Development of a Monitoring System for a Smart Planing Machine for Real-Time Operation

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ABSTRACT

In planing and moulding which are commonly used within the woodworking industry, surface defects, torn and raised grain result in high production costs. In order to meet the requirements for a consistent surface quality and increased production efficiency, surface quality information is needed for enhanced process control. Whilst some techniques have been researched based on optical sensing these are too bulky to fit near to the machining process. Furthermore these optical sensing systems are costly and generally sophisticated image processing algorithms which require a considerable computation time are required to measure the surface profile. Therefore additional real-time surface feature extraction is desirable. The objective of this paper is to introduce a novel surface profile re-creation strategy which can potentially be employed for the real-time operation as feedback for a smart planing system. In this method spindle speed and spindle vibrations are measured in real-time to re-create the machined surface profile. Numerical analysis and experimental work have been carried out to demonstrate the capabilities of this technique.

1. INTRODUCTION

The dynamic behaviour of wood machining process has a negative impact on the surface quality of machined timber. The dynamic behaviour is due to the factors such as workpiece properties, cutting tool condition, engineering quality of the machine, cutterhead vibrations, spindle imbalance [1, 2]. Although modern planing machines are capable of providing good surface finish, they are highly susceptible to machine system variations. These variations are reflected to the machined surface, resulting in unacceptable quality levels. Therefore it is essential to deploy a feedback system in order to ensure the product quality and increase the efficiency by minimizing the variations during the machining process. Various surface profile measurement systems have been developed in recent years for an automated environment. The measurement techniques can be classified into two main groups; contact based and non-contact methods.

The nature of the wood machining process (i.e. high feed speed > 1m/sec, machined surface features < 5 μm, and high inherent surface texture of the timber > 20 μm), rules out tactile surface measurement techniques such as mechanical stylus. For this method, the stylus tip contacts the machined surface and it is driven along the workpiece and the surface profile is recorded by the vertical movement of the stylus tip. The two main drawbacks associated with this technique are the lack of measurement speed and the loading effect of the stylus tip which lead to deformation on the surface [3]. Moreover this method is not suitable for surface profile measurement of timber machined at high throughput rates, since the stylus tip tends to jump at high measuring speed (i.e. 1 – 2 m/sec). This "bouncing" effect occurs when the stylus tip loses contact with the machined

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surface which limits its in-process deployment. In order to monitor the quality of machined surfaces, various non-contact measurement techniques have been deployed over the years. Most of the methods used for non-contact measurements are optical method which include optical profilometers (mostly laser based), microscopes, image analyzers, imaging spectrographs, interferometers, fibre-optic transducers, white-light speckles, laser scattering, optical light sectioning systems [4, 5, 6, 7]. Most of these non-contact based methods are too expensive, bulky and lack the measurement speed due to the sophisticated image processing algorithms, thus they are not sufficient for applications where real-time control action is required. These drawbacks limit their application range for an automated process environment. Therefore an additional surface profile extraction is desirable to assist the optical methods which would enable real-time control action during the machining process. This paper introduces a new surface profile re-recreation method by considering the spindle speed and spindle vibration during the machining operation.

1.1 WOOD MACHINING PROCESS

Rotary machining has been an essential part of the woodworking industry for over two centuries and is applied to good effect in planing and moulding machinery. The principle of the rotary machining process is such that timber is fed towards a rotating cutterhead containing a number of cutting knives. This process is illustrated in figure 1.

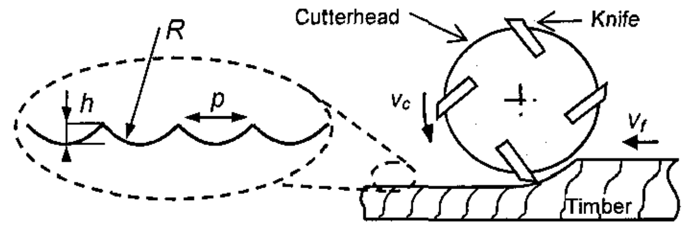

Fig. 1 Principle of rotary machining process

Rotary machined surfaces are not ideally smooth and flat. The machined surface has a series of waves due to the kinematics of the rotary machining process. The surface waves, also called cuttermarks, are generally accepted as unavoidable. The length of the cuttermark p, also called pitch, is usually taken as a measure of surface quality. A good surface finish should have a pitch p lower than 1.8 mm and surface waviness should follow a uniform pattern. The length of the cuttermarks p is dependent on workpiece feed speed v_f, cutterhead rotational speed v_c and the number of finishing cutting knives N. This relationship can be expressed by the following equation:

