

ORIGINAL ARTICLE

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Aerodynamic sound and self-excited vibration of circular saw with step thickness I: Comparison of dynamic characteristics between the common circular saw and the circular saw with step thickness*

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Abstract The natural frequencies, aerodynamic noise, whistling noise, and self-excited vibration between the common circular saw with uniform thickness and the circular saw with step thickness (thin on its outer part and thick on its inner part) were researched during idling. The natural frequencies of the circular saw with step thickness increased with an increase in the thickness and in the radius of the thick part. The frequencies of the circular saws with step thickness (thick at the inner part) were higher than that of the thin circular saw with a uniform thickness of 0.5 mm. The aerodynamic sound pressure level induced from circular saw teeth increased with an increase in the tooth thickness. The whistling noise and self-excited vibration easily occurred in the thick circular saws (1.5, 2.0, and 2.5 mm). The whistling sound pressure level and the vibration amplitude increased with an increase in the thickness of the saw. None of the designed circular saws with step thickness generated whistling noises or self-excited vibration during idling.

Key words Step thickness · Aerodynamic sound · Whistling noise · Self-excited vibration · Saw-tooth thickness

Introduction

Circular saws with uniform thickness are widely used in the wood industry. To control or reduce their vibration may improve sawing accuracy; and to reduce the noise, which is

harmful to the operators' health, may increase working efficiency. Because use of a thin saw blade decreases the amount of sawdust (kerfloss), efficient use of resources is thus possible. The thin saw, however, has some dynamic problems regarding idling noise, vibration during cutting, critical speed, stiffness, and so on.

Many studies on the noise of the circular saw or noise reduction, especially reduction of the whistling noise, have been presented.¹⁻¹⁰ The noise of the circular saw is mainly caused by the vortices generated behind the rotating teeth, and the circular saw blade is excited by the vortices during idling.^{5,6} The noise of the circular saw consists of the aerodynamic sound and the whistling noise. The noise during idling is often more intense than that during cutting when the whistling noise occurs.

To reduce the whistling noise the tapered teeth,⁷ nonuniform tooth pitch,⁸ slots,^{5,9} and saw blade of high-damping metal¹⁰ have been developed, but these techniques were not always effective for controlling the noise. Taki et al.⁵ reported the relations between the thickness of a disk and noise during idling, but they analyzed only the noise. Yokochi et al.⁸ studied the relation between the teeth number and noise during idling. The relations between self-excited vibration of the circular saw due to the aerodynamic force during idling and saw-tooth thickness have not been investigated.

The thin circular saw^{11,12} has low stiffness and low critical speed,¹³ and so it can be easily deformed owing to cutting resistance. We designed a circular saw with stepped thickness that is thin at its outer part and thick at its inner part, thereby having a narrower kerf, higher stiffness, and higher critical speed.

Experimental

Tested circular saws

Figure 1 shows the circular saw blade and saw tooth tested in this study. The blade thicknesses (t) were 0.5, 1.0, 1.5, 2.0,

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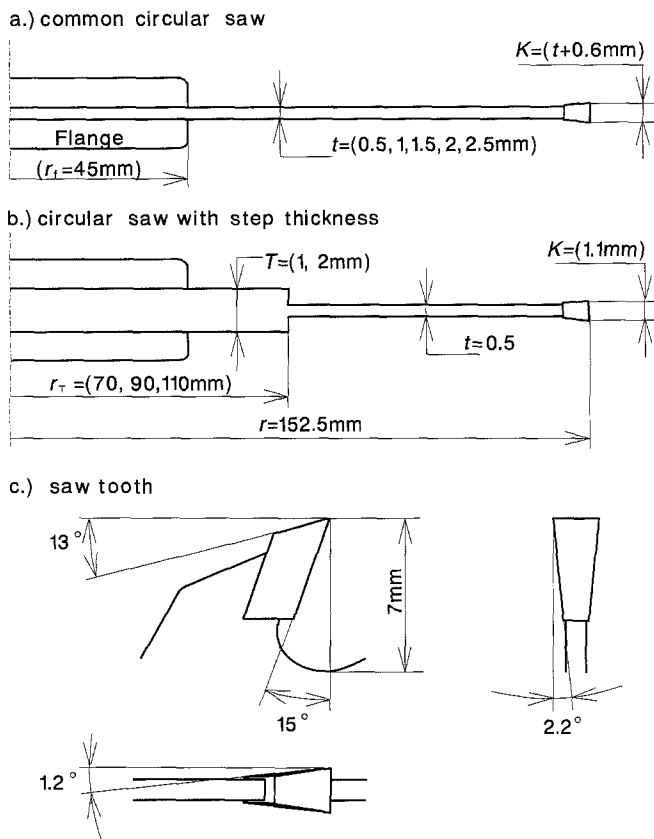


