Autoresonant Excitation and Control of Non-Linear Mode for Ultrasonically-Assisted Machining

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Abstract

Application of high-frequency vibration processes for intensification of machining requires a control technique for identification, excitation and stabilisation of the nonlinear resonant mode in machining systems with unpredictable variation of processing loads. Such a technique was developed with the use of self-exciting mechatronic systems. This method of control is known as *autoresonance*. Autoresonant control of ultrasonically assisted cutting machine intended to improve machining process is thoroughly analysed and the results of analysis and experimentation are presented.

Key words: Vibration control, autoresonant control, ultrasonic machining.

Introduction

Ultrasonically-assisted machining is superimposition of ultrasonic vibration on conventional machining processes such as turning, milling, drilling etc., when the vibration is applied directly to a cutting tip [1]. Fig. 1 presents the typical set-up for ultrasonically-assisted drilling. The ultrasonic transducer consists of piezoceramic rings clamped together with a wave-guide (concentrator) and a back section.

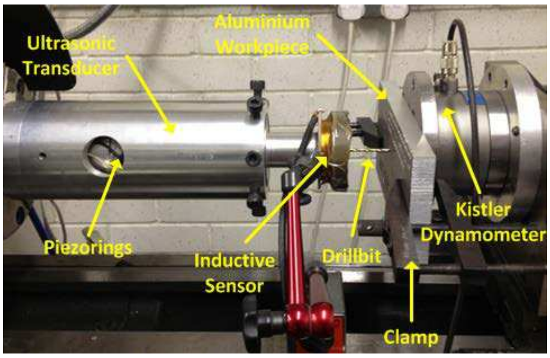

Fig. 1: Experimental set-up of ultrasonically-assisted drilling

A 3mm drillbit is fixed at the narrow end of the concentrator. The transducer is supported and rigidly clumped at its physical nodal cross section in an aluminium tube mounted by a three-jaw chuck on the lathe. The workpiece is clamped firmly on the surface of Kistler dynamometer installed at the saddle. When a high frequency electric impulse from an electronic amplifier is fed to the input of the piezo transducer it begins to vibrate due to the piezoelectric effect. This vibration excites the longitudinal waves in the concentrator (which intensifies the amplitude of vibration in the longitudinal direction) and produces intense vibration at the tip of a 3mm drillbit.

The key problem in the promotion of ultrasonically-assisted machining is the development of proper adaptive control of the ultrasonic vibration. It was shown that frequency control (forced excitation with a prescribed frequency) is inefficient in achieving peak performance of ultrasonic cutting systems [2]. The main reasons for this are the non-linear behaviour of ultrasonic vibrating systems, when several regimes are possible with the same frequency applied, and the ill-defined nature of the cutting process [3]. The most advanced control method for overcoming these problems is *autoresonance* [4].

Autoresonant control is a self-sustaining excitation of a vibration mode at the natural frequency of an ultrasonic vibrating system, which maintains the resonant condition of oscillation automatically by means of positive feedback based on the transformation (phase shift, limitation) and amplification of a sensor's signal.

Modelling of autoresonant control of a loaded ultrasonic transducer is presented. Investigation of different control strategies is discussed. Numerical simulations were considered as the most appropriate method for analysis and a Matlab-Simulink computer model of a non-linear ultrasonic vibrating system with the possibility of autoresonant control was developed. The ultrasonic vibrating system consists of two modules, the first of which is an electromechanical model of the ultrasonic transducer comprising a piezoelectric transducer and a 2-step concentrator. The second module simulates influence from the machining process. Coefficients of the electromechanical model were calculated through an identification process based on the real measurement of the ultrasonic transducer's vibration. The validity of the computer model of the ultrasonic vibrating system has been confirmed experimentally. Furthermore, a numerical model of autoresonant control of this system has been developed. The model allows exercise and comparison of different control strategies based on the feedback signal proportional to the displacement of the end of the concentrator (mechanical feedback) or on the signals proportional to the electrical characteristics of the piezoelectric transducer (electrical feedback). The results from simulation are presented and discussed. To validate the results obtained through numerical simulations a prototype of an autoresonant control system was developed and manufactured. For all listed control

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strategies, machining experiments have been conducted with the manufactured control system. Experimental results take into account the effect of a drillbit where simulation results exclude.