$$p = \frac{v_f}{v_c \cdot N} \tag{1}$$

It is often assumed, for simplicity, that the shape of the cuttermarks is circular and that the surface can be considered as a series of intersecting circular arcs. The waviness height h of the simplified surface can then be expressed by the following equation:

$$h = R - \sqrt{R^2 - \frac{p^2}{4}} \tag{2}$$

where R is the cutterhead radius. These equations (1) and (2) are well established and widely used [1, 2]. Indeed, the shape of the cuttermarks is cycloid and the surface height is ca. 5% lower than the simplified height expressed by the equation (2) [8]. This low error ratio justifies the use of surface waviness approximation by the circular arcs for rotary machining process used within the woodworking domain [1].

1.2 SMART PLANING SYSTEM

A new surface profile re-creation method is intended to be used as a feedback loop for a smart planing system designed within the Mechatronics Research Centre at Loughborough University (Fig 2) [9]. The smart planing system consists of a base frame on which the feed table and spindle system are mounted. The smart spindle unit is the main part of the test rig. Four piezoelectric actuators are mounted on the front bearing. Two opposing actuators for each axis have been chosen in order to achieve a "push-pull" operation. Applying appropriate voltage levels to the piezoelectric actuators controls the movement of the spindle. The smart spindle unit is a based on mechatronics control approach which comprises appropriate sensors, signal conditioning circuits, driving amplifiers and control computer.

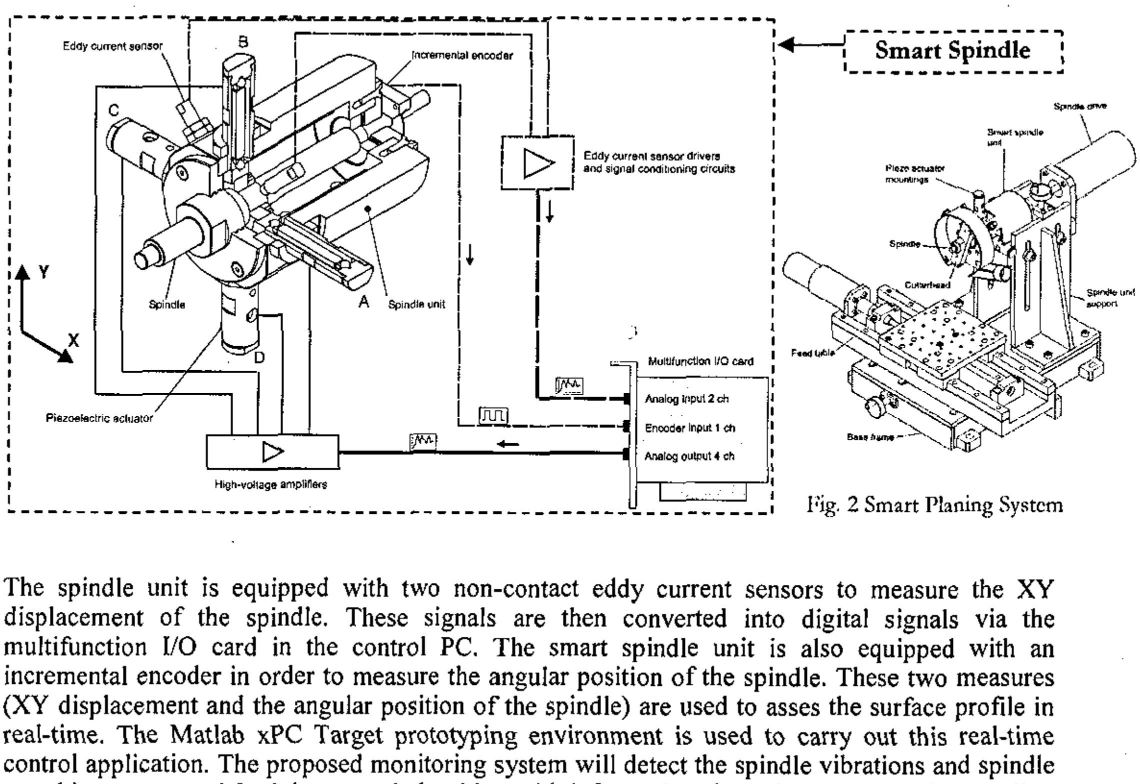

Fig. 2 Smart Planing System

The spindle unit is equipped with two non-contact eddy current sensors to measure the XY displacement of the spindle. These signals are then converted into digital signals via the multifunction I/O card in the control PC. The smart spindle unit is also equipped with an incremental encoder in order to measure the angular position of the spindle. These two measures (XY displacement and the angular position of the spindle) are used to asses the surface profile in real-time. The Matlab xPC Target prototyping environment is used to carry out this real-time control application. The proposed monitoring system will detect the spindle vibrations and spindle speed in-process and feed the control algorithm with information about the current surface quality. Thus, the new proposed smart planing system will be able to adapt the spindle displacement in real-time to the current surface waviness. As a result of this machining process, the disturbances and the machining variability will be reduced and a consistent and improved surface quality will be achieved.