Fig. 1. Geometry of the circular saw and saw tooth. t , thickness; r_f , flange radius; r_r , thick part of saw blade radius; K , kerf

and 2.5 mm; and the radius of the blade was 152.5 mm (Fig. 1a). For blade thicknesses of 1 and 2 mm, there were two plate thicknesses within a radius of 152.5 mm (Fig. 1b). That is, the thickness of its outer part was thin and the thickness of its inner part was thick. The thicknesses of the thick part of the saw blade (T) were 1 and 2 mm; and the radii of the thick part of the saw blade (r_r) were 70, 90, and 110 mm. The thickness of the thin portion of the saw blade (t) was 0.5 mm. We called it a circular saw with step thickness.

All of the circular saws have 80 swage teeth without a slot; and all of the circular saw teeth have the same geometry: hook angle 15° , clearance angle 13° , side clearance angle 1.2° , and radial clearance angle 2.2° (Fig. 1c). The amount of set was 0.3 mm for each side of the kerf.

The saw blade was made of alloyed tool steel. Young's modulus, density, and the Poisson ratio were 2.1×10^{11} N/m², 7.8×10^3 kg/m³, and 0.3, respectively. The radius of the flange was 45 mm.

Experimental apparatus and methods

The experimental apparatus is shown in Fig. 2. The rotation speed of the cutting machine was controlled with the variable-speed motor, which received commands from the computer through the input-output interface (I/O), digital-analog converter (DAC), and frequency converter. The

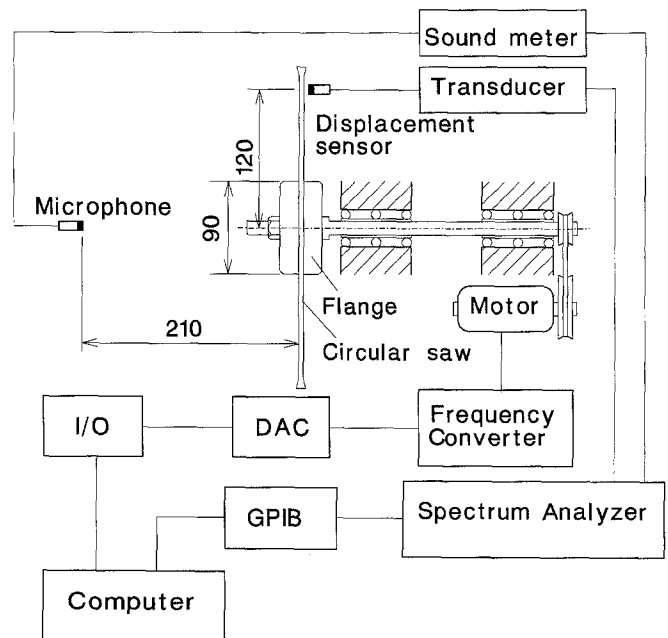


Fig. 2. Experimental apparatus for measuring sound pressure and displacement of the circular saws. I/O, input-output interface; DAC, digital analogue converter; GPIB, general purpose interface bus

experimental rotation speed ranged from 10 to 65 rps in steps of 1 rps.

The microphone was placed at a distance of 210 mm in the normal direction from the center of the saw blade. The eddy-current displacement sensor was set at a radial distance of 120 mm from the center of the spindle and about 1 mm in the normal direction from the circular saw blade. The two electric signals of displacement and sound were measured and analyzed with a fast Fourier transformation (FFT) spectrum analyzer. Finally, the spectra were sent to the computer through a general purpose interface bus (GPIB) and were stored on the computer hard disk.

The sound pressure of circular saws was measured with a flat response. The frequency range was from 0 to 5 kHz, the rate of decomposition was 12.5 Hz, and the average number was 8.

The natural frequencies of the circular saws were measured under static conditions. To obtain the sound generated only by aerodynamic force, the damping disk was used, which consists of an alloy steel disk 240 mm in diameter, 0.25 mm thick, and having a viscoelastic material layer 0.05 mm thick. The damping disk was bonded on one of the blade surfaces. The sound that radiated from the saw blade without a damped disk and the amplitude of its vibration were also measured.

