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Waves on wood

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Abstract: The rotary machining process as applied to timber is introduced and compared with the milling and grinding of metals. The emphasis of this work is on the waviness surface quality of the machined timber and initially focuses on a review of the techniques applied to improve surface quality at higher workpiece feed velocities—typically 120 m/min. The main work concentrates on mathematical and computer-based modelling of surface waviness defects generated by two classical woodworking machine engineering science phenomena, caused primarily by forced structural vibration. Surface assessment of machined timber is discussed, with results from contact and non-contact methods highlighted. The causes of surface waviness defects are presented and possible solutions are outlined.

Keywords: waviness, modelling, surface finish, vibration, wood

NOTATION

- \( a_{1/rev} \) interfering radial displacement every cutterhead revolution (mm)
- \( a_{1/rev_{crit}} \) value of \( a_{1/rev} \) where one cutter out of four ceases to finish (mm)
- \( a_{1/2rev} \) interfering radial displacement every two cutterhead revolutions (mm)
- \( a_{1/2rev_{crit}} \) value of \( a_{1/2rev} \) where wave pitch equals \( 2p \) (mm)
- \( h \) depth of cutter mark (mm)
- \( n \) cutterhead rotational velocity (r/min)
- \( N \) number of cutters producing a finishing surface wave
- \( p \) cutter wave pitch (mm)
- \( R \) cutterhead radius (mm)
- \( R_h \) wave height ratio
- \( R_w \) wave width ratio
- \( V \) workpiece feed velocity (m/min)
- \( W_n \) width of surface wave \( n \) (mm)

1 INTRODUCTION

Rotary planing and moulding of timber is a complex and subtle machining process that has much in common with milling and grinding of metals. These metal machining processes have been widely studied. A substantial historical record of research can be traced from the early 1940s to the present day. Typical references of relevance to this paper are noted [1–12]. In contrast to the vast amount of research and publication for metal machining, the rotary machining of timber has received little attention. There are, however, landmark publications that can be traced back over the last half century [13–30]. A brief introduction to the wood machining process is now given to enable the reader to assimilate sufficient knowledge for the detailed technical material in the body of the paper.

2 ROTARY MACHINING OF TIMBER

The timber raw material for this process is normally in the form of rough sawn pieces that are of constant nominal rectangular cross-section along the length. End-section dimensions typically range from 10 to 100 mm thick and from 20 to 300 mm wide. These workpieces can be of any length between 250 mm and 6 m, the longer lengths usually being processed at higher feed speeds, typically 120 m/min. The output of the process is machined timber lengths of constant cross-section. These are classified as ‘planed’ sections in the case where rotating cutter heads containing straight cutters are employed on all four faces, and ‘profiled’ sections (Fig. 1) (known as ‘mouldings’) where one or more surfaces of the section are produced by rotating cutterheads containing suitably shaped cutters. A selection of cutterheads is shown in Fig. 2. The term ‘mouldings’ is...
somewhat misleading but is widely used. No actual material deformation takes place as such; i.e. this is a material removal and not a material forming process.

Planing and moulding machines (Fig. 3) comprise a number of horizontal and vertical cutterheads configured in position and type (Fig. 4) to suit a particular market segment (e.g. saw milling, joinery, furniture). In all cases, the material removal process is similar to that of up-milling, where a cutterhead containing typically two or more cutting edges is used to sever timber chips from the advancing workpiece (Fig. 5).

Rotary machining of timber is characterized by high cutting tool tip velocities which are typically within the range 30–125 m/s with correspondingly high workpiece feed speeds ranging from 5 to 120 m/min. The material removal rate in this wood machining process is typically $5 \times 10^{-4} - 0.5 \text{ m}^3/\text{min}$ with power requirements per cutting head of 5–20 kW. Cutting forces are highly impulsive owing to the nature of the cutter heads used [21].

The noise emission from unenclosed machines operating with cutting tip velocities of 125 m/s is typically 127 dB(A) at 1 m from the machine. The noise spectra of these machines contain pronounced pure tones at the blade passing frequency in the region of 125–500 Hz at the fundamental and at the first, second and third harmonics. These types of machine present a challenging noise control problem, particularly when coupled with the need for low cost of purchase and ease and safety of operation.

The unique nature of woodworking machinery is such that it is often overlooked in terms of the 'more
Fig. 3  Planing and moulding machine

Fig. 4  Cutterhead configuration

Fig. 5  Rotary machining process
glamorous’ metal machining sector, particularly in terms of research funding. There have been no major research contracts awarded for the woodworking machine sector. Often, the industry is assumed to have similar needs to the metal working sector and hence to benefit directly from research in the latter.

Some of this is true—the advances in computer control and automatic tooling change systems have found their way into niche markets of the wood processing industry routers and moulders, for example. However, the fundamentals of the high-speed wood machining process have never been studied adequately. Research effort applied now would be especially timely in light of improvements in sensors, data logging and high-speed video systems. This would provide a firmer basis for future product development.

3 SURFACE QUALITY

The quality of the machined timber surface is characterized by two features:

(a) surface roughness,
(b) surface waviness.

Clearly, there is a third quality parameter—the geometric accuracy of the sections produced. This is not investigated here. Tolerances for this are generally between \( \pm (0.5\pm0.1) \text{mm} \), depending on the end-usage of the machined timber. **Surface roughness** is described as texture effects due to the timber structure, which is cellular by nature, and the effects produced by cutting the timber with a sharp knife edge.

**Surface waviness** is defined as the longer-wavelength components produced by the rotary machining process, including any deviations from the ideal waviness profile (Fig. 6). The roughness and waviness quality of a timber surface is influenced by the following key factors [21]:

(a) type and condition of the timber workpiece,
(b) type and condition of the cutter equipment used,
(c) machine configuration,
(d) method of machine operation,
(e) engineering quality of the machine.