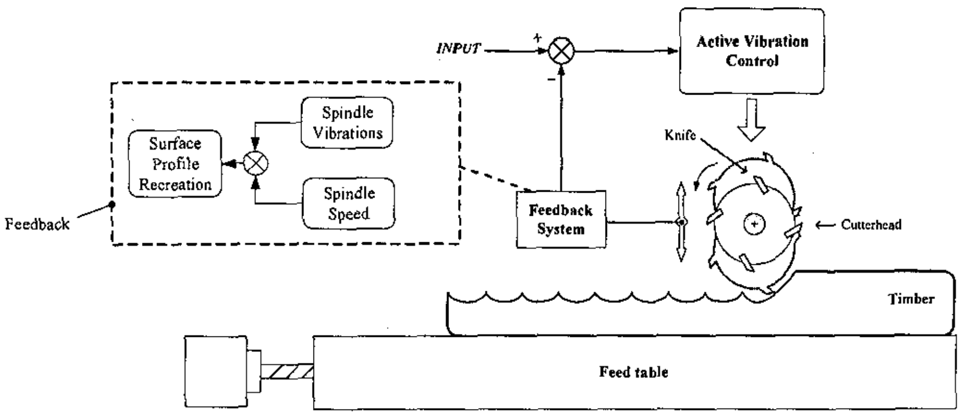

Fig. 3: Active vibration control strategy with a feedback system

2 NOVEL SURFACE PROFILE RE-CREATION TECHNIQUE

For any dynamic optimization of the machining process with the focus on an increased surface quality, characteristics of those vibration components can be used in a feedback loop so that the control system can compensate for it. The feedback system is mainly focused on cutterhead vibrations and cutterhead speed. Figure 3 shows the monitoring system integrated within the controller. Spindle vibrations are measured with the eddy current probes and the spindle speed is monitored via an incremental encoder. From these sensors output, surface profile of the machined timber is re-created and then compared with the input values. For example if the spindle speed is set to *600 rpm* and the feed speed to *20 mm/s* then according to the equation (1) and (2) the pitch is *2 mm* with *8.33 μm* of height. These values are taken as input parameters which are compared with the re-created surface pitch and height.

2.1 SURFACE PROFILE RE-CREATION BY USING SPINDLE SPEED

During the machining process, the spindle speed is monitored by an incremental encoder. The encoder is counting two thousand pulses for each revolution. The time that the cutterhead needs to perform one revolution is extracted from these readings. When the spindle speed is monitored over the whole machining cycle, from figure 4 it can be seen that the spindle speed is varying during the machining process.

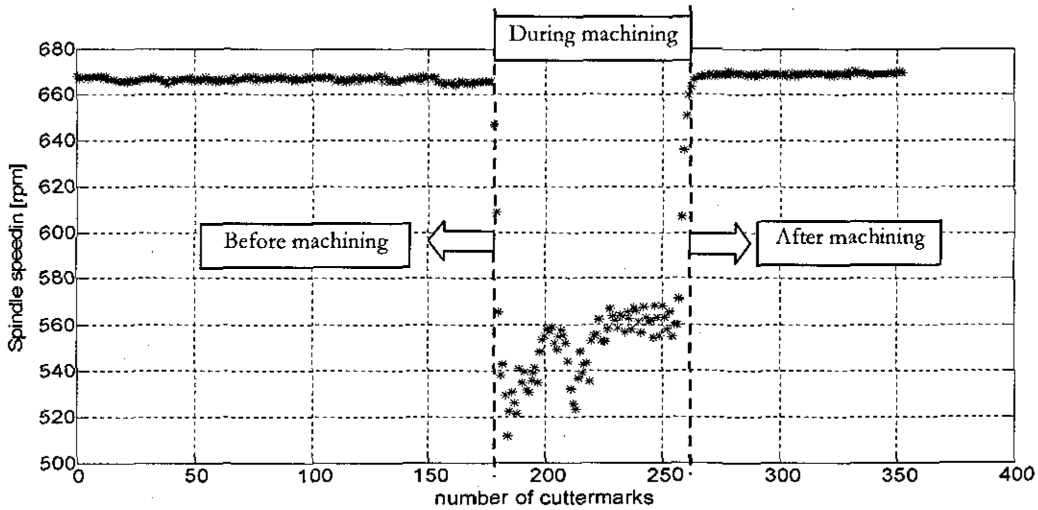

Fig. 4: Variation of the spindle speed during the machining process

Since the spindle speed is measured, the surface profile characteristics such as pitch and height can be calculated by the equations (1) and (2) respectively. The calculated pitch and corresponding heights are shown in figure 5.

