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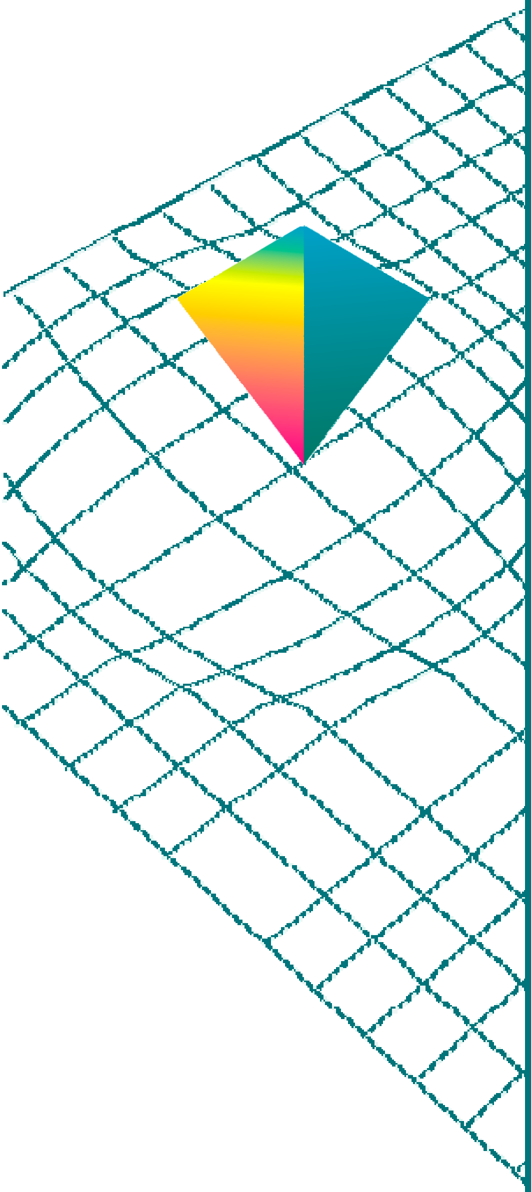

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50. Internationales Wissenschaftliches Kolloquium
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Active Timber Machining: From Theory to Reality

Abstract

This paper presents a novel approach for improving the quality of timber surfaces, produced by a rotary machining process. The approach is based on a real-time adjustment of the cutting tool tip trajectory. A specially designed spindle unit controlled by piezoelectric actuators is used to control the tool tip trajectory. The focus of the work is on reducing the timber surface waviness, inherent to the rotary-machined surface.

INTRODUCTION

The rotary machining process is used throughout the woodworking industry. This process is similar to milling of metals in up-cutting mode. The rotary machining principle is shown in figure 1. Timber is advanced towards a rotating cutterhead, and material is removed by knives (cutters), which are clamped in the cutterhead. When viewed closely, the machined surface appears as a series of waves called cuttermarks. The length of the cuttermarks is considered as a primary surface quality parameter. A good quality surface should have cuttermark length typically lower than 1.5 mm, and surface waviness should follow a uniform pattern [1].

The cuttermarks are generally accepted as unavoidable. Many applications for machined timber are such that the surface waviness is not an issue (e.g. surfaces that are intended for low-grade work or where the surface is coated or hidden by other materials). However, there are

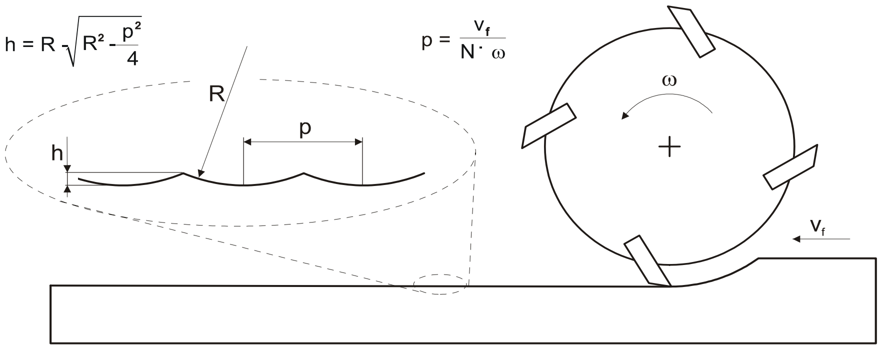

Fig. 1 Rotary machining process

applications, notably furniture, where solid wood is a feature of construction that will be observed and that must be of the highest quality. This is because the human eye is very good on perception of regular patterns such as surface waviness or waviness defects that appear on the surface in regular intervals. Thus, it is desirable to produce a surface that appears ‘wave free’ to the human eye.