Results and discussion

Natural frequencies of circular saws

Figure 3 shows the relations between the natural frequencies of the circular saws with uniform thickness and the

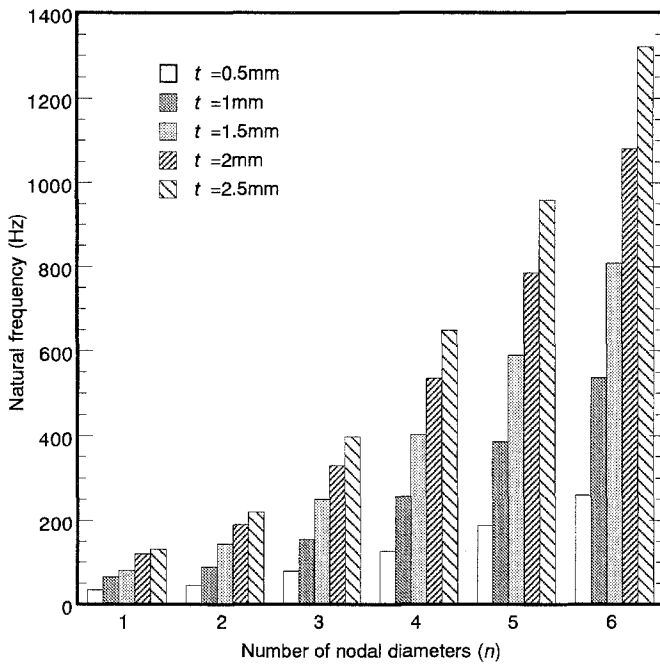


Fig. 3. Relations between the natural frequencies of circular saws with uniform thickness (t) and the number of nodal diameters

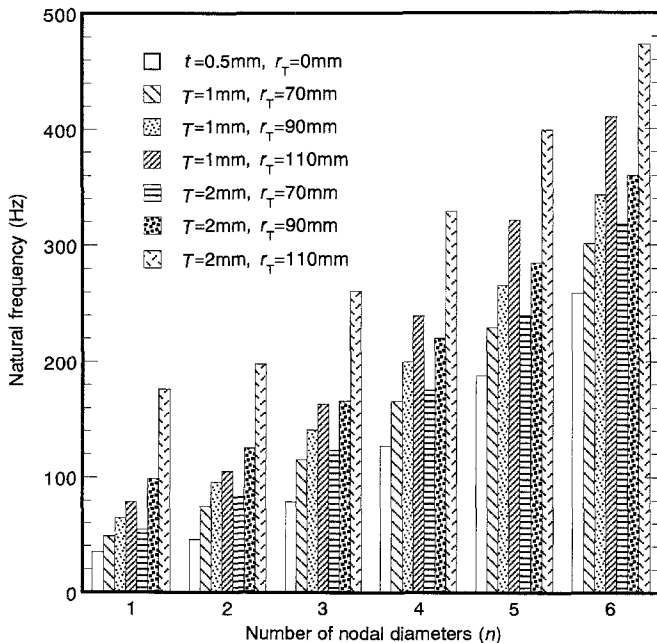


Fig. 4. Natural frequencies of circular saws with step thickness (T) and the number of nodal diameters

number of nodal diameters. These results were in agreement with the theoretical calculation, where the natural frequencies were in directly proportion to the thickness of the circular saw blade.

Figure 4 shows the natural frequencies of the circular saws with step thickness and the number of nodal diam-

eters. All of the natural frequencies of the circular saw with step thickness were higher than those of the circular saw of 0.5mm uniform thickness. The natural frequencies of the circular saws with step thickness increased with the increase in the thickness of the thick part and with an increase in the radius of the thick part.

Sound of the circular saw

Aerodynamic sound

Figure 5 shows the aerodynamic sound pressure level spectra radiated from the damped circular saws as the rotation speed increases. The uneven lines in the figures show the vortex-shedding frequencies. The aerodynamic sound of the circular saw appear in the sound pressure level spectra as gentle peaks. The spectra of the thin circular saw gradually became smoother with a decrease in thickness from 2.5mm to 0.5mm. Two peaks occurred in the spectra of the 0.5-, 1.0-, and 1.5-mm circular saws, whereas one peak appeared in the spectra of the 2.0- and 2.5-mm circular saws. It means the generated vortices were classified into either two peaks or one peak.¹⁴

The relations between the rotation speed and the vortex-shedding frequencies of the uniform-thickness circular saws are shown in Fig. 6. The vortex-shedding frequencies were divided into two groups: low frequencies (f_{s1} , filled symbols) and high frequencies (f_{s2} , open symbols). The vortex-shedding frequencies increased with an increase in the rotation speed, and they decreased with an increase in saw blade thickness. The vortex-shedding frequencies of the 2.5-mm circular saw were the lowest among all the saws, and the f_{s1} and f_{s2} of the 0.5-mm circular saw were the highest.

Figure 7 shows the relations between the rotation speed and the overall sound pressure levels radiated from the damped circular saws. The levels increased with an increase in the thickness of the saw blade. There was no obvious difference in overall sound pressure level between the 2.0- and 2.5-mm saw blades. The overall sound pressure level of the 0.5-mm circular saws were always the lowest for all circular saws: It was about 3–5 dB lower than that of 2.5-mm circular saw at all rotation speeds.