Surface roughness quality is primarily influenced by workpiece properties, choice of cutting tools, velocity of the cutting edge relative to the workpiece and the average chip thickness [15, 16]. In contrast, while the surface waviness quality is influenced by the workpiece properties and choice of tooling, it is primarily determined by the type of planing and moulding machine, its operation and, most importantly, the engineering quality of the machine. Advice is readily available for selecting the appropriate cutting tool equipment for the type and condition of the timber to suit the required roughness quality. Advice is also available for the configuration and operation of machines to achieve a given waviness quality in accordance with equation (1).

While there is information widely available for machine settings, there is no documented knowledge that explains the influence of planing machine quality on timber surface waviness quality. Many applications for machined timber are such that the waviness features of the product will not be an issue (e.g. surfaces that are intended for low-grade work or where the surface will be coated or hidden by other materials). There are other applications, notably furniture, where solid wood or high-quality, medium-density fibreboard (MDF) is a feature of the construction that will be observed and that must be of the highest quality. While these surfaces may be sanded to remove surface waviness features, this is a costly operation and can lead to a reduction in the geometric quality of profiled sections of timber. Therefore, timber sections that can be produced at high speed and at high quality directly from the planing and moulding machine are an essential requirement.

4 SURFACE WAVINESS

The surface waviness of the machined timber is characterized by a regular series of waves that are perpendicular to the workpiece feed direction. These waves (sometimes called ‘cusps’), caused by the rotary machining process, are primarily dependent on workpiece feed speed, cutterhead rotational speed and the number of finishing cutting edges in the cutterhead. This relationship is well established and widely used, and is shown by the equation

\[
p = \frac{V}{Nn}
\]

where

\( p \) = surface wave pitch (mm)

\( V \) = workpiece feed velocity (mm/min)

\( N \) = number of cutting edges

\( n \) = angular velocity of the cutter head (r/min)
While the underlying kinematics of the rotary machining process is a curvate trochoid, for simplicity, the resulting surface waves, which are essentially circular in form, may be visualized in an idealized way by a series of intersecting circular arcs (Fig. 7). The wave pitch increases with feed speed, producing a corresponding increase in wave height and hence a reduction in the visual and tactile quality of the timber surface. A good-quality surface is classified by a wave pitch of typically <1.5 mm, and a lower-quality surface by a wave pitch of typically >2.5 mm. The wave height of the idealized surface is described by the following equation and is typically 2 µm for the higher-quality surfaces:

\[ h = R - \sqrt{R^2 - \frac{p^2}{4}} \]  

(2)

where

- \( h \) = wave height (mm)
- \( R \) = cutter tracking radius (mm)

This, again, is a well-established relationship [14]. Table 1 shows theoretical wave heights for wave widths produced by a cutting radius of 63 mm.

Typical wave widths and corresponding wave heights are shown for three market sectors. There is a clear technological challenge to achieve a high-quality wave pitch consistently in both the joinery and furniture industry given the very small wave heights involved.

The need to assess the uniformity of the surface waviness can be addressed by measuring the width of a sample of waves and calculating the wave width variation ratio, \( R_w \), as defined by

\[ R_w = \frac{W_{min}}{W_{max}} \]  

(3a)

where

- \( W_{min} \) = minimum wave width (mm)
- \( W_{max} \) = maximum wave width (mm)

While a corresponding height variation ratio may be calculated from the following equation:

\[ R_h = \frac{h_{min}}{h_{max}} \]  

(3b)

where

- \( h_{min} \) = minimum wave height (mm)
- \( h_{max} \) = maximum wave height (mm)

It is easier to work with wave widths for timber surfaces, primarily because wave width variation can be measured using vernier calipers (the practical resolution of the operator and instrument is 0.1 mm) more easily than can wave height variation (the instrument must be better than 1 µm resolution). A secondary factor is that the timber processing industry already uses wave width variation as a measure of surface quality.

5 TECHNIQUES FOR GENERATING A HIGH-QUALITY SURFACE FINISH

Two widely used techniques for generating a good-quality surface finish directly from the rotary machining process are now presented and discussed. A third new approach is also presented.

5.1 Single-knife finish

The waviness quality of a machined surface is subject to many different types of ‘defect’. The small values of surface wave height make the waviness quality highly sensitive to displacements between cutting edges and workpiece normal to the machined surface. In this respect, the timber machining process is very similar to the precision grinding of metals [6–10]. For wood machining, a condition known as ‘single-knife finish’ exists, where the surface wave pitch is determined by the cutter with the largest radius in the cutterhead. Consider a cutterhead containing two cutters ground to within 0.025 mm radius of each other, located on a good-quality machine spindle rotating at 6000 r/min with a timber feed speed of 12 m/min. This will produce surface waves of 2 mm pitch on the timber surface, corresponding to \( N = 1 \) in equation (1). This results from the problem of setting and grinding cutter radii to a very high level of precision.
Setting cutters using typical tool room equipment can result in a total indicated run-out (TIR) from the maximum radius cutter to the minimum radius cutter of typically 50 µm. Grinding the cutters in the cutterhead will result in improved TIR values in the range 5–10 µm. The ‘high-quality’ TIR is preserved between the grinding machine and the planing machine by employing high-precision spindles on both machines, coupled with ‘Hydrogrip’ tooling cutterheads. These heads are designed so that the bore of the cutterhead is elastically collapsed under hydrostatic pressure in order to remove clearances and improve the interface stiffness between the cutterhead and the spindle. Even when small (5 µm) TIR values are achieved on a two-knife cutterhead on the planing machine, the cutter that has the smaller cutting radius will remove timber chips from the bulk of the material but not produce a surface wave. Total indicated run-out values of less than 1 µm are required in order to achieve a satisfactory two-knife finish, and this is currently not technically possible at an economic price. This two-knife cutterhead is in fact the worst case.

This phenomenon also applies to three-, four-, six-, eight-, ten- and 20-knife cutterheads, but, as the number of cutting edges increases, more cutters will produce a surface wave, albeit at irregular pitch and wave height [21]. The widely used four- and six-knife cutterheads result in a single-knife finish (Table 1) even with these high-quality cutter tracking conditions. The single-knife finish phenomenon restricts the range of feed speeds for softwood timber processing, counter to the economics of timber processing which dictates that higher feed speeds must be used in order to provide reasonable payback of capital plant on a relatively low added value workpiece.

