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Development of an Ultrasonic Vibration Cutting system for Stavax mould machining

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Abstract

Diamond cutting is superior to generate complex surface of high accuracy and good quality. Ultrasonic Vibration Cutting (UVC) technique is used to further improve the machining performance of conventional diamond cutting by adding vibrations to standard cutting motions. The one-dimensional (1D) linear and two-dimensional (2D) elliptical vibration cutting has been proven to offer superior performance over conventional diamond cutting process. However, massive production of ferrous and hard-to-machine materials by vibration-assisted diamond cutting at industry scale is still unachievable due to severe tool wear. To make diamond cutting a mass production available for manufacturing of cost-effective surface on various materials, high efficiency diamond cutting technology assisted by multi-degrees of freedom vibration is developed in this research. The system will be used to machine complex mirror surfaces of ferrous and hard-to-machine materials by utilizing turning process. The novel and advanced machining technology will be developed to provide economic fabrication of complex surfaces on ferrous and hard-to-machine materials. In this paper, the development of software platform for experimental data acquisition and control signal generation is presented. The presented methodology is an efficient diamond cutting technique resulting in a significant reduction of cutting forces and tool wear, improvement of surface quality, and massive extension of tool life.

Ultrasonic Vibration Cutting (UVC), system development, mould machining

1. Introduction

Diamond cutting allows the surfaces to be manufactured with mirror-finished quality and fine-groove microstructures [1]. However, diamond cutting tools are not suitable for machining ferrous alloys at high speeds, as carbon is soluble in iron at high temperature created by high-speed machining, leading to greatly increased wear on diamond tools. To overcome this problem, vibration-assisted cutting technique is introduced to improve the machining performance of conventional diamond cutting by adding vibrations to standard cutting motions. Vibrations with small amplitude (2 to 100 μm) and high frequency (1 kHz to 60 kHz) are added to the initial machining motions. The 1D linear and 2D elliptical vibration cutting has been proven to offer superior performance over conventional diamond cutting process. The objective of this work is to develop a three-dimensional (3D) ellipsoidal vibration cutting system. The hardware experimental rig set up and control software platform development will be presented in this paper.

2. Hardware and Software System Development

The 3D ellipsoidal vibration cutting system will be working at resonance to give desired tool path in 1D, 2D and 3D space under micron amplitudes and ultrasonic frequencies. This technology is used to machine complex mirror surfaces of ferrous and hard-to-machine materials by utilizing turning process. To achieve a successful prototype design, the simulation based calculation is critical.

In this system, the horn is expected to have vibrations in three directions with a 1-D actuator at the resonant frequency. The inherent frequency of the horn was designed to ~ 100 kHz as shown in Figure 1. The asymmetric structure of the horn design was adjusted slightly to create similar inherent frequency (similarity over 95%) in continuous three vibration modes. The overall design of the UVC was drawn in Figure 1 left. This design includes the horn, the tool, and the exciter with a cooling cover [2]. This paper focuses on the hardware and hardware development for the system.

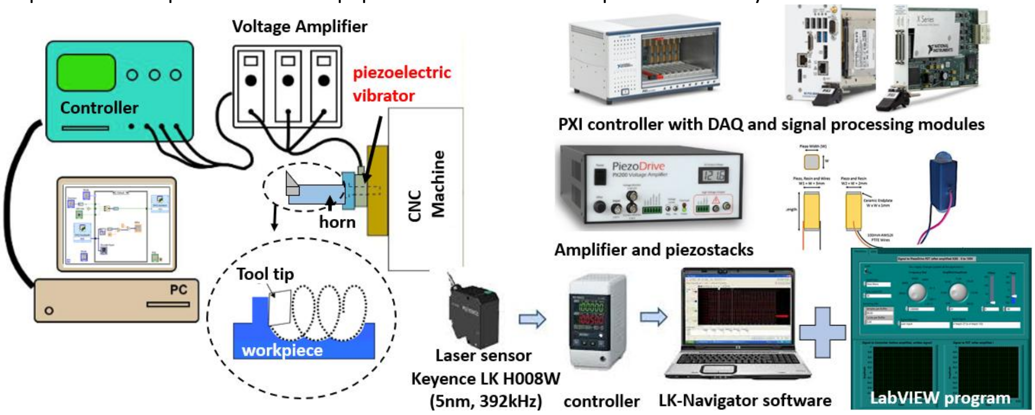

Figure 1. Hardware and software development for ultrasonic vibration cutting system.