Whistling noise

The sound pressure level spectra radiated from undamped circular saws with an increase in rotation speed are shown in Fig. 8. Compared with the aerodynamic sound pressure level spectra radiated from damped circular saws in Fig. 5, sharp peaks appeared in the spectra (Fig. 8, parts 2–5). The sharp peaks indicate the appearance of the whistling noise, which was radiated by the vibration of saw blades excited by vortices generated in the back of the teeth. The whistling noise levels of the 1.0-, 1.5-, 2.0-, and 2.5-mm circular saws, (i.e., the sharp peaks) increased with the increase in circular saw-tooth thickness. The number of nodal diameters increased with the decrease in circular saw-tooth thickness.

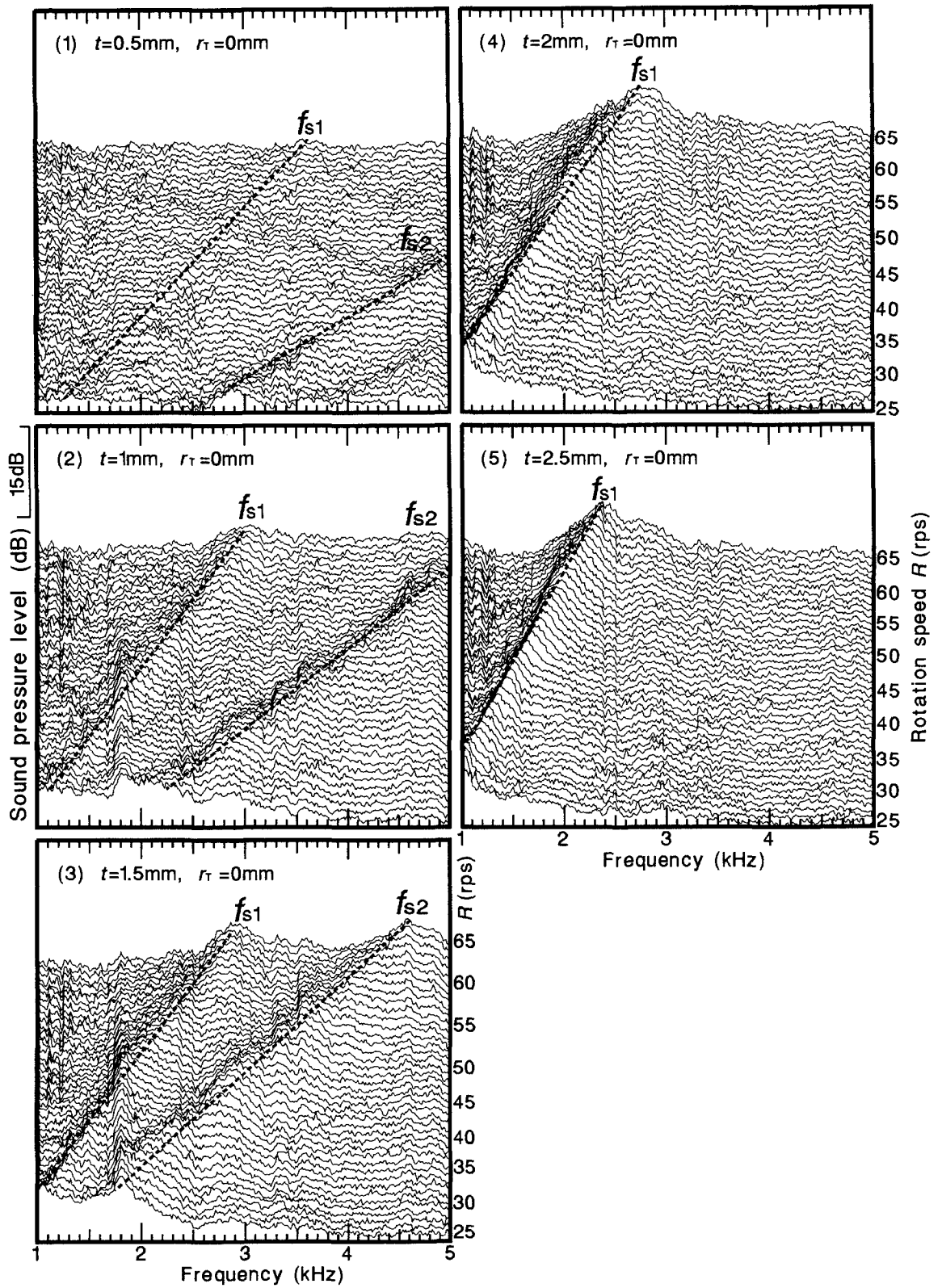


Fig. 5. Aerodynamic sound pressure level spectra radiated from damped circular saws as the rotation speed increases. f_{s1} , f_{s2} , vortex-shedding frequencies