Figure 8 shows the range of wave pitches and feed speeds possible with a single-knife finish approach. The current technology limit is 15 000 r/min. Higher speeds are also shown to identify future trends and possibilities. While the single-knife finish approach limits absolute top feed velocity, the absence of jointing equipment (see Section 5.2) and the use of smaller-diameter tooling provides quick set-up and reduced job changeover times and tool servicing costs.

5.2 Multiknife finish

A process known as ‘jointing’ is applied to the rotating cutterhead in order to reduce all the cutting edges to the same cutting radius. This process is similar to the dressing of a grinding wheel at the operating speed in order to true the wheel at the cutting point. The result of the jointing process is usually that all of the cutting edges will now produce a surface wave on the timber, provided that the feed speed is correspondingly increased to place the wave pitch in the region of 1.5–2.5 mm. This ‘multiknife finish’ technique increases the timber feed speed and allows the machinery to be operated economically on certain types of work such as saw milling.

The action of jointing produces a ‘land’ on the cutting edge, thus removing any back clearance angle on the cutter (Fig. 9). In order to ensure that all cutting edges are dressed to a common cutting radius, the jointing stone must touch each cutter. It follows that, if there is a difference in radius of the individual cutters owing to setting or grinding, there will be increased amounts of material removed from those cutters with larger radius values. These cutters exhibit correspondingly larger land widths. The cutter tracking errors (typically 75 µm) within the cutterhead in early types of equipment led to unacceptable differences in joint land width between cutters, causing significant cutting force variation and correspondingly poor roughness and waviness quality.

Research and development work carried out during the early 1980s by leading woodworking machinery and tooling manufacturers concentrated on developing cutter equipment and tool grinders. These relatively
high-precision products aimed to grind cutting edges to within 5–10 µm and transfer this quality to the planing machine by means of Hydrogrip tooling (previously described in Section 5.1). Thus, the concentricity between grinder and planing machine spindle was sufficiently preserved to reduce the size of the jointed land and, more importantly, the variation in land width between adjacent cutters to an acceptable level [21]. The results of this work are embodied in all types of high-quality tools and machines now available on the market.

Figure 10 shows the range of feed speeds that are possible with multiknife finish techniques (the legend indicates revolutions per minute × number of finishing cutters). The greater the number of finishing cutters employed, the greater the size of the cutterhead. This introduces the need to reduce spindle speeds to 4500 r/min for more than ten knives to preserve cutterhead safety factors (based on hoop and radial stress bursting criteria). The larger cutterheads are more difficult to handle manually, more difficult to service (clean, sharpen) and introduce extended machine set-up times and associated costs. Accordingly, these techniques are used only where longer production runs are required (~days). The surfaces produced are of medium to high quality, but will from time to time contain waviness defect types, one of which is described in Section 7.2 of this paper.

5.3 Cutterhead oscillation

An idea first postulated by Jackson [21] and investigated at research level by Brown [29] is to oscillate the cutterhead in the horizontal plane by an amplitude that is of the order of one wave pitch p at a frequency of the finishing cutter period (Fig. 11). This corresponds to peak-to-peak amplitudes of 1 mm at 100 Hz for a 6000 r/min cutterhead working in single-knife finish mode. This approach has been simulated and proven out for the basic kinematics on a test rig and promises a 75 per cent reduction in wave height. This mechatronic approach provides a virtual cutterhead radius that can be far greater than the actual cutterhead radius (typically ×4). It also allows a two-knife cutterhead to perform at extended feed speeds while producing a surface waveform far superior to a 20-knife cutterhead, for example (Fig. 11). This system has yet to be applied to the rotary machining process to investigate the true effect on a machined surface. Clearly, the implications for machine and tooling design are exciting and substantial.

6 STRUCTURAL VIBRATION

Multispindle planing and moulding machines are a formidable vibration control problem. The sensitive nature of the surface waviness geometry means that displacement amplitudes between the tool edge and the workpiece normal to the machined surface as small as 0.5 µm can produce an observable surface defect. The vibration quality therefore needs to be similar to that
of grinding machine tools. There are a multitude of interfering vibrations of various frequencies and amplitudes from the multiple vibration sources such as drive motors and spindle assemblies on these types of machine [21]. The mode of excitation is primarily one of forced vibration usually influenced by the spindle and drive motor operating speeds, the degree of tooling and drive motor imbalance, together with the presence of shaft whirling, and structural resonances can significantly amplify structural displacements. The rotational speeds of each spindle/cutterhead unit can be slightly different, for example, because of differing cutting loads. In this case the forced vibrations interact to form a beat modulation frequency of a few hertz which can be transferred to the timber surface in the form of a modulated wave pattern which is classed as a ‘defect’.

In the search for improved surface finish at higher feed speeds, the single-knife finish technique has been extended into the regime of 15 000 r/min for spindle rotational speeds with tooling assemblies of typically 7 kg on a cantilevered spindle arrangement. This approach, which produces a smooth texture at advanced feed velocities, can generate a serious vibration control problem, significantly reducing the service life of the rolling element spindle bearings, if not controlled.

Structural vibration is one of the major causes of machine-induced waviness defects and as such is an indicator of the machine structural quality. A good machine structure is more tolerant of operator shortcomings and will outperform sensitive machinery. Appearances can be deceptive, however. In the authors’ experience, larger machinery does not always guarantee high-quality performance and can often conceal structural weaknesses. On the other hand, a machine that is of lighter construction but thoroughly investigated and corrected for unwanted vibration can produce excellent results.

Variations in waviness quality can occur for both single-knife finish and multiknife finish operating conditions. There are differences in the mechanism of defect generation, and structural vibration is one of the factors for consideration.