The mechanical engineering nature of the rotary machining process relies on large diameter (~300 mm) cutterheads to achieve reduced surface waviness height for higher quality surfaces (wave pitch p ~ 1.25 mm) as indicated by the equation in figure 1. An extensive analysis is reported in [1]. The cutters are also trued to a common cutting point by a process called *jointing*. This allows all cutters to produce a surface wave provided the feed velocity of the timber is increased in accordance with the number of cutters in the cutterhead. The end result is high production speeds (~200 m/min for 20 cutters in a cutterhead). This approach results in large and expensive cutterheads that also require large and expensive planing and moulding machines. The jointing process also destroys the sharpness of the cutting edge and results in increased rubbing of the cutter on the timber, increasing power consumption and reducing surface texture quality. There are also issues with interfering vibrations from adjacent cutterheads and drive systems reducing the machined surface quality. The concept reported in [2,3] simulates an alternative *mechatronic* way of achieving high quality timber surfaces with small cutterheads and reduced number of cutters. The principle is one of surface waviness measurement *in-process* and active vibration of the cutter through the cutting loci to dramatically reduce surface waviness height, and also modify the cutterhead orbit to bring all cutters to a common cutting point without jointing. Such a solution would also compensate for any interfering vibrations thus resulting in enhanced machined surface quality as well as increased ease of machine operation. The impact on machines and tooling will be dramatic, allowing small low cost machinery to produce high quality work at high speeds without long set up times.

This paper describes the experimental work focused on the wood surface form improvement by a real-time adjustment of the tool tip trajectory. The work reports on the feasibility of modifying each surface wave normal to the surface i.e. in the height direction (Fig. 1). The experiments have been performed with a specially designed spindle unit equipped with piezoelectric actuators that provide the tool tip trajectory adjustment. Experimental results are presented for this surface waviness reduction method previously reported on a theoretical and simulation level in [2,3].

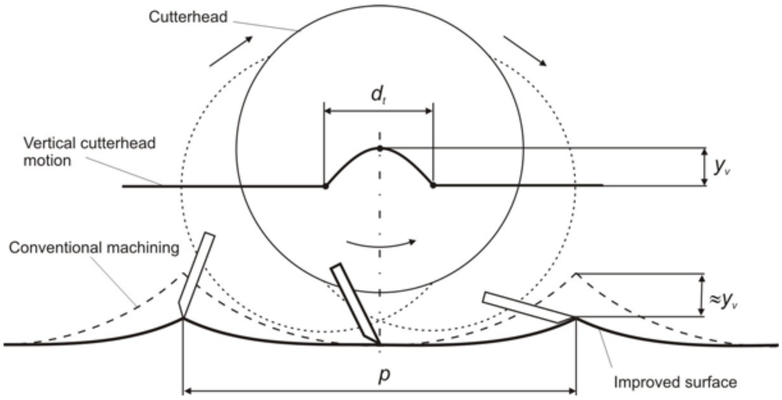

Fig.2 Principle of the waviness reduction approach

IMPROVING WOOD SURFACE QUALITY

The vertical cutterhead movement required to achieve an effective waviness height reduction should have a frequency in the range from 4 kHz to 80 kHz [2,3]. The vertical movement amplitude must be comparable with the surface waviness height i.e. in the range from 1 to 10 µm. Both of these parameters will depend on the actual machining conditions. The vertical cutterhead movement for waviness reduction can be implemented as a pulse train with the pulse width equal to the cuttermark formation time window and the pulse magnitude equal to the desired waviness reduction (i.e. 10-20 µm considering typical waviness height). The general approach is shown in figure 2. The conventional rotary machining of timber is characterized by a high cutting speed, typically within the range 20-100 m/s. Implementing the waviness reduction for the typical cutting speed, would require an extremely narrow pulse. For example, a surface with cuttermark length 1 mm machined with cutting speed 40 m/s would require the pulse width 25 µs to reduce the surface waviness.

