Mechatronics 46 (2017) 21–31

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Active vibration control and real-time cutter path modification in rotary wood planing[☆]

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ARTICLE INFO

Article history:
Received 1 July 2016
Revised 22 March 2017
Accepted 13 June 2017

Keywords:
Wood machining
Eddy current sensor
Piezoelectric actuator
Vibration control
Cutter path optimisation
LQG controller

ABSTRACT

Forced structural vibration and cutting tool inaccuracy have been identified to be the primary causes of surface defects in rotary wood planing. This paper presents the development of a control strategy used to compensate for the effects of both vibration and cutting tool inaccuracy on planed wood surface finish. The solution is based on active vibration control and real-time modification of the cutting tool trajectory using an optimal Linear Quadratic Gaussian tracking controller. A small-scale mechatronic wood planing machine, which has an actively controlled spindle unit, has been designed for practical investigation of the proposed technique. Experimental results show that the applied compensation increased the dynamic performance of the machine and the quality of the surface finish produced.

1. Introduction

Rotary planing is one of the most important machining processes in the value-added woodworking industry [1,2]. The details of the process are well reported in the literature [2–5]. Due to the kinematics of the process, waves known as cuttermarks are formed on the machined wood surfaces. The surface waviness is the key parameter used in the woodworking industry to determine the quality and production efficiency of the machine. A high quality surface finish is classified by cuttermarks width typically less than 1.5 mm, and cuttermarks width greater than 2.5 mm is typically considered to be a lower quality surface finish [3]. The uniformity of the cuttermarks is also one of the main parameters used to determine the quality of the surface finish.

It has been established that forced vibration and cutting tool inaccuracy are the primary causes of surface quality degradation in wood planing [3]. Although the defects can be amplified by the type and the condition of the wood material, they are primarily caused by the machine deficiencies [3,4]. It is estimated that defects could reduce processing yield in wood plaining by 27% [1]. Cutting tool inaccuracy occurs due to the difficulty in grinding all the cutting edges in a cutterhead to a common radius. The use of the best available precision tools and techniques would still produce a total indicated run-out (TIR) typically within the range of 5–10μm [5]. The TIR is the difference between the largest radius cutter and the smallest radius cutter on a cutterhead. A TIR value of less than 1μm is required to produce an acceptable multi-knife finish but this is not technically feasible at any reasonable price via mechanical methods [3].

The current solution to the problem of cutting tool inaccuracy in the woodworking industry is to apply a process known as jointing. The term is used to describe the dressing of cutting tools in order to true all the cutting edges to a common radius [3]. Non-jointed cutting edges produce significant repeating patterns of non-uniform cuttermarks on the machined workpiece. The disadvantage of jointing is that it removes or reduces any back clearance angle from the cutter leading to accelerated tool wear. Tool wear does not only increase tooling costs, but it also increases the normal cutting forces generated during the machining process, which leads to an undesirable burnishing action on the timber surface.

In addition to cutting tool inaccuracy, structural vibration is another major cause of defects in rotary wood planing. Vibrations can arise from multiple sources such as mass imbalances, and bearing misalignments. Vibration results into eccentric running of the cutterhead relative to the workpiece thereby altering the dynamic cutter run-outs of the cutting edges. In cases where jointing is applied, the jointing device could also modify the cutter tracking orbit due to the jointer vibration, which is excited by cutterhead imbalance [5]. Also, the cutting forces generated due to the relative

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[☆] Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Cesare Fantuzzi.

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http://dx.doi.org/10.1016/j.mechatronics.2017.06.007

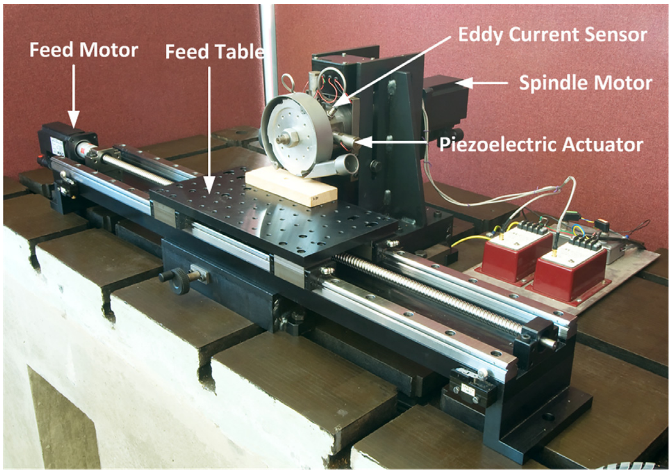

Fig. 1. Small-scale mechatronic wood planing machine.

motion between the cutter and the workpiece could also lead to vibration.