2.1. Piezostack Specifications

To meet the frequency and amplitude requirements, higher resonant frequency of the selected piezo stack is preferred and ideally with a free-loading amplitude of 5-6 µm. The specifications of the piezostack is listed in Table 1 . There are mainly two challenges when using ultrasonic vibrating piezo stacks: quick heat up and high dynamic force. The quick heat up problem can be overcome by using external cooling system as demonstrated in [2]. Generally, 10% of the blocking force is recommended under static operation, while the maximum recommended preload under dynamic operation is 50% of the blocking force. However, due to a high dynamic vibration as in this project, higher preloading force may be applied. The dynamic force generated by piezo component can be calculated by:

$$F_{dyn} \approx \pm 4\pi^2 m_{eff} \frac{\Delta L}{2} f^2 \quad (1)$$

In which, F_{dyn} is Max. dynamic force, N; m_{eff} is Effective mass of the piezo stack actuator, kg; ΔL is Displacement (peak-to-peak), m; f is Resonant frequency. In the proposed project, the displacement is assumed to be 1.42 µm in cutting direction, the frequency is 100kHz, so the dynamic force per kilogram is ±14.2 kN/kg as (2).

$$\frac{F_{dyn}}{m_{eff}} \approx \Delta L f^2 = \pm 1.42 \times 10^{-6} \times (100 \times 10^3)^2 \quad (2)$$

The flexure and horn parts are 40 g, so the dynamic force is ±14.2×0.04=568 N, which is 57.9 tonforce. A preloading force higher than this value is needed to protect the piezo stack from a tensile force. Due to the limit of amplifier bandwidth, the final vibrating amplitude will be much smaller than 2 µm, taking piezo stack SA030305 and amplifier PX200 as an example, the full voltage (150 V) amplitude of piezo stack is 5.6 µm, so the amplitude under 90 kHz (20 V) is only 0.7 µm, and the dynamic force is calculated as 22.75 kg force (223 N). If the preload is using a M2 screw hole, the tensile stress is 497.8 MPa, corresponding to 1.03 kN tensile force which is bigger than the calculated minimum preload force. The piezo stack will then be safe under the preload applied by a M2 screw.

Table 1 The specification of the piezo stack selected

Range +/-10%	**Length**	**Cross Section**	**Cap. +/-20%**
5.6 [um]	5 [mm]	3x3 [mm]	140 [nF]
Mass	**Blocking Force**	**Stiffness**	**Res. Freq.**
0.53 [g]	330 [N]	80 [N/um]	300 [kHz]

2.2. Amplifier Specifications

A high-speed amplifier/piezo driver which can process 90 kHz driving voltage is needed in the proposed system. Accordingly, the bandwidth is the major parameter when choosing the amplifier. The power bandwidth is defined as the maximum frequency of an amplifier under full output voltage, while the small signal bandwidth (−3 dB gain bandwidth) is defined as the maximum frequency of an amplifier with a small signal applied, usually 200 mVp-p. When the amplifier output is open-circuit, the power bandwidth is limited by the slew-rate; however, with a capacitive load, the power bandwidth will be influenced by the values of 1). output voltage range, 2). load capacitance, 3). output voltage (peak to peak), and 4). driving frequency. The author did not find any existing commercial available amplifier with a power bandwidth up to 90 kHz. None of the selected amplifiers can process a full voltage with 90 kHz, the final output frequency is a compromised result between voltage range, piezo capacitance and the driving voltage peak.

2.3. Controlling system

To meet the high-speed signal updating requirement, the National Instruments PXI system was selected as the controlling platform. A PXI express chassis PXIe-1073 was chosen to provide power, cooling and a communication bus for following modular instruments and I/O modules. Waveform generator and multi-functional A/O were then selected to PXIe-5413 and PXIe-6361 (or PXIe-6363 with more A/O channels). These modules will be controlled by a controller PXIe-8301 that remotely connect to an external PC. Finally, the control system can be customized by NI software LabVIEW.

2.4. Software Development

Experimental rig and LabVIEW platform were developed to verify the simulation results. In this system (shown in Figure 2), piezoelectric stacks are employed as core oscillators due to their quick response, high acceleration, high accuracy and high stiffness. The following research aspects have been addressed: piezo-stack dynamic response characterization; system resonant frequency identification; system nodal position determination and verification; and mechanical structure design and optimization. In the system, a high resolution displacement sensor is used to monitor tip position and frequency.

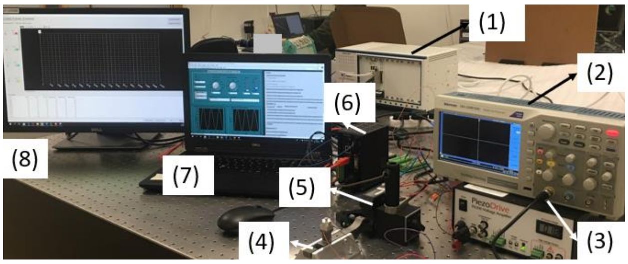

Figure 2. Experimental set up and the assmebled UVC system

The experimental set up includes: (1) NI controller for DAQ; (2) Oscilloscope monitoring amplified voltage; (3) Piezoelectric voltage amplifier; (4) 3D UVC horn fixed on isolation stage; (5) Laser displacement sensor; (6) Laser sensor controller; (7) PC for signal generation; (8) Monitor for laser signal sampling.

3. Summary

A 3D ellipsoidal UVC system is designed in this work. The developed prototype is working under micron amplitudes and ultrasonic frequencies. Hardware and software are developed for the system. The following research aspects have been invested: piezo-stack and amplifier dynamic response characterization; system resonant frequency identification; system nodal position determination. Till present, the proposed system works near ultrasonic vibrations. To further increase the frequency, the mechanical structure of the horn and the piezo-stack preload mechanism will be optimized as future work.

Acknowledgement

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