EXPERIMENTAL FACILITY

The idea of a hybrid spindle system based on rolling element bearings with piezo-electric actuator small displacement compensation has been examined [2,3]. Piezoelectric devices are deployed radially against the spindle bearing supports to provide the high frequencies needed for vertical cutterhead movement. The principle of a simple lightweight spindle system arrangement and the piezoelectric actuators is shown in figure 3. The cutterhead mass is intentionally quite small (2 kg) but realistic for narrow width (50 mm) machining applications (mouldings). Figure 3 shows the arrangement of sensors, piezo actuators, bearing support and spindle/bearings.

The test rig shown in figure 4 is essentially a small-scale planer. It consists of a base frame on which feed table and spindle assembly are mounted. The spindle unit can be moved vertically in order to control the depth of cut. The feed movement is provided by the feed table. It features a preloaded ball screw and high precision linear guides to ensure consistent cutting conditions.

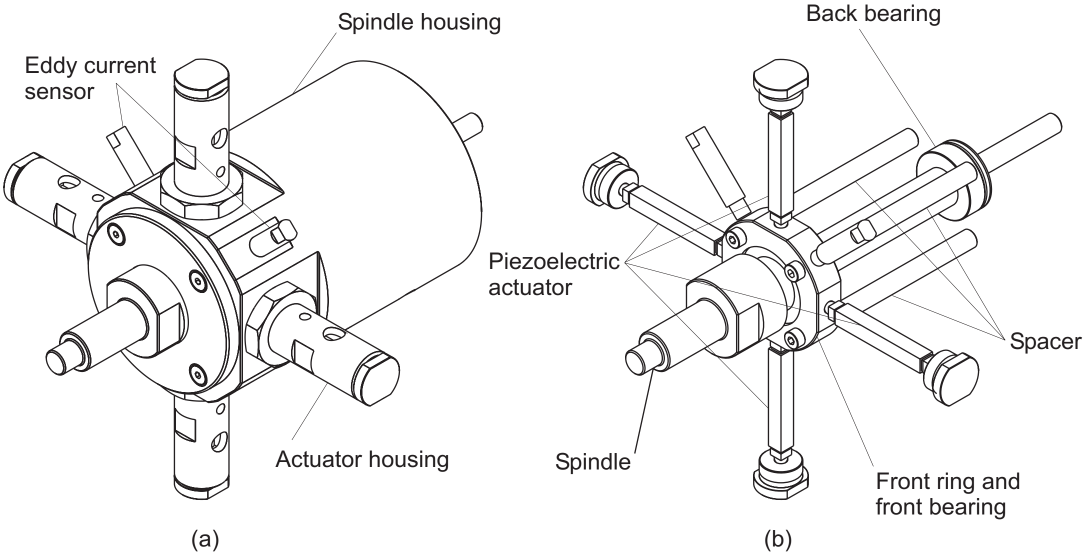

Fig. 3 Spindle unit

The main part of the test rig is the spindle unit. The spindle is supported by two bearings. The cutterhead is located on the overhung end of the spindle (Fig. 4). The cutterhead consists of an aluminium holder and two carbide knives. The control of the tool tip trajectory is achieved by controlling the displacement of the front bearing. This design arrangement was chosen mainly for its simplicity. Only one bearing is controlled thus fewer actuator are required. This arrangement introduces cutterhead and knife tilt that affects the machined surface. However, relatively large bearing span (i.e. 90 mm) in combination with a narrow knife (i.e. 14 mm) minimises the effect of the cutterhead tilt.

Piezoelectric stack type actuators have been selected to control the movement of the front bearing, because they are able to provide high force, fast response and a controllable displacement in micrometer range. The piezoelectric actuators are able to act only in one direction, because they are very susceptible to tensile stress. If there is a possibility of tensile forces acting on the actuator, special care must be taken to protect the piezoelectric stack itself from tensile stress in order to avoid actuator damage. Therefore, two opposing actuators for each axis have been chosen in order to achieve a “push-pull” operation. This approach was also adopted by other researchers [8], [9]. Two actuators would be sufficient to generate the movement in the vertical direction. However, there are disturbances in the machining process that are omni-directional, such as unbalance forces for example. Thus four actuators, arranged in the 'push–pull' configuration, are used in order to control the movement of the spindle.