Model of the control system

In order to make possible investigation of different control strategies, the model of the control system based on the principle of autoresonance [4] has to be developed. Autoresonant control is a method based on phase control [5], which maintains the resonant regime of oscillation automatically by means of positive feedback using transformation (phase shift, limitation) and amplification of the sensor's signal. It is based on the fact that during resonance the phase lag between the vibration of the working element (cutter) and the excitation force applied to the latter is constant.

Depending on choice of the sensor, two different control strategies are possible: *mechanical feedback*, when the sensor placed at the end of the concentrator for measuring the mechanical characteristics of the oscillations (displacement, velocity or acceleration) is used for the control system, and *electrical feedback*, which uses the signal from any electrical sensor measuring the electrical characteristics of the piezoelectric transducer (current, voltage, power).

Comparison investigation of amplitude-frequency characteristic of displacement and electrical characteristics (voltage and power) showed that resonant peak of current, displacement and power coincides with displacement very well at a same frequency resonant peak. This suggests a similar supplied voltage for the ultrasonic vibrating system at resonance regime.

Experimental results

The numerical investigation revealed the advantages and drawbacks of different control strategies and estimated the efficiency of each of them. To validate the results obtained through simulations a prototype of an autoresonant control system was designed and manufactured. For all the listed control strategies the drilling experiments for different feed rates have been conducted with the control system. A lathe *Harrison M300* was employed in the experiments as shown in Fig. 1.

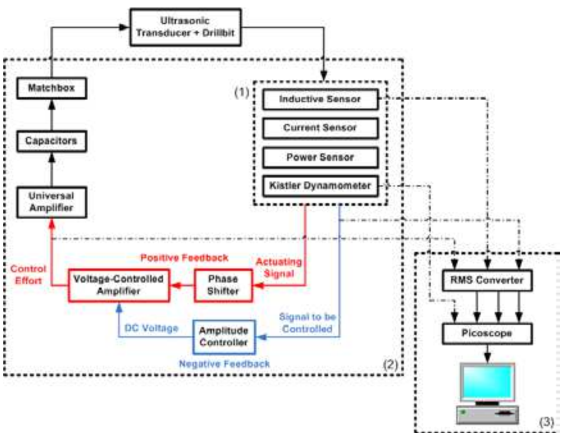

Fig. 2: Experimental set-up used for experiments with different control strategies

Workpiece materials are soft aluminium alloy plates with grade number 5083. The hardness of such specimen is 77*HV* and thickness is 15*mm*. Spindle rotational speed spindle is fixed 40*rev/min* and three feed rates were employed 0.03*mm/rev*, 0.06*mm/rev* and 0.09*mm/rev*.

Fig. 2 shows a schematic diagram of experimental setup used for the drilling experiments with different control strategies. Contour 1 indicates the performance sensors. Contour 2 shows the autoresonant control system elements. Contour 3 designates the arrangement used to record the experimental data.

Fig. 3 represents the oscilloscope readings of the drilling experiment with mechanical feedback control system. Blue line depicts the RMS of the inductive sensor's output measuring vibration at the end of concentrator; red curve illustrates the RMS value of the control efforts.