7 MODELLING OF SURFACE DEFECTS

The theoretical surface of the machined timber can be modelled as described in references [18] to [21] by superimposing adjacent circles in a plane representing the depth and length of the classic surface. The intersections of these overlapping circles may be defined theoretically and computed with suitable algorithms to form a sequence of intersecting arcs. A number of different types of surface waviness defect have been observed in practice, and these may be modelled using the theory developed in reference [21]. The basic principle of the theory is one of providing displacements of the adjacent circles in the plane normal to the surface as shown in Fig. 12. The circles displaced depend on the type of defect modelling scenario (the general case is shown in a sequence of intersecting arcs. A number of different types of surface waviness defect have been observed in practice, and these may be modelled using the theory developed in reference [21]. The basic principle of the theory is one of providing displacements of the adjacent circles in the plane normal to the surface as shown in Fig. 12. The circles displaced depend on the type of defect modelling scenario (the general case is shown in

![Fig. 11 Cutterhead oscillation](Image)

![Fig. 12 Defect modelling principle](Image)
Fig. 12). The displacement $a_{qrev}$, where $q$ represents the relationship between interfering displacement and the cutterhead rotation, may be increased, and the effect on wave width and height noted. Five different defect types are reported by Jackson [21], and many others are possible depending on the different mix of machine engineering quality and machine operating conditions. The need for a generalized model for surface defect simulation was identified. Recent work [25, 29] has established and refined such a model environment currently implemented via MATLAB™ [30].

Once modelled, the way in which the surface degenerates with increasing defect conditions may be investigated. This allows the sensitivity of the machine operating conditions to be established numerically. This approach allows engineers to assess the sensitivity of different machining conditions and to relate them to vibration measurements made on the machine for a better understanding of the defect production process.

The surface wave width change ratio given by equation (3) may be taken as the key parameter. The variation calculation and limit are defect condition dependent. Two typical cases are now examined.

### 7.1 Single-knife finish

This case is shown in Fig. 13. The theoretically perfect single-knife finish surface of wave pitch $p$ is disturbed by a vibration once every two revolutions of the cutterhead spindle, $a_{1/2rev}$. This condition is commonplace on machinery in the field and is one of the most difficult cases to alleviate. A typical example is when a 6000 $r/min$ (100 Hz) cutterhead spindle is driven from a 3000 $r/min$ (50 Hz) motor via a two- to one-speed step-up belt drive and pulley arrangement. The motor mechanical and electrical imbalance interacts to varying degrees with the machine structure, which can also have resonances within the range 25–65 Hz. This causes every other cut of the knife creating the single-knife finish to be pulled out of the workpiece by $a_{1/2rev}$. On the next rotation the same knife is pushed into the workpiece by an amount $a_{1/2rev}$. Variations in this condition occur, depending on the phase relationship between the knife rotational angle and the maximum or minimum point of the interfering vibration cycle. The greatest influence occurs when the knife and vibration crests coincide, as shown in Fig. 13. When the points of zero vibration coincide with the finishing knife, there is no surface defect condition. This phase alignment is not controlled on planing and moulding machines and explains why the surface finish waviness defect severity sometimes varies with each new tooling set-up. Current machinery does not use any phase-referenced condition to achieve this condition. It is doubtful if this could be maintained by a purely mechanical (i.e. passive) solution. Some form of active control may be possible, but current cost restrictions prevent this, although technology trends in vibration and signal processing are favourable.

The relationships for minimum and maximum wave widths of a theoretical surface derived from the model in Fig. 13 are given by

$$W_{\text{min}} = p - \frac{4a_{1/2rev}R}{p}$$  \hspace{1cm} (4a)

$$W_{\text{max}} = p + \frac{4a_{1/2rev}R}{p}$$  \hspace{1cm} (4b)

These equations are obtained by solving the simultaneous equations for circular arcs 1, 2 and 3 encompassing points A, B and C identified in Fig. 13.

As $a_{1/2rev}$ increases in value, the surface exhibits an increased light–heavy–light–heavy wave marking. As
The wave pitch is $2\pi$, giving an apparently perfect surface at first glance. This condition may be confirmed by noting machine operation parameters and using equation (1). Figure 14 shows the way in which this type of surface degenerates with increasing $a_{1/2\text{rev}}$. Two extremes of cutterhead and machine operation are shown. In Fig. 14 the notation $W_{\text{min}}(2,50)$ is for operating conditions such that a combination of spindle speed and feed speed will produce a wave pitch of 2 mm for a 50 mm radius cutterhead. The case of the 2 mm pitch surface achieved with a 50 mm cutterhead radius is considerably more tolerant to increased amplitudes of interfering vibration by comparison with the 1 mm wave pitch and 100 mm cutterhead radius case. This is to be expected from equations (4a) and (4b). The surface deterioration as measured in wave width terms is linear. The height deterioration is non-linear. The rate at which each type of surface deteriorates is given by the slope of the line in Fig. 14. The 1 mm ($R = 100\text{mm}$) surface degenerates at 4 times the rate of the 2 mm ($R = 50\text{mm}$) surface in accordance with the wave pitch and $R$ values. This does not appear overly sensitive. However, the value of $a_{1/2\text{rev\text{crit}}}$ can be taken as a measure of surface sensitivity to external vibration. Figure 15 shows how this changes with cutterhead radius and wave pitch. The $a_{1/2\text{rev\text{crit}}}$ value for a 2 mm wave is 4 times that of a 1 mm wave. Also shown are structural displacements of typical machinery measured at the cutterhead using non-contact capacitive displacement transducers (NCDTs). This is clear evidence of the problem definition for improved surfaces. A fine wave pitch of 1 mm produced by a

$$a_{1/2\text{rev\text{crit}}} = \frac{p^2}{4R}$$

(4c)
100 mm radius cutterhead is the most sensitive condition examined. In terms of \(a_{1/2\text{rev}}\), a 2 mm wave pitch produced by a 50 mm radius cutterhead is a factor of 8 less sensitive. This is also more than a factor of 2 above the largest measured structural vibration at \(n/2\).

Typical industrial operating conditions are such that a wave pitch of 1.5 mm can sometimes be achieved with a 'perfect' surface waveform. More usually, in the authors' experience, for \(p = 5\) mm, the ratio of minimum wave width to maximum wave width \(R_w [\text{equation (3)}]\) is generally 0.7. This is explained by considering Fig. 16 which shows how variation in \(R_w\) results from increases in \(a_{1/2\text{rev}}\) for both 50 and 100 mm radius cutterheads at \(p = 1.5\) mm wave pitch. It has been observed by instrumentation \[21\] that planing and moulding machines with 6000 r/min spindles exhibit run-outs at 50 Hz of typically 5 \(\mu\)m peak to peak (measured by NCDTs).