The spindle is supported by two precision angular contact ball bearings arranged in a face-to-face configuration. The back bearing is fitted in the spindle unit housing. The front bearing is fitted in the front ring, which is retained in the axial direction by four spacers as shown in figure 3. The bearings are preloaded by a pair of disc springs to eliminate any axial play of the spindle. The spacers and the front ring provide a flexible support for the front bearing. The stiffness of the support, without actuators, is low (approx 2 N/µm) in the radial direction, which is desirable, because the actuator then needs to exert less force to move the spindle. This is also the reason for choosing the face-to-face bearing configuration as this arrangement has generally lower stiffness than back-to-back configuration. The four piezoelectric actuators provide the main support for the front bearing in radial direction. Applying appropriate voltage levels to the piezoelectric actuators controls the movement of the spindle in the plane perpendicular to the rotation axis of the spindle. The actuators are capable of moving the spindle by ±17 µm.

The test rig has been instrumented with appropriate sensors, signal conditioning circuits, driving amplifiers and control computer in order to implement the controlled cutterhead movement. All key components of the instrumentation along with the signal flow between the test rig and the

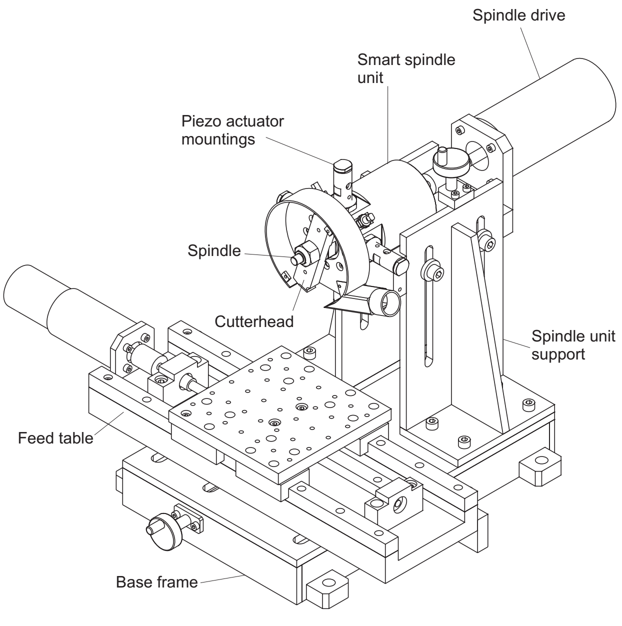

Fig. 4 Test rig

control computer (PC) are via a multifunction I/O card. The displacement of the spindle in the plane perpendicular to the spindle axis is measured by two non-contact eddy current sensors. The spindle unit was also equipped with an incremental encoder in order to measure the angular position of the cutterhead so that the vertical cutterhead movement can be synchronized with the knife positions. The voltage to the piezoelectric actuators is supplied by four high-voltage linear amplifiers, capable of supplying 150 V output voltage and 1.5 A peak output current. A standard PC (PentiumII/233Mhz) equipped with a multifunction IO card and running xPC real-time kernel has been used to control the piezoelectric actuators and to acquire readings from the sensors. In closed loop operation, a control algorithm adjusts the input voltage of the piezoelectric actuators according to the sensor readings in real time. The control computer also allows logging the sensor readings during tests, in order to evaluate the system performance. A sampling frequency 10 kHz was used for all tests.

INITIAL EXPERIMENTS

The capabilities of the spindle unit actuation system are limited with respect to the speed of the real industrial process. The minimum pulse width achievable on the test rig is approximately 650 μs. Therefore, the machining parameters (Table 1), used to experimentally verify the waviness reduction method, have been chosen so that the required pulse width meets the test rig capabilities. The spindle is equipped with a cutterhead that consists of an aluminium holder and two carbide tips. However, one of the two carbide tips has been ground back in order to achieve a single knife finish, which results in longer cuttermarks and thus allows using wider pulses for the waviness reduction. The position of the vertical pulse has to be synchronized with the cutterhead rotation so that, at the peak of the pulse, the knife tip is in the cuttermark centre. The cutterhead angular position, measured by the encoder attached to the spindle, was used to trigger the pulse. It should be pointed out that the movement outside the cuttermark formation window does not influence the resultant surface. Thus, it was possible to use the simple open loop system to generate the vertical pulses.