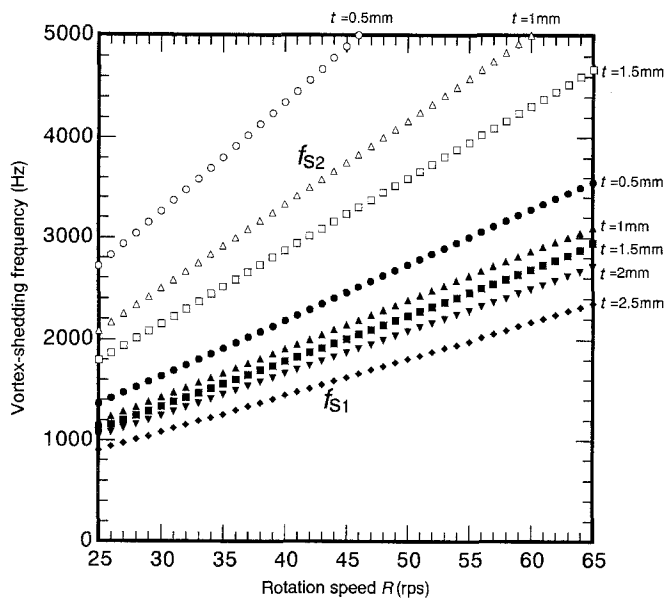


Fig. 6. Relation between the rotation speed and vortex-shedding frequency of uniform-thickness circular saws

The sound pressure level spectra radiated from undamped 0.5-mm circular saws shown in Fig. 8(1) were identical with those radiated from the damped one shown in Fig. 5(1). It means that the self-excited vibration of the 0.5-mm circular saw was not induced. Figure 8(6) demonstrates one of the spectra for the circular saw with step thickness, with the sharp peak not seen in the spectra. Therefore all spectra of the circular saw with step thickness were identical to those of the 0.5-mm circular saw.

Figure 9 shows the relations between the rotation speed and the overall sound pressure levels radiated from the circular saws. The thin lines show the sound pressure levels radiated from the damped circular saws, and the thick lines indicate the sound pressure levels radiated from the undamped circular saws. The overall sound pressure levels radiated from the damped 0.5-mm circular saw were in a good agreement with that of the undamped 0.5-mm circular saw, as shown in Fig. 9(1).

With the increase in thickness from 1.0mm to 2.5mm, the difference between the overall sound pressure levels radiated from the damped and undamped circular saws, shown in Fig. 9(2)–(5), were increased. For the 1.5-, 2.0-, and 2.5-mm circular saws, shown in Fig. 9(3)–(5), many large, sharp peaks are generated compared with those from the damped circular saws. The whistling noise was generated by the forward-traveling waves and the backward-traveling waves with n th nodal diameter vibration mode in the experimental rotation speed range. With the 2.5-mm circular saw the difference between aerodynamic sound pressure level and the whistling noise level was 15 dB, reaching 101 dB at 55 rps, as seen in Fig. 9(5).

Figure 9(6) shows the relations between the rotation speed and the overall sound pressure levels of the circular

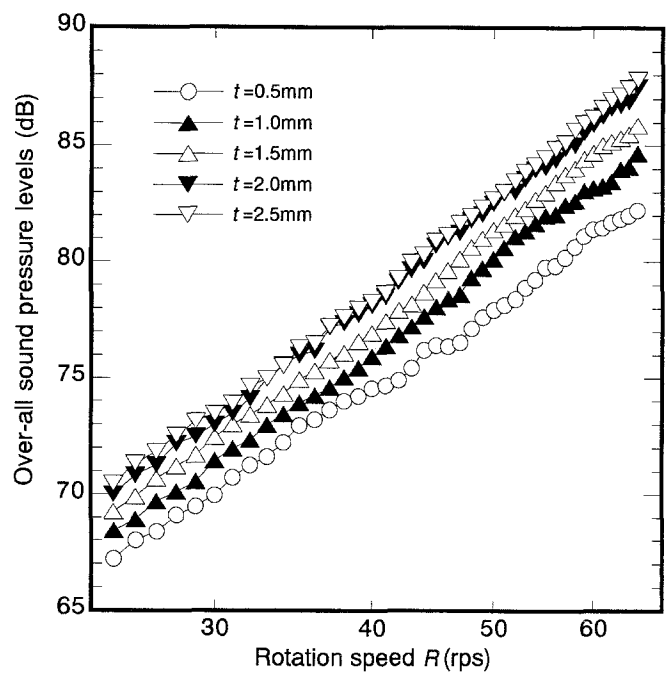


Fig. 7. Relations between the rotation speed and the overall sound pressure levels radiated from damped circular saws. Circles, $t = 0.5$ mm; filled triangles, $t = 1.0$ mm; open triangles, $t = 1.5$ mm; filled inverted triangles, $t = 2.0$ mm; open inverted triangles, $t = 2.5$ mm

saw with step thickness. No large, sharp peak was generated, as with the undamped 0.5-mm circular saw.