In Fig. 16, selecting \(a_{1/2\text{rev}} = 2.5\) \(\mu\)m and \(R = 50\) mm results in a value of \(R_w = 0.64\). A similar exercise on the dataset for \(p = 1.0\) mm and \(R = 50\) mm results in \(R_w = 0.33\), i.e. approximately twice the variation in wave width compared with \(p = 1.5\) mm. Clearly, for coarser wave pitch generation conditions, e.g. 2 mm, \(R = 50\) mm, the corresponding wave variation will be less (\(R_w = 0.78\)). These effects have been observed generally in practice. A summary is provided in Table 2. For larger diameter cutterheads the situation becomes less favourable. The case for \(R = 100\) mm and \(p = 1.0\) mm results in \(R_w = 0\), i.e. the half-knife finish condition occurs.

This type of 1/2rev defect is the main reason why fine surfaces such as furniture components are sanded to achieve the necessary surface quality—at the expense of profile quality and also manufacturing costs. The current approach to improving this 1/2rev condition is to pay attention to motor and drive pulley imbalance and to change the machine structure to avoid resonances in the 50 Hz region—not always possible, of course.

Table 2 \(R_w\) values for \(a_{1/2\text{rev}} = 0.0025\) mm

<table>
<thead>
<tr>
<th>(p) (mm)</th>
<th>(R = 50) mm</th>
<th>(R = 100) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.64</td>
<td>0.38</td>
</tr>
<tr>
<td>2.0</td>
<td>0.78</td>
<td>0.6</td>
</tr>
</tbody>
</table>

![Fig. 16 SKF surface deterioration](image_url)

7.2 Four-knife jointed finish

This case is shown in Fig. 17. The theoretically perfect four-knife finish surface of wave pitch \(p\) is disturbed by a vibration once every revolution of the cutterhead spindle. This occurs where the cutterhead is jointed to true up knife grinding inaccuracies but, for some reason, the cutterhead spindle frequency is still present in the cutter tracking path. There are several possible reasons for this. These will be the subject of a future paper.

From Fig. 17 it is clear that cutters 2 and 4 are not affected by the 1/rev vibration for this case, as defined. Cutter 1 is pulled out of the workpiece by a small amount \(a_{1/\text{rev}}\). Similarly, cutter 3 is pushed into the workpiece by an amount \(a_{1/\text{rev}}\). Variations in this condition occur, depending on the phase relationship between the knife rotational angle and the maximum or minimum point of the interfering vibration cycle. The greatest influence occurs when a knife coincides with a vibration crest—again, a condition that is not controlled on normal machines. As \(a_{1/\text{rev}}\) increases in value, the surface exhibits a light–unchanged–heavy–unchanged–light wave marking, as shown in Fig. 17.

The relationships for minimum and maximum wave widths of a theoretical surface derived from the model
These equations are obtained by solving the simultaneous equations for circular arcs 1 to 5 encompassing points A to E identified in Fig. 17.

As \( a_1/rev \) reaches \( a_1/rev_{crit} \), defined by

\[
a_1/rev_{crit} = \frac{p^2}{2R}
\]

the wave pitch associated with cutter 1 is zero, leaving the irregular three-knife finish surface shown in Fig. 18.

Further increases in \( a_1/rev \) above \( a_1/rev_{crit} \) eventually reduce the wave pitch to \( 4p \), i.e. a single-knife finish. This is a severe vibration condition and normally does not occur. Figure 19 shows how the four-knife finish surface deteriorates to \( a_1/rev_{crit} \) with increasing \( a_1/rev \). Again, two extremes of cutterhead and machine operation are shown. The same notation as for Fig. 14 applies.

As determined by equations (5a) and (5b), the 2 mm pitch surface achieved with a 50 mm cutterhead radius is more tolerant to increased amplitudes of interfering vibration \( a_1/rev \). In contrast, the 1 mm wave pitch and 100 mm cutterhead radius surface deteriorates at a markedly increased rate. As before, the surface deterioration as measured in wave width terms is linear. The height deterioration is non-linear. The rate at which each type of surface deteriorates is given by the slope of the line in Fig. 19. The 1 mm \((R = 100\text{ mm})\) surface degrades...
at 4 times the rate of the 2 mm \((R = 50\, \text{mm})\) surface in accordance with the wave pitch and radius values. This is at half the rate of the 1/2rev case described in Section 7.1. The value of \(a_{1/\text{rev}}\) can be taken as a measure of surface sensitivity to external vibration. Figure 20 shows how this changes with cutterhead radius and wave pitch. The \(a_{1/\text{rev}}\) value for a 2 mm wave is 4 times that of a 1 mm wave. This is the same factor as for the 1/2rev case, although the values are twice those of the corresponding waves for the case described in Section 7.1. Structural displacements at the 1/rev frequency on typical machinery measured at the cutterhead (using NCDTs) are also shown in Fig. 20. This defines the problem for improved surface waviness. A fine wave pitch of 1 mm produced by a 100 mm radius cutterhead is the most sensitive condition examined. In terms of \(a_{1/\text{rev}}\), a 2 mm wave pitch produced by a 50 mm radius cutterhead is a factor of 8 less sensitive. This is more than a factor of 2 above the largest measured structural vibration at the cutterhead rotational speed \(n\).

Typical industrial operating conditions are such that a wave pitch of 1.5 mm can sometimes be achieved with a ‘perfect’ surface waveform. More usually, in the authors’ experience, the ratio of minimum wave width to maximum wave width, \(R_w\), for the 1/rev case is generally 0.8. This is explained by considering Fig. 21 which shows how variation in \(R_w\) results from increases in \(a_{1/\text{rev}}\) for both 50 and 100 mm radius cutterheads at \(p = 1.5\, \text{mm}\) wave pitch.