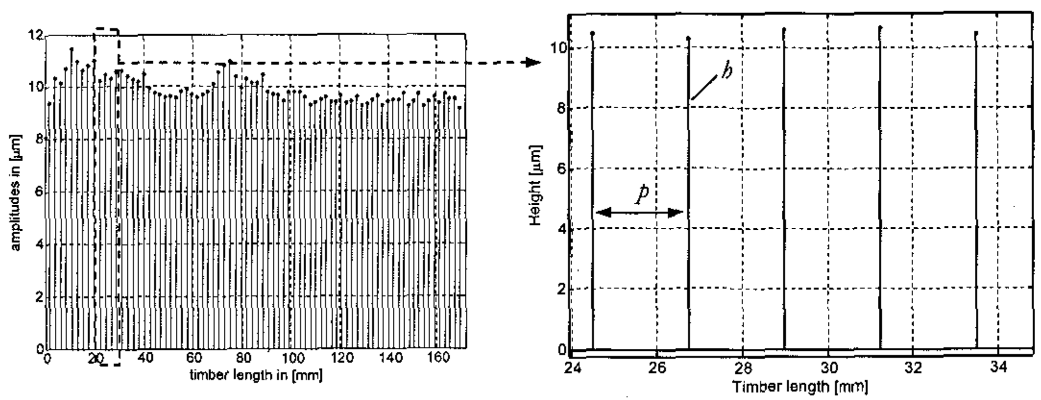

Fig. 5 Re-created surface profile by using spindle speed

In order to assess the performance of the introduced method, the same machined profile is also measured via a contact based stylus tracer for comparison reasons only, because during the machining operation the surface quality will solely be assessed by the feedback system.

As it is shown in table 1, the difference between the mean pitch values and the re-created and measured surface profile is at about 3 % which is in a good agreement, however the re-created surface profile does not take the work piece properties as well as the dynamic behaviour of the machining process (i.e. vibrations between workpiece and cutterhead) into account. Spindle vibrations can cause severe surface defects, hence reduce the surface quality immensely. The effect of spindle vibrations on the machined surface has extensively been studied in [2] and proved through simulation and experimental work in [1]. Therefore this method has been further improved by analysing and considering spindle vibrations which enables a more reliable monitoring system with accurate surface profile information.

2.2 SURFACE PROFILE RE-CREATION BY USING SPINDLE VIBRATION

The spindle vibrations are measured via eddy current probes during the machining process. Figure 6 shows the spindle vibrations during the cutting process where the time for one vibration event caused by one cuttermark is expanded along the time axis.