Some ideas on how to improve the quality of planed wood surfaces through real-time adjustments of the cutting tool trajectories have been reported in the literature. The first one is the introduction of horizontal cutterhead movement during the machining process [6,7]. Similar approach that introduces vertical cutterhead movement has also been reported [8]. The aim is to produce surface finish with reduced waviness heights. Results show that these methods produce cuttermark heights below what is obtained from the conventional machining. However, these techniques still do not compensate for the effects of vibration and cutter inaccuracy. Real-time optimisation of the cutter path has also been used to compensate for cutting tool inaccuracy [9,10]. The technique used is to adjust the cutterhead vertical position in such a way that all the cutting edges are at the same radius when engaged with the workpiece. Tool path optimisation is not limited to wood planing as the technique has also been used in other wood machining operations to minimise cutting force and tool wear [11].

The adjustment of cutter path has been extensively studied in wood planing but vibration control has received less attention. Work reported so far on vibration control in wood machining has focused on circular sawing and milling [12–18] and other wood machining processes [19]. Work on the improvement of the dynamic performance of a wood planer spindle using piezoelectric actuators has also been reported in [20].

Although cutting tool inaccuracy compensation and active vibration control in rotary wood planing have been studied independently [9,10,20] there is a greater challenge in solving the two problems concurrently. Therefore, the aim of this paper is to develop an appropriate control strategy that is capable of combining real-time tool trajectory adjustment with dynamic process disturbance compensation. The proposed controller is a combination of feedforward and feedback control loops. Experiments are performed on a small-scale mechatronic wood planing machine in order to investigate the effects of the compensation on the surface finish quality.

2. Mechatronic wood planing machine

The work reported in this paper is based on an experimental test facility designed to explore different techniques that can be used to improve the performance of industrial wood planing machines (Fig. 1). The small-scale mechatronic wood planing machine is instrumented with two non-contact eddy current sensors and four piezoelectric actuators for controlling the spindle in the plane perpendicular to its rotational axis. The eddy current sensors are used to measure the spindle displacement in the X-Y plane. The actuators are capable of moving the spindle up to a peak-to-peak amplitude of 36μm. The spindle is also equipped with a rotary encoder for measuring its angular position so that its displacements can be synchronised with its rotational angle. The encoder generates 2000 counts per revolution and an index pulse once every revolution. The index pulse is used to establish an absolute rotational angle of the spindle. The eddy current sensors are aligned with the actuators in axial direction but rotated by 45○ with respect to the actuators as shown in Fig. 2. Therefore, the sensor readings are always converted from the sensors coordinate system (x_s, y_s) to the actuators coordinate system (x_a, y_a).

Table 1
Angular positions and the static run-outs of the four cutters.

Cutter	Static run-out (μm)	Angular position (counts)
1	$y_1 = 0$	$\theta_1 = 60$
2	$y_2 = -12$	$\theta_2 = 560$
3	$y_3 = -2$	$\theta_3 = 1060$
4	$y_4 = 1$	$\theta_4 = 1560$

Cutting tool inaccuracy compensation through periodic vertical displacements of the spindle has already been explored and tested on the machine [9,10]. The compensation was applied to a four-knife cutterhead based on the static run-outs of the cutters and their absolute angular positions on the spindle.

The four-knife cutterhead mounted on the spindle has a mass of 293g and a nominal diameter of 120 mm. The cutters are numbered from one to four in the clockwise direction. The measured static run-outs and the angular positions of the cutters at their lowest points are given in Table 1. As seen in the table, the TIR of the cutterhead is about 13μm (cutter 2 and 4).

The run-outs were measured after the cutterhead had been mounted on the spindle in order to eliminate the effect of any misalignments between the centre of the cutterhead and the spindle centre. The main shortcoming of the approach explored in [9,10] is that the dynamics of the machine are not taken into account. Vibration could cause the dynamic run-outs of the cutters to be significantly different from the statically measured values. The resultant effect of superimposed vibration on the surface finish quality depends on its amplitude and phase. Therefore, an approach which optimises the cutter path based on the static cutter measurements and also compensates for the effects of vibration is required for reliable operations of the machine.

3. Controller design

The proposed control system for achieving the aim of this paper is a combination of disturbance feedforward and feedback control loops. A simple feedback control mechanism alone may not meet extra high tracking performance requirements, especially in the presence of large disturbances and when there is a long delay between the plant output measurements and the firing of the actuators. Significant improvements in the tracking performance can be obtained if some of the process disturbances are measured and fed forward into the control loop, so that corrective actions can be initiated in advance before they affect the system's response. The feedback loop consists of a Linear Quadratic Gaussian (LQG) tracking controller with integral action. The LQG controller is used because it provides the best possible performance using the least amount of control effort [21]. Apart from its optimality, it is also stable and robust to process disturbances and measurement noise.

An LQG controller can be used either as a regulator or a set-point tracker. When it is used as a regulator, the control objective is to drive the plant output to zero. A regulator-type LQG controller