Planing and moulding machines with 6000 r/min spindles exhibit eccentricities at 100 Hz of typically 5 \(\mu\text{m}\) peak-to-peak amplitude. In Fig. 21, selecting \(a_{1/\text{rev}}\) as 2.5 \(\mu\text{m}\) and \(R = 50\, \text{mm}\) results in a value of \(R_w = 0.8\). A similar exercise on the dataset for \(p = 1.0\, \text{mm}\) and \(R = 50\, \text{mm}\) results in \(R_w = 0.6\), i.e. approximately 25 per cent greater variation in wave width compared with \(p = 1.5\, \text{mm}\). A comparison with the case of \(p = 2.0\, \text{mm}\) for the same spindle eccentricity and \(R = 50\, \text{mm}\) results in \(R_w = 0.88\).

Table 3 shows the broad limits of these modelling results, the most sensitive case being a large-diameter
seven-four-knife cutterhead with $R = 100\text{mm}$ when $p = 1.0\text{mm}$ and $R_w = 0.33$. This is in marked contrast to the least sensitive case with $R = 50\text{mm}$ and $p = 2.0\text{mm}$, where $R_w = 0.88$.

To date, it has not been possible to control the wood machining process to the extent that the severity of the specific defect types can be generated as required for confirmation of the theory presented. The current approach is to observe defects as they occur and then make surface measurements using instruments to establish if the particular waveforms measured fit with the theoretical understanding. There are limitations in the measurement of wave height, especially when the wave pitch is less than $1.5\text{mm}$. The four-knife 1/rev condition has been extensively studied for one type of cutterhead on a special test rig with full instrumentation [21]. This approach is not possible on production machinery because it is too invasive.

7.3 Comparison of surface defects

Despite the wave ratio, $R_w$, for a given amplitude of disturbance being similar between the 1/2rev and 1/rev cases described, the fact that the minimum and maximum waves of the 1/rev case are interspersed with waves of nominal wave pitch makes the 1/rev case less sensitive to machine vibration and also less noticeable to the naked eye. The 1/rev case is, however, still a significant waviness defect condition, widely occurring in industry, although, depending on the machine user experience and end-product application, it is not always reported as a fault. While the jointing process increases output considerably over a single-knife finish, this 1/rev defect has limited jointing applications mainly to wave pitches of $1.5\text{mm}$ and above—primarily in the sawmilling industry.

A further factor has to be considered. The rub/cut action of the ‘land’ of the jointed cutters, which tends to burnish the timber surface, makes the application of stains more difficult owing to the generation of a semi-sealed surface texture. This process is not therefore used in the furniture industry. There are a number of fundamental as well as detail engineering design and manufacture reasons as to why some types of planing and moulding machine exhibit better surface waviness performance. This work is to be presented as part of a future paper.

It is observed that smaller-diameter cutterheads are less sensitive to structural vibration. However, in order to increase the number of knives in a cutterhead to achieve a faster feed velocity through jointing, the cutterhead must increase in diameter to accommodate the greater number of knives, therefore making the process more sensitive as a result of the larger cutting circle radius produced. Generally, the larger the number of knives, the longer will be the eccentricity wavelength in the case of the 1/rev defect. This allows larger structural displacements before a defect is perceived. These cases will be reported on in the future. A comparison of the predictions of this surface defect theory with some experimental results is presented in Section 9.

8 SURFACE ASSESSMENT

The nature of the machined timber surface is such that conventional surface assessment stylus tracing techniques, developed primarily for metal surfaces, cannot
be used successfully to detect waviness defects, but can be used to assess texture to some extent. The nature of the difficulties of assessing the surface waviness is due to the texture amplitude typically being 2–3 times the waviness amplitude. This shows in the marked differences between surfaces traced with different stylus types (Fig. 22). The large texture amplitudes are due to the openness of the timber surface, caused by the cellular nature of wood and the interaction with the cutting edge of the high-speed rotating tool. The texture features are usually of higher frequency than the waviness features of the surface. These higher-frequency, higher-amplitude texture features tend to mask the waviness effects. However, when the wood surface is viewed under oblique lighting, the periodicity of the waviness features is picked out by the human eye and the waviness is most readily observed. Any variations in waviness quality are similarly highlighted.

Many of the present assessment techniques used in the wood processing industries use the human being as the visual and tactile sensor in the assessment of surface quality. While these techniques are mainly qualitative, some can be quantitative, e.g. counting the number of wave marks per 10 mm and then inferring the resultant wave pitch. If the cutting radius of the process is known, it is also possible to calculate the theoretical surface height using equation (2). Similarly, the basic type of waviness defect can be determined by counting wave mark pattern repeats on the timber surface. What is needed, however, is a surface measurement and analysis system to quantify the machined surface in the same way as human beings interpret the quality.

Many of the advanced measurement systems developed for assessment of metal surfaces have provision for digital filtering of the input signal. However, it is not possible, in the authors’ experience [21, 25], to make sense of the resultant filtered trace. This is degraded by the fluctuation in texture amplitudes, to such an extent that it becomes a formidable if not impossible task to interpret the filtered trace as the surface waviness observed by the human eye. A waviness recording instrument (WRI) developed in reference [21] uses mechanical techniques (5 mm diameter roller stylus x 5 mm long) to filter out the primary texture of the timber surface (Fig. 23) and provides excellent results for investigating machine vibration phenomena as discussed in Section 9. However, this instrument employs a relatively high contact force (90 g) between the stylus and the surface, which compresses the peaks of the surface waves and thus produces a reduced height profile trace. This instrument is not suitable for absolute measurement of wave height. The device is useful for identifying interfering wavelengths and amplitudes measured at the lowest point of each wave mark on a machined surface. The area of contact of the roller probe on the timber is greatest here and provides a good indicator of cutterhead vibration [21]. The current embodiment is a low-cost PC-based version using a ‘mouse’ sensing head, shown in Fig. 24.

Non-contact methods for sensing wood surface waviness using optical techniques have been investigated [22, 23, 25]. By using the method outlined in Fig. 25, the intensity of oblique light incident on a machined surface produces an intensity variation proportional to the width and height of the surface wave marks resulting from the cutting process. The intensity is also modified by the reflectance of the timber (Fig. 25).