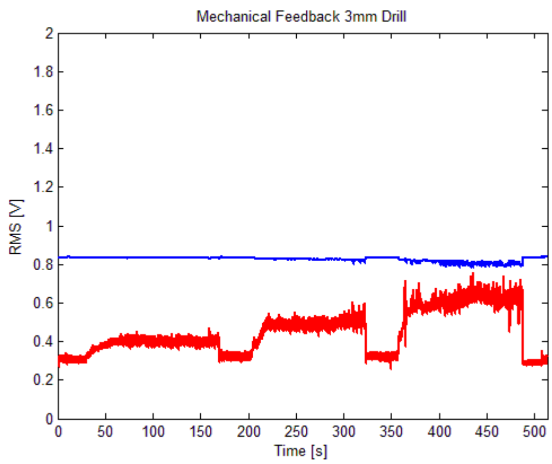

Fig. 3: Drilling experiments with mechanical feedback control system; RMS value of the inductive sensor's output – blue line, RMS value of control effort – red line

Initial contact between drillbit and workpiece occurs at 30 sec with feed rate 0.03*mm/rev*. An increase is observed in control effort (voltage-controlled amplifier's output). It is the reaction of the control system trying to compensate for the changes in the inductive sensor's signal which is caused by the applied load. After nearly 2.8*mm* depth of drilling, the drillbit is separated from the workpiece at 170 sec. 0.06*mm/rev* feed rate is applied at 205 sec which results in a more increase in control efforts. Meanwhile, inductive sensor's output presents a slightly more obvious drop than previous feed rate. Drillbit is separated from workpiece at 325 sec with a restore of both signals. Drilling depth for this feed rate is 4.8*mm*. At 360 sec, 0.09*mm/rev* is setup and the supplied voltage to the transduce increase even more while the inductive sensor signal displays a slight drop however can still be maintained at a desired level. Drilling depth for this feedrate is 7.8*mm*. As feed rates increases, control effort climbs up gradually against the change in inductive sensor's output which seems to drop proportionally.

Fig. 4 represents the oscilloscope readings of the drilling experiment with current feedback control system. In this experiment output of the current signal is used as both actuating signal and signal to be controlled (Fig. 2). Same as the previous experiment three different feed rates have been applied, these are: 0.03*mm/rev* (at 15 sec), 0.06*mm/rev* (at 185 sec) and 0.09*mm/rev* (at 345 sec). For

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all 3 intervals when the feed is applied the increase in the control effort (red curve) can be observed.

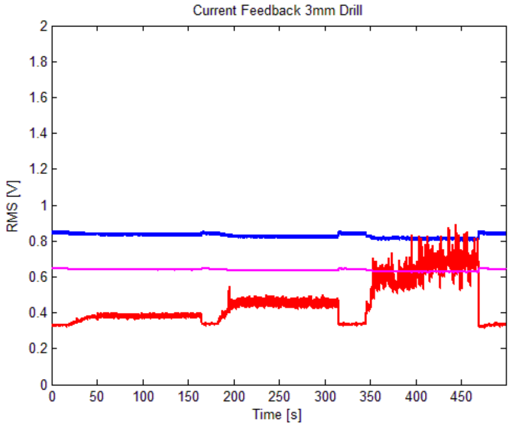

Fig. 4: Drilling experiments with current feedback control system; RMS value of inductive sensor's output – blue line, RMS value of the current sensor's output – purple line, RMS value of control effort (amplifier's output) – red curve

This demonstrates that the control system is working to compensate for the changes in the current sensor's signal, caused by the applied load. It can be also seen that the output of the current signal (purple line) slightly drops during the experiment but still can be kept at a desired level. This shows the efficiency of the control system, as it is able to stabilise the amplitude level of the signal to be controlled. Regarding the inductive sensor's output, it demonstrates moderate decreases for 3 intervals which imply a close relationship between current and vibration in reality. In other words, stabilising ultrasonic vibration through maintaining the current is an effective method. As a result, it highlights the reliability and convenience of current feedback control.