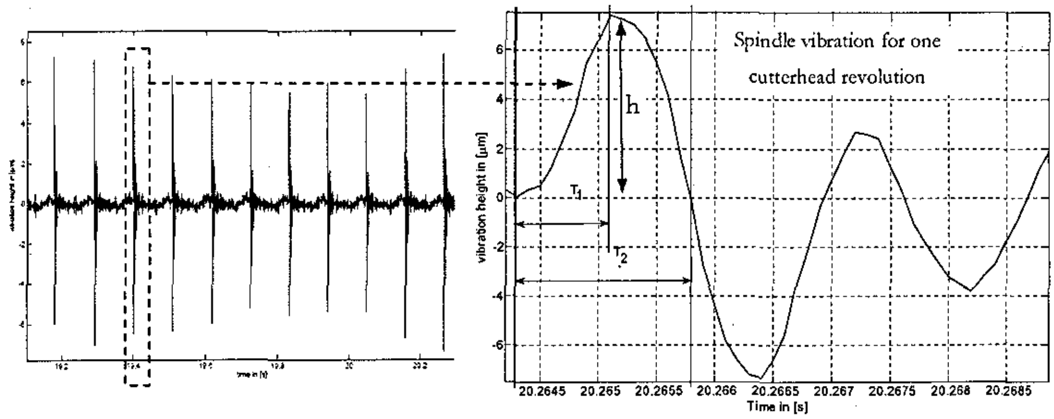

Fig 6: Spindle vibrations during the machining process

Spindle vibration magnitudes as well as spindle speed vary during the machining operation. The vibration magnitudes are extracted via programming code within Matlab. As it can bee seen from figure 2, eddy current probes do not provide the vibrations at the tool tip, as they are located on the front bearing. Therefore these vibration magnitudes are extrapolated from the node of the measurement to the tool tip by considering the geometry as well as the dynamic characteristics of the spindle through an FEM model. The FEM model of the spindle revealed that the displacement of the tool tip and the node of measurement are in the same direction for the first vibration mode. However at higher frequencies where higher vibration modes become involved the extrapolation is more complicated. Especially at the second vibration mode of the spindle system, the displacement of the measurement node and the tool tip node are in opposite directions. Therefore a simple extrapolation with a factor is only reliable for the frequencies below the first vibration mode of the spindle. Considering the fact that vibrations caused during the machining operation can be arbitrarily and contain higher vibration modes, an extrapolation through FEM is carried out, thus the introduced method is capable of providing reliable and accurate information about the surface profile over a wide range of frequencies. The pitches p are then calculated by rearranging the equation (2) and shown in figure 8. The re-created surface profile from spindle vibrations are in a good agreement with both previous methods. The deviation from the measured mean pitch value is less than 3 % with less than 2 µm divergence from the mean surface heights. This relatively high accuracy and the straightforward instrumentation make this method suitable for surface profile monitoring purposes within the planing operation.

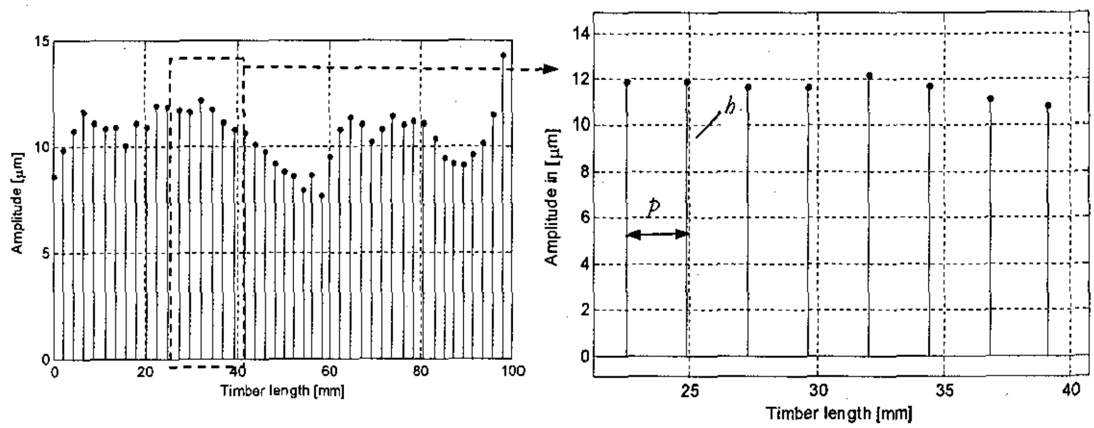

Fig 8: Surface profile recreation by using spindle vibrations

Table 1: Comparison among the simulated, measured and re-created surface profiles

	Simulated ideal surface	measured surface with stylus	re-created surface from spindle speed	re-created surface from spindle vibration
p_{mean} [mm]	2.0	2.11	2.18	2.16
h_{mean} [µm]	8.33	11.66	9.89	10.11

3. SUMMARY AND CONCLUSIONS

The dynamic behaviour of wood machining process has a negative impact on the surface quality. In order to meet the quality requirements, surface profile information is needed for enhanced process control. Most of the surface profile in-process monitoring systems are either too expensive, bulky or too slow to feed the control system with real-time information. A method comprising of two steps has been introduced which can potentially be employed for planing operation where real-time control action can be performed. The first step is the re-creation of the surface profile by analysing the spindle speed of the smart planing system. This method shows relatively accurate surface profile information, however it is not capable of classifying surface defects caused by the spindle vibrations. Therefore a second complementary step has been introduced which considers the dynamic behaviour of the spindle system during the machining operation. The vibrations caused during the machining operation are captured and the surface profile is re-created. These two steps allow a classification of the surface profile relatively accurately when compared with the surfaces traced by the mechanical stylus. With this method the surface profile information can be obtained with only two sensors (i.e. eddy current probes and incremental encoder) which make it cost effective and easy to implement. Furthermore it can provide surface profile information where real-time control action is required.

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