This latter point makes it difficult to provide a universal instrument for wave height measurement on all types of timber. The spatial intensity map of the surface may be transformed into the frequency domain using custom or proprietary fast Fourier transform (FFT) software so that the wave pitch periodicity is seen. The variation in wave width because of surface defects causes additional lower frequencies to be present in the FFT plot. These can be related to certain types of classical defect [25].

9 EXPERIMENTAL RESULTS

Two sets of results are presented here. The first set is for steel samples generated by controlled indexing of a grinding wheel in the horizontal and vertical directions. This method is used to establish if the general circular arc theory can be replicated in simple geometric terms. The samples so produced can also be used as reference examples for testing surface measurement equipment and comparison with machined timber sample traces. The method of production and calibration of these pieces is outlined in reference [21]. For all samples, the accuracy of horizontal placement of the grinding wheel is within ±0.05 mm and the placement of the vertical direction is within ±1 μm. Even with great care, the degree of control of the vertical position is such that defects of precise characteristic cannot be generated. The alternative approach of generating a defect of general form and then measuring and recording the resulting
The wave pitch and peak-to-valley height of each steel sample were measured with standard room quality comparators. The grinding wheel was dressed to within ±0.1 mm of the desired diameter.

The second set of results is from timber samples produced from a test rig designed to introduce waviness defects. Again, the degree of control is not as precise as is desired. The approach is to vary engineering parameters such as drive motor imbalance in a ‘controlled’ manner, observing the effects on machine vibration and machined timber surface. Displacement readings from NCDTs in the vertical direction are measured at the interfering frequency of interest. The operation of the test rig and configuration is such that the accuracy of the wave pitch variable cannot be controlled to better than ±0.2 mm. The NCDTs have an accuracy of 0.1 μm, as determined by external calibration [21]. The cutterhead diameter was controlled to within 0.05 mm of the desired value.

Figures 26 to 30 show several examples of surfaces traced from steel reference samples and rotary machined timber surfaces. Figures 26 and 27 are traced by Talysurf 5. Figures 28 to 30 are traced by the WRI developed in reference [21]. The traces in Figs 27 and 28 are of the same steel sample to allow comparison between the established technology of Talysurf 5 and the new approach (specific for waviness measurement) embodied in the WRI. Figures 28 to 30 could only be recorded using the WRI. Talysurf 5 could not separate waviness effects associated with timber grain sufficiently to provide a sensible trace.

Figure 26 shows a trace from a single-knife finish 1/2rev defect generated in steel. Also shown is a table allowing comparison of surface waviness features as...
developed in Section 7. Three columns of results are presented in the table. The ‘Actual trace’ column states the values extracted from the annotated trace in Fig. 26. The ‘Predicted’ columns show the theoretical parameters predicted by the theory [equations (4a) and (4b)] using $a_{1/2rev}$ measurement by the comparator and the predicted surface using the $a_{1/2rev}$ traced from the Talyurf 5 trace of the steel sample. Comparison of all three columns shows good agreement, proving equations (4a) and (4b) for this particular case. In this table, $h_{\text{min}}$ and $h_{\text{max}}$ are calculated from equation (2) using values of $W_{\text{min}}$ and $W_{\text{max}}$ in place of $p$. 

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**Fig. 24** PC based measurement system

**Fig. 25** Optical surface finish measurement and spectrum from wood surface trace
Figure 27 shows a trace from a four-knife jointed finish 1/rev defect generated in steel. The corresponding table is constructed in the same way as the previously described table in Fig. 26. Again there is good agreement, but the steel sample accuracy needs to be better to allow further verification. The measured value of $W_{\text{min}}$ and the predicted value of $W_{\text{min}}$ are in error by 19 per cent. This is reflected in the $R_w$ values. Further inspection reveals that there is a 1 µm offset for the intermediate waves $W_2$ and $W_4$; i.e. the centre of curvature of these waves is 1 µm too high. This creates correspondingly smaller wave widths and heights for these waves. Wave $W_1$ is thus wider than predicted, because, relatively, the simulated interfering displacement is 1 µm lower than desired. It is possible to reverse engineer the wave displacements using a general case of the theory presented here, instead of using 'classical' defect equations. The general theory is the subject of a later paper. In essence, each circular arc is influenced by its vertical displacement and the two adjacent arc vertical displacements. Table 4 shows the data predicted in this way and compares almost exactly with the measured results, again proving the theory for the steel sample generation along with the measurement approach. Improved quality of steel sample production is under investigation.

Figure 28 shows a trace from a four-knife jointed finish 1/rev defect generated in steel. This is traced by the WRI and may be compared directly with Fig. 27 for the same steel sample traced by Talysurf 5. The corresponding table is constructed in the same way as the previously described table in Fig. 26. These two traces and datasets compare well, the only difference being a slightly suppressed wave height from the WRI trace. This is mainly due to the slew rate of the chart recorder characteristics, despite a very slow (~0.2 mm/s) stylus traverse speed along the timber. The newer digital recorders do not have this problem. A second factor also suppresses wave height. The WRI uses a 6 mm diameter × 8 mm long cylindrical roller to filter out texture effects, and this is applied to the timber surface with an optimized force of ~100 g [21]. The downside of this approach is a reduction in measured wave height on timber; this effect is negligible when measuring steel.

Figure 29 shows a trace from a single-knife finish 1/2rev defect generated by the rotary machining process applied to softwood. The corresponding table is constructed in the same way as the previously described table in Fig. 26. NCDT readings for $a_{1/2\text{rev}}$ are used in the theory to predict waviness characteristics. There is excellent agreement.
correlation between \( a_{1/rev} \) values and corresponding wave widths. A relatively coarse wave pitch of 3.5 mm is chosen to allow individual waves to be observed. However, WRI measured wave heights are significantly less than predicted by theory, especially for the smaller wave widths. While the characteristics of the WRI are definitely a contributing factor, it is not yet clear to what extent. A non-contact height measurement system is needed further to advance this area of understanding. Work is continuing on this. The interfering vibration amplitude is the focus of the present paper, and the WRI provides very reliable data for comparison of engineering-induced waviness defects.