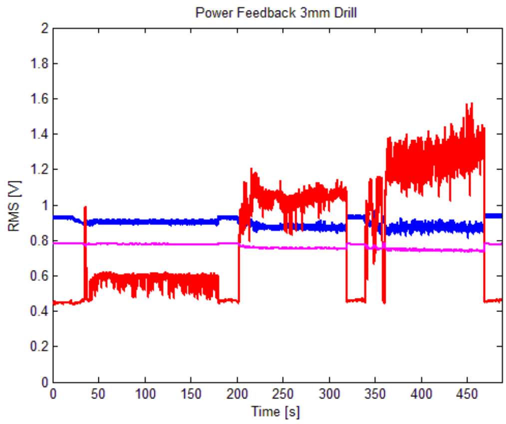

Fig. 5: Drilling experiments with power feedback control system; RMS value of the inductive sensor's output – blue line, RMS value of power sensor's output – purple line, RMS value of control effort – red curve

The oscilloscope readings of the drilling experiment for power feedback control system have been obtained too. In this case the output of the current signal is used as the actuating signal for the positive feedback loop and the power signal serves as the signal to be controlled for the negative feedback loop. Experimental results are presented in Fig. 5. Three different feed rates have been setup: 0.03*mm/rev* (at 35 sec), 0.06*mm/rev* (at 200 sec) and 0.09*mm/rev* (at 340 sec). Voltage-controlled amplifier's output for high feed rates (0.06*mm/rev* and 0.09*mm/rev*) increases considerably compared with mechanical feedback and current feedback. This is caused by the obvious drop in power sensor's output (purple line) under load. Control system generates higher supplied voltage for transducer to compensate the energy loss at the drilling tip during vibro-impact. The ability of the control system to stabilise the amplitude level of the power signal confirms its efficiency. For the signal from inductive sensor, a more obvious decrease has been witnessed for three feed rates.

Conclusions

Autoresonant control allows keeping the non-linear resonant mode of vibration in ill-defined and time changing conditions. The completed investigation revealed that the control system based on mechanical feedback provides the highest efficiency of keeping the RMS of vibrations (although the vibration information on the tip of drillbit is unavailable, it has been experimentally verified vibration at end of concentrator is in proportion with that of on the tip due to the regular waveform of ultrasonic vibrating system). Advantages of mechanical feedback are linked to the location of the sensor. In the case of mechanical feedback, the sensor is placed near the cutting zone and provides the most reliable and direct information of the dynamical machining process.

Electrical feedback is based on the sensor measuring the electrical characteristics of the piezoelectric transducer, which reflects the real vibrations of the ultrasonic system in an indirect way. The piezoelectric transducer is distant from the cutting zone and its electrical characteristics (current and power) are much less subject to the influence of the cutting process than are the mechanical characteristics. This explains the reduced efficiency of the control system with electrical feedback in maintaining the vibration level.

Hole surface roughness examinations have been executed. Interestingly, for low feed rate 0.03*mm/rev*, mechanical feedback produced holes demonstrate an overall best surface finish quality. In contrast, for high feed rate 0.09*mm/rev*, minimum surface roughness holes are produced by power feedback. This result indicates the surface finish quality seems to depend on the control effort generated by the control systems. Aggressive control produces higher supplied voltage which drives ultrasonic vibrating system to deform the material and break metal chips more effectively. As a result, more advantages will be obtained by autoresonant control during machining.

References

[1] V.K.Astashev, V.I.Babitsky, **Ultrasonic Processes and Machines**, Dynamics, Control and Application, Berlin:Springer, 2007.

[2] V.I.Babitsky, A.N.Kalashnikov, F.V.Molodtsov, **Autoresonant Control of Ultrasonically Assisted Cutting**, Mechatronics, 2004, 14(1), (91-114).

[3] V.I.Babitsky, **Theory of Vibro-Impact Systems and Applications**, Berlin:Springer, 1998 (Revised translation from Russian, Moscow:Nauka, 1978).

[4] V.I.Babitsky, **Autoresonant Mechatronic Systems**, Mechatronics, 1995, 5, (483-495).

[5] I.J.Sokolov and V.I.Babitsky, **Phase Control of Self-Sustained Vibration**, Journal of Sound and Vibration, 2001, 248(4), (725-744).

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