Self-excited vibration caused by aerodynamic force

Figure 10 shows the relations between the displacement spectra of circular saws and rotation speed. The higher peaks occurred in the displacement spectra of the 1.5-, 2.0-, and 2.5-mm circular saws but was not observed in the spectra of the 0.5-mm circular saw. The lower peaks were rarely observed in the spectra of the 1.0-mm circular saw, which means that the resonance needs sufficient energy from aerodynamic power to be excited.

The aerodynamic power increased with the increase in saw-tooth thickness. When the aerodynamic power was increased, the saw blade generated self-excited vibration – the whistling noise from the circular saw blade. Self-excited vibrations did not occur with all the circular saws with step thickness.

Conclusions

The dynamic characteristics, natural frequencies, aerodynamic noise, whistling noise, and self-excited vibration during idling were compared for the common circular saw and a circular saw with step thickness. The natural frequencies of the circular saw with step thickness increased with the increase in thickness and radius of the thick part. The

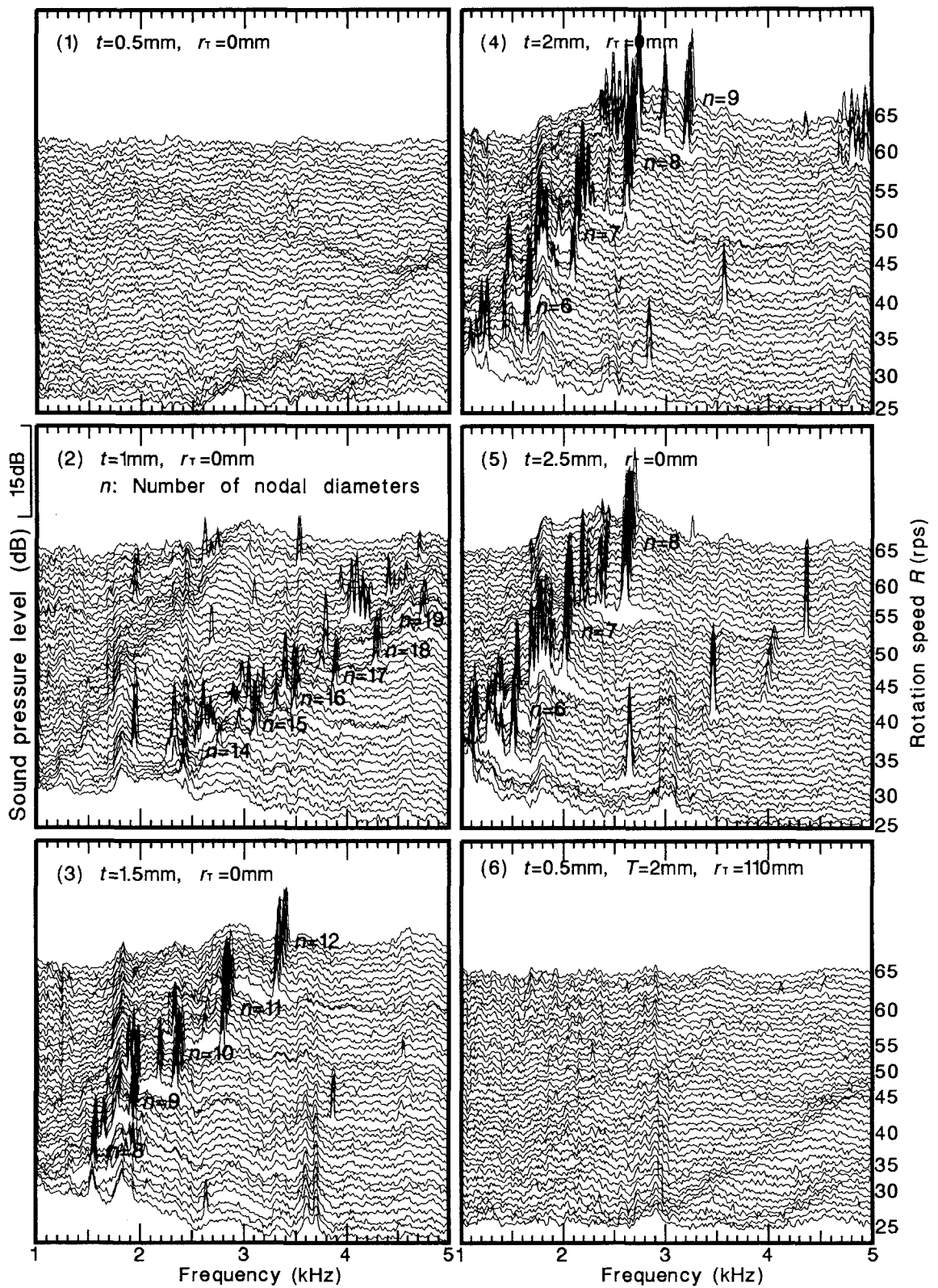


Fig. 8. Sound pressure level spectra radiated from undamped circular saws with increase rotation speeds. Numbers in (2), (3), (4), and (5) indicate the number of nodal diameters

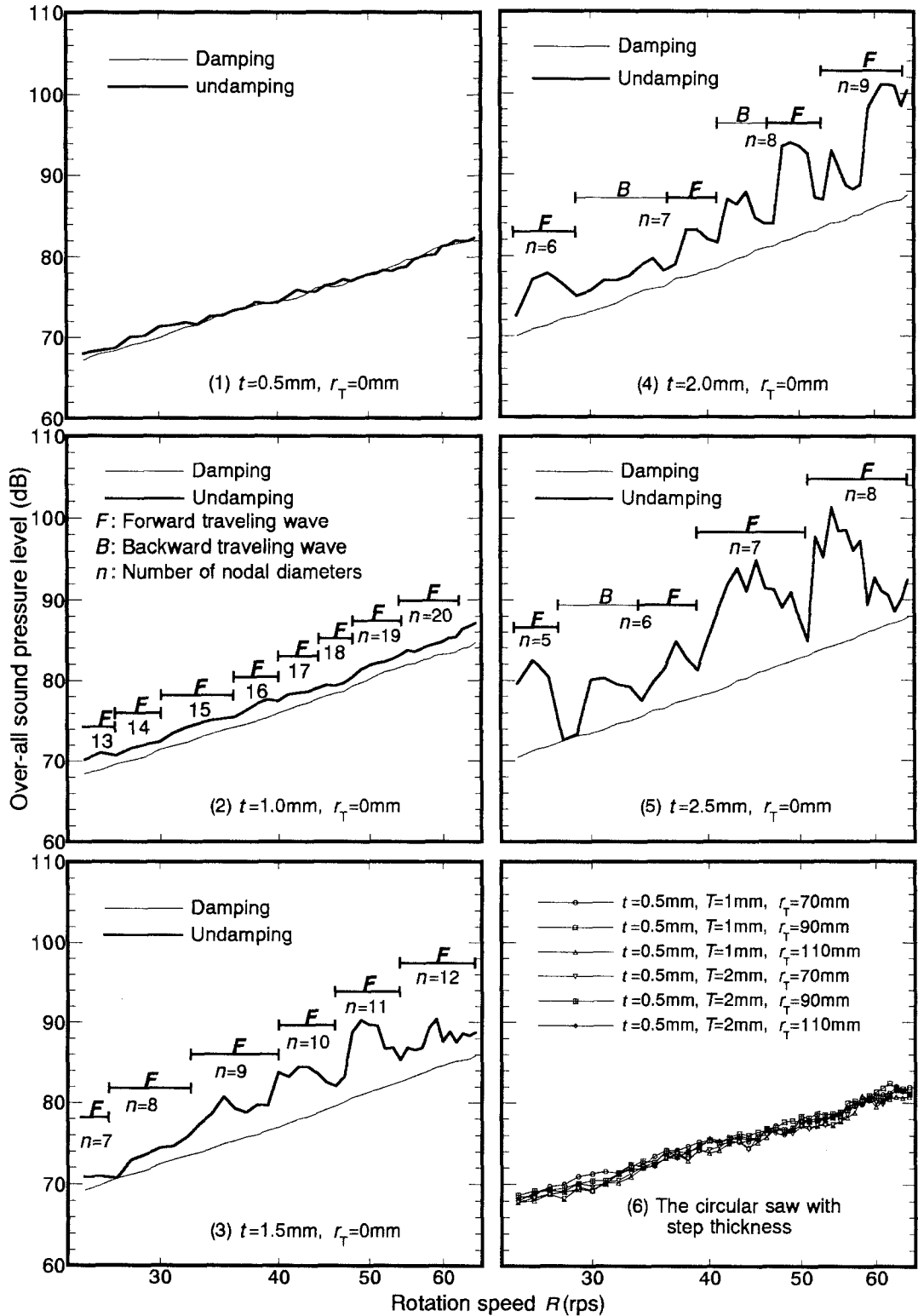


Fig. 9. Relations between the rotation speed and the overall sound pressure levels radiated from the circular saws. *Fine* curves, damping; *heavy* curves, undamping; *F*, forward-traveling wave; *B*, backward-traveling wave; *n*, number of nodal diameters