Figure 30 shows a WRI trace from a four-knife jointed finish with a suspected 1/rev defect generated by rotary machining of softwood. The source trace at the top of the figure shows three wave features of varying form. On initial inspection the trace appears to repeat, nominally, every 5–6 mm. A section of this waveform is selected for annotation as shown. Definite information available to help identify the type of defect is as follows: a cutterhead radius of 76 mm, a wave pitch of 1.3 mm, calculated from the measured spindle speed and measured feed speed, a measured peak-to-valley height of 19.2 μm from the trace and an apparent 1/rev period of 6.1 mm. Individual wave marks are not obvious, so it is difficult to interpret this trace initially. The theoretical modelling and the reference samples can help with this. The theoretical 1/rev period is 5.2 mm. This is used as a template initially to define the expected 1/rev wavelength in Fig. 30. This does not correspond to the repeat wave period of the trace. Further inspection of the main trace in Fig. 30 shows the waveform changing with time (distance). There are clearly other effects influencing the form. The process cannot always be controlled to generate defects under specific conditions. The resultant traces need to be analysed bearing in mind that other vibration frequencies may be present owing to other sources on the

<table>
<thead>
<tr>
<th>Cutting Radius = 75 mm</th>
<th>Actual</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>units</td>
<td>trace</td>
</tr>
<tr>
<td>p</td>
<td>mm</td>
<td>2.0</td>
</tr>
<tr>
<td>( a_{1/Rev} )</td>
<td>μm</td>
<td>9.0</td>
</tr>
<tr>
<td>Wmin</td>
<td>mm</td>
<td>1.6</td>
</tr>
<tr>
<td>Wmax</td>
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</tr>
<tr>
<td>hmin</td>
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</tr>
<tr>
<td>hmax</td>
<td>μm</td>
<td>13.0</td>
</tr>
<tr>
<td>peak-valley</td>
<td>μm</td>
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</tr>
<tr>
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<td>0.57</td>
</tr>
<tr>
<td>Rh</td>
<td>-</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Table 4** Waviness for 1/rev steel sample, predicted by generalized theory (cutting radius 75 mm)
machine. Using the 1/rev template as shown, the period between points A and B (5.3 mm) is chosen for analysis. The annotation is carried out on this basis. In this analysis, a line is drawn from the crest of the wave at point A to the crest of the wave at point B. The vertical distance between this line and the root of the lowest wave, \( W_{\text{max}} \), defines an \( a_{1/\text{rev}} \) value of \( \approx 0.8 \) mm. This corresponds almost exactly to NCDT measurements at this frequency. The waveform data are compared in Fig. 30, broadly with good results. Note that \( h_{\text{min}} \) is effectively zero, so these data are not stated for the trace. The cause of this waviness defect was vibration interference due to a lack of structural stiffness excited by cutterhead imbalance, producing excessive vertical displacement. The waviness defect is clearly not constant. Greater detail on the causes and solutions to this particular problem is part of a future paper.

In summary, specific steel sample cases show that the surface theory presented in Section 7 allows good prediction of waviness defects. Actual measurement of machined timber samples using the current WRI approach allows measurement of interfering vibration amplitudes and wavelengths. To this end, the initial design concept of the instrument has been realized. Further research is necessary to establish an instrument that will reveal this vibration information and also the true surface height of the waves. There is good correlation between measured and predicted waviness using vertical displacements, \( a_{1/\text{rev}} \), of the cutterhead (measured by NCDTs) in the theory. As wave pitch is reduced (\( \approx 1.3 \) mm in Fig. 30), the only data that can be measured using the WRI are \( a_{1/\text{rev}} \) values. These data are very useful for investigating machinery vibration problems.

### 10 FUTURE RESEARCH

The optical surface frequency measurement technique described in reference [25] has been extended to allow real-time surface waviness acquisition and diagnosis [27]. This now presents the opportunity for a mechatronic solution to the production of ultra-smooth wood surfaces by monitoring the surface quality while still at the human non-perception level and then vibrating the cutting head spindle assembly in some manner to reduce surface waviness defects. There is also an opportunity to create a virtual cutter block radius far greater than mechanical systems [29], resulting in very shallow wave heights and hence smoother surfaces with only two knives or even...
one knife per cutter block. This approach is potentially more sensitive to machine vibration, and hence the mechatronic approach must be applied in total. Such a system would clearly be a high-speed ‘smart’ process. The implications for tooling provision and subsequent servicing are tremendous. The impact on machinery design and manufacture are similarly long reaching. Planing and moulding machines would become truly advanced-technology, high-performance mechatronic products. Research to this end continues at Loughborough. Elsewhere, several ideas are emerging in similar or related processes [28, 31, 32].

11 CONCLUSIONS

The rotary machining of wood has much in common with the milling and grinding of metals, but is subtly different from the latter in that it requires very high-quality repeatability from the impulsive cutting edge on what is, at the micrometre level, a flexible workpiece. Rotor dynamics and structural vibration problems exist and can degrade an apparently substantial machine to a second- or third-grade performer. Modelling of two general cases has been presented, showing typical variations and degradation of surface waviness quality with increased structural vibration.

Contact and contactless methods of wood surface waviness assessment have been presented, together with the strengths and weaknesses of each approach. Optical techniques have shown promise for in-process sensing of waviness variation.

Good comparison between the steel reference samples traced with surfaces predicted by the theory presented in Section 7 has been demonstrated. Surfaces traced from timber samples using the WRI show variable results depending on wave pitch. At the finer wave pitch of 1.3 mm, individual wave mark heights are not discernible. The 1/rev interfering vibration amplitude is easily detected with this system. This allows the instrument to be used as a crucial machine diagnostic tool when troubleshooting surface finish phenomena.

It can be argued that the current mechanical approach of the rotary machining process has reached limits that can only be resolved by an active machining process involving optical sensing, control and actuation in an
advanced manner. Such a solution would be classed as a ‘smart’ machining process.

REFERENCES