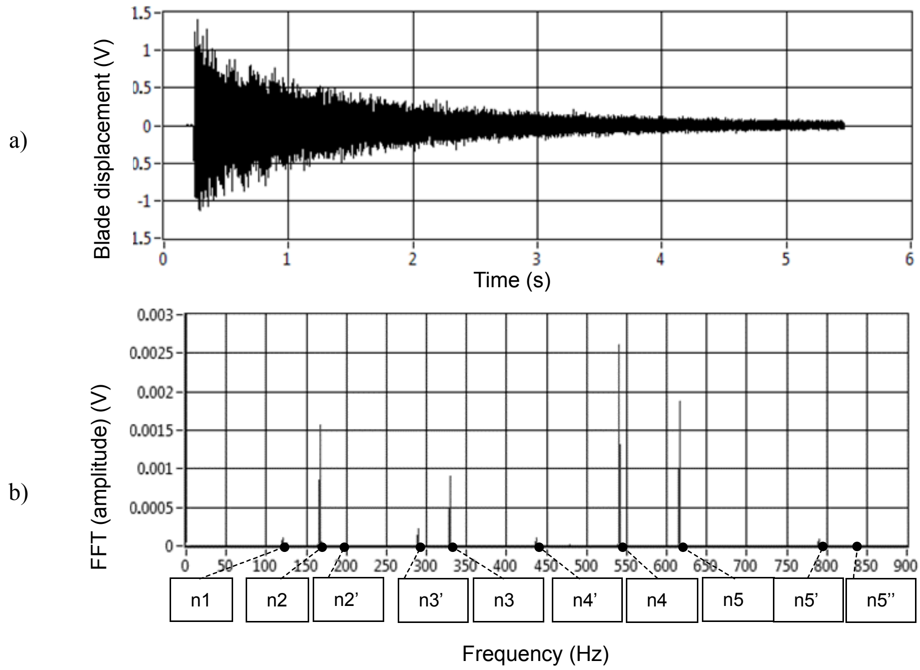

Fig. 1. Determination of the natural frequencies of the circular saw using the impact test: a – time domain data from inductive displacement sensor, b – FFT of the time data, (saw diameter *D* = 350 mm, hole diameter *d* = 30 mm, saw blade thickness *s* = 2.5 mm, clamping diameter *A* = 90 mm, *A*/*D* = 0.26)

In the last column of table 1, the data showing the difference between the frequencies from both tests is given, calculated as follows:

$$\Delta f = |f_h - f_i| \quad (1)$$

In general, the modulus of Δf gradually increased with an increase in the mode number from 1.81 Hz to 12.04 Hz, with the exception of $n = 2'$, for which a minimum value was obtained.

In figure 2, the gaps between the quasi twin frequencies of the compared modal shapes (Chladni's patterns) obtained in the harmonic test are presented. The value of the gap g_n in Hz for the n modal shape is given by:

$$g_{n=j} = f_h(n=j) - f_h(n'=j) \quad (2)$$

where: j = 2, 3,…, 5. It must be emphasized that for n = 5 the gap between the frequencies for the modal shapes n' and n'' was also determined. An increase can be observed in the gap values for the modal shapes from n = 2 to n = 5, where the maximum occurred. For the larger values of the frequencies of the modal shape n = 5’ and n = 5’’, an inverse phenomenon emerged (a decrease in gaps).

Table 1. Chladni’s patterns corresponding to the modal shapes, natural frequencies of the examined circular saw blade D = 350 mm, d = 30 mm, a = 2.5 mm (clamped with collars A = 90 mm) from the harmonic f_h and the impulse f_i tests

Modal shape number n [-]	Natural frequency f_h [Hz]	Natural frequency f_i [Hz]	Modulus $\|\Delta f\|$ [Hz]
1	123.26	125.074	1.81
2	165.82	167.558	1.74
2’	194.66	194.477	0.18
3’	293.30	289.610	3.69
3	332.50	329.440	3.06
4’	444.00	437.483	6.52
4	548.40	540.581	7.82
5	623.30	616.395	6.90
5’	799.40	789.996	9.40
5’’	846.90	834.863	12.04

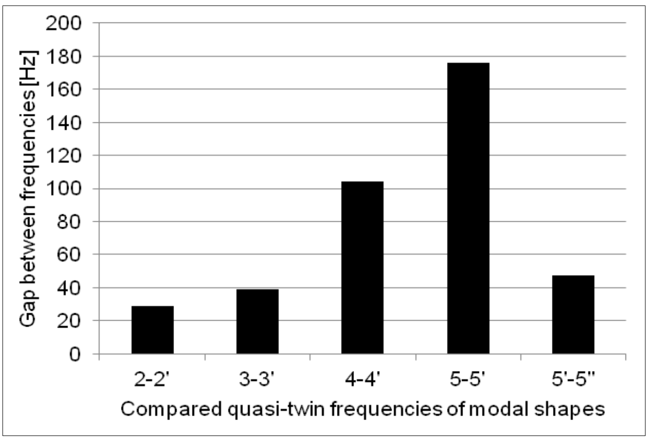

Fig. 2. The gaps between quasi twin (natural) frequencies of compared modal shapes (Chladni’s patterns) obtained in the harmonic test (saw diameter D = 350 mm, hole diameter d = 30 mm, saw blade thickness s = 2.5 mm, clamping diameter A = 90 mm, A/D = 0.26)

Conclusions

Although the harmonic test is time-consuming, it makes it possible to unambiguously determine the natural frequencies of a circular saw blade of complex design.

The analyses of the results obtained in the harmonic test revealed the existence of similar modal shapes (Chladni's patterns) for different frequencies. Nevertheless, the registered shapes had dissimilar positions on the saw blade. For this reason they have been called quasi twin natural frequencies.

Gaps between quasi twin frequencies depend on the modal shape. An increase was observed in the gap values for the modal shapes from $n = 2$ to $n = 5$, where the maximum occurred. For the larger values of the frequencies of the modal shape $n = 5'$ and $n = 5''$, an inverse phenomenon emerged.

The experiments carried out to determine the natural frequencies of a circular saw blade of complex design revealed the limited usefulness of the impulse test, since, in the FFT spectrum of the lateral saw blade displacements, natural frequencies appeared which were difficult to unequivocally identify. This was caused by the phenomenon of quasi twin resonant frequencies.

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