Parameter	Designation	Value	Unit
Spindle speed	ω	540	rpm
Feed speed	v_f	20	mm/sec

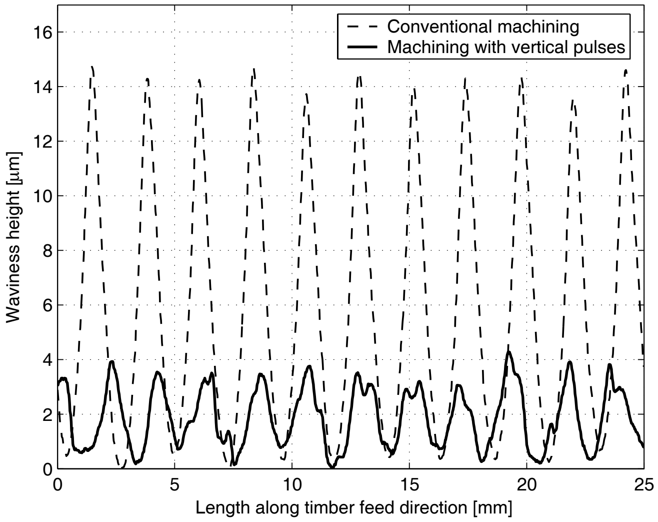

Fig. 5 Delrin surface trace

Cutterhead radius	*R*	60	mm
Number of knives	*N*	1	-

Table 1 Machining parameters

The samples used for the cutting experiments include a plastic sample and three wood samples. Only results for the plastic sample are reported here. The plastic (Delrin) was chosen because it shows the surface waviness produced by the cutting tool better than the wood samples, where the openness of the surface caused by the cellular nature of wood tends to make quantitative assessment of the surface waviness difficult.

The generation of the vertical pulses was switched off, during machining, for a part of the machined surface on each sample in order to obtain a reference surface for comparison and evaluation of the waviness reduction method. Surface traces were obtained for each sample surface using a stylus technique. The comparisons of the surface traces for a typical Delrin sample are shown in figure 5. An image of the Delrin sample under oblique light was taken in order to evaluate the visual quality of the machined surface (Fig. 6).

The effect of the waviness reduction method is clear from both figure 5 and figure 6. With compensation pulses applied the waviness height was reduced by 10 µm as can be seen from figure 5, which approximately corresponds to the magnitude of the vertical pulse and represents

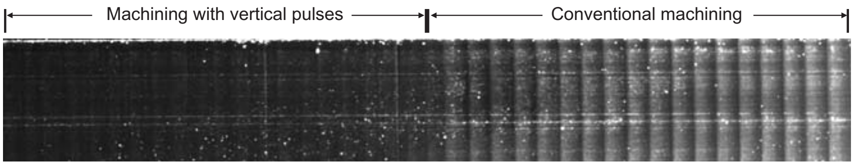

Fig. 6 Delrin surface image

waviness reduction of 70%. The surface images (Fig. 6) clearly show that the visual quality of the surface has improved dramatically. It should be pointed out that the cutting experiments were conducted at cutting speed of 3.4 m/s. This is lower than the typical speeds (~ 40 m/s) used in woodworking industry, because of the limitations of the spindle actuation system. Nevertheless, the experimental results clearly show that the waviness reduction method can effectively reduce the surface waviness.

CONCLUSION

This paper describes an experimental implementation of a new approach for improving rotary machining of timber. The approach is based on a real-time adjustment of the tool tip trajectory with the use of piezoelectric actuators. An experimental small-scale planer, used to conduct the cutting experiments is briefly described. A method of modifying the surface wave form to improve timber surface quality is explained and experimental results presented. The experimental results demonstrate the effectiveness of the new approach.

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