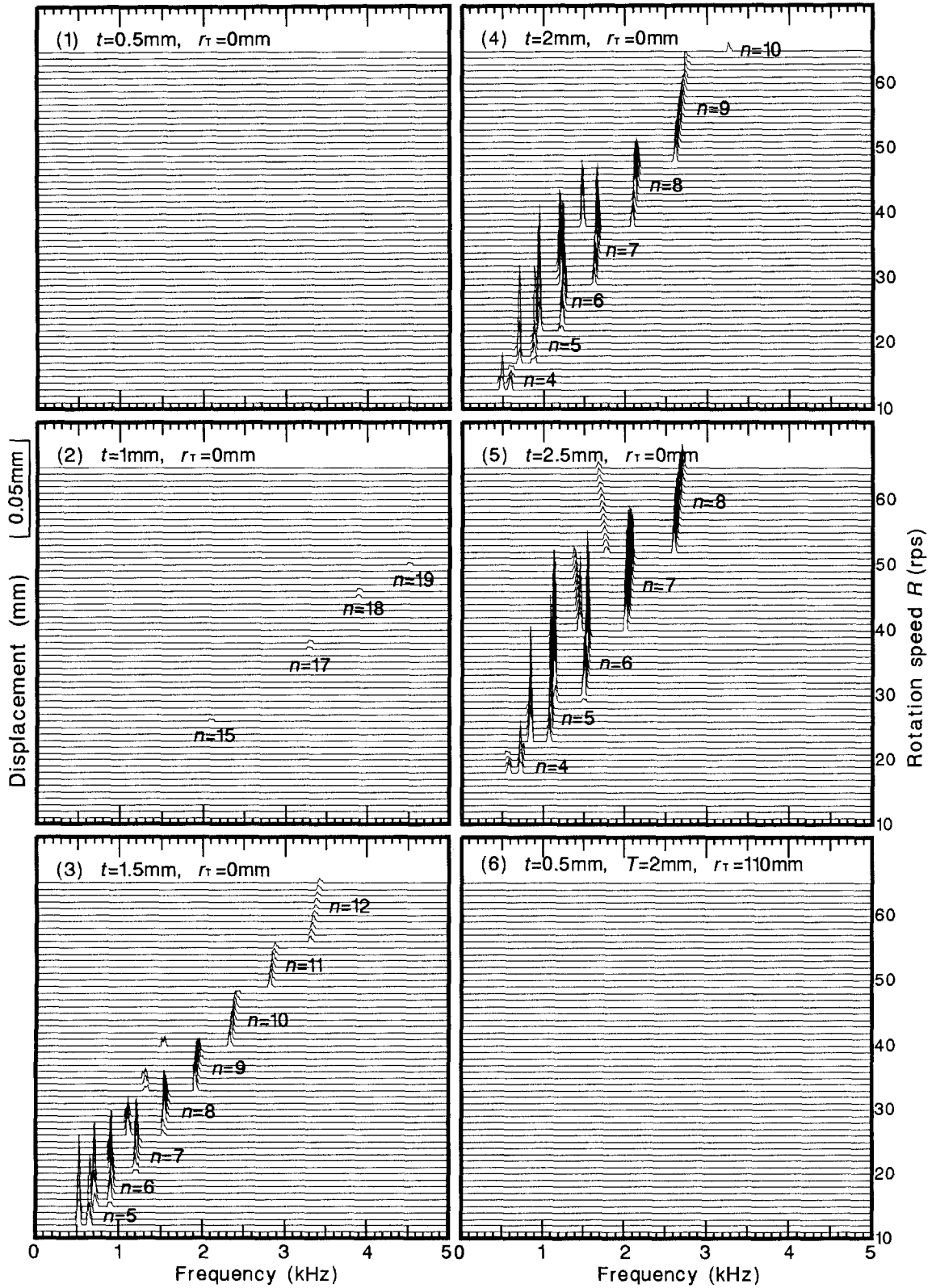


Fig. 10. Relations between the rotation speed and the displacement spectra of circular saws

circular saws with step thickness, which were thick at the inner part, were higher than that of the thin circular saw with a uniform thickness of 0.5 mm. The aerodynamic sound pressure level induced from circular saw teeth increased

with an increase in the tooth thickness. The whistling noise and the self-excited vibration easily occurred in the thick-thickness circular saws (1.5, 2.0, and 2.5 mm). The whistling sound pressure level and the vibration amplitude increased

with an increase in the thickness of the saw blade. None of the circular saws with step thickness generated the whistling noises or self-excited vibration during idling.

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