Taking active control of vibration

by Nico Theron

The high vibration levels of cutting tools during machining causes a deterioration of surface finish and a reduction in tool life. Machining with worn tools, on the other hand, also causes high vibration levels and at a certain point in the life of a cutting tool, the deterioration may spiral out of control.

Active control of the vibration associated with the machining process thus holds the promise of attaining improved work piece surface finish, as well as prolonged tool life. Alternatively, productivity may be increased by machining at high speeds that would otherwise have been prohibited by resulting high vibration levels.

The Dynamic Systems Group of the Department of Mechanical and Aeronautical Engineering at the University of Pretoria has long been involved in vibration measurement during machining processes, initially mainly for the purpose of tool condition monitoring, but now increasingly also for active tool vibration control.

More about active vibration control

Active vibration control during machining is a relatively new field, prompted by the advent of high-speed digital signal processing. The vibration in question is generally, in mechanical engineering terms, at a high frequency. To control this type of vibration, high speed calculations on the controlling computer system are required.

A structure continually vibrates as a result of a continued excitation by some time-varying force acting on the system. The force with which material is removed from the work piece at the cutting surface is an excellent example of such a time-varying force. In this case it excites vibration in the structures of both the work piece and the tool holder.

The purpose of active vibration control is generally to attenuate vibration. Active vibration control can be considered as the application of an additional time-varying force on the structure of which the vibration needs to be attenuated in such a way that the resulting vibration cancels the original offending vibration. This generally means that energy is consumed in order to reduce the vibration; that is, at a cost to the operator.

In order to actively control vibration, it is necessary to measure the vibration. Think of this measurement process, employing a vibration sensor, as the conversion of a small amount of mechanical energy of motion into electrical energy in the form of an electronic signal. The control system essentially deals with either analogue electronic signals or digital signals.

A digital signal is the result of a computer measuring the analogue electronic signal. The digital control system uses the measured vibration information to decide what action it should take to control it. Once the decision has been made, the control system writes this out as an analogue electronic command signal. It then needs an actuator to convert this electronic signal into a mechanical action, for instance a force acting on the vibrating structure. This actuation may be thought of as the inverse of the vibration sensing, except that the actuation involves considerably more energy, which is supplied from an external source, like mains electricity.

Challenges facing the active control of vibration

A major problem with active control of vibration during machining processes is the lack of space to mount the vibration sensor and the actuator. Both of these should be positioned quite close to the cutting face to be effective, and to the general hostile environment to which both these elements would be exposed.

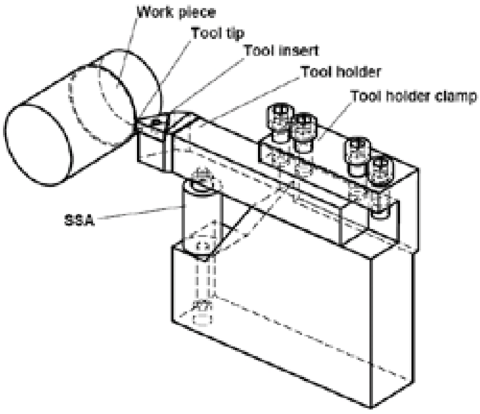
For this reason, it would be largely beneficial if the vibration sensor and the actuator could be combined into a single electro-mechanical device.
A research project currently undertaken by the Dynamic Systems Group is investigating the possible use of piezo-electric material to create a so-called self-sensing actuator for active vibration control during turning operations; essentially an actuator that is also used for measuring vibration.

More about piezo-electric material

Piezo-electric material has two properties that are very useful for the sensing and actuation of mechanical systems, the first of which can be considered the inverse of the other. When piezo-electric material is subjected to mechanical stress, an electric charge is generated through the material. This charge is proportional to the mechanical stress, and can easily be sensed with an appropriate electronic circuit. This property enables the use of piezo-electric material as sensing elements in transducers used to measure acceleration, force or pressure. On the other hand, when an electric voltage is applied across piezo-electric material, the material element contracts or expands according to the polarity of the applied voltage. This expansion or contraction is directly proportional to the applied voltage, which means that piezo-electric material can also be used in actuators where the generated force needs to be accurately controlled. Both these properties of piezo-electric materials are widely used in various products available on the market.

Researchers elsewhere have shown that the two properties of sensing and actuation can be combined simultaneously in a single piezo-electric element, although this is not currently used in any product, and some problems associated with this simultaneous sensing and actuation need to be resolved. An actuator that is used for simultaneous actuation and sensing is called a self-sensing actuator.

Figure 1 illustrates one possible configuration for the use of a self-



→ 1. The proposed configuration for using a self-sensing actuator to actively control vibration during lathe turning operations

sensing actuator when turning on a lathe. Here the tool holder is mounted in the tool post with a larger overhang than usual. The overhang is then supported by the piezo-electric actuator, which is cylindrical in shape. The actuator is supported on an extension of the tool post.

When devising a control system for the actuator, the structural dynamic properties of the tool holder should be taken into account. The frequency response functions in terms of displacement response at the tool tip and at the actuator position due to vibration excitation at both these positions are required. These may be obtained through calculation with the finite element method, or by measurement on the actual tool holder and actuator system.

In the control system, these frequency response functions are represented with infinite impulse response digital filters. This allows the calculation of the tool tip vibration from the displacement measurement at the actuator position. Since the tool tip vibration needs to be minimised, the calculated tool tip vibration is used to calculate the coefficients of an adaptive filter that forms the heart of the control system.

An adaptive filter is required, because of the rather complex nature of the vibrations that need to be attenuated. Cutting processes in general cause random vibration, which means that it is impossible to predict the future vibratory motion. Furthermore, the vibration is non-stationary, which means that even the statistical properties with which random vibration is normally described change all the time. This change is due to the fact that the structural dynamic properties of the work piece, both in terms of mass and stiffness, change as material is removed while the machining proceeds. The structural dynamics of the work piece interact with those of the tool to cause the overall vibration. When vibration of this nature is to be attenuated through active control, an adaptive controller is required. The use of a filtered x-LMS algorithm is currently being investigated for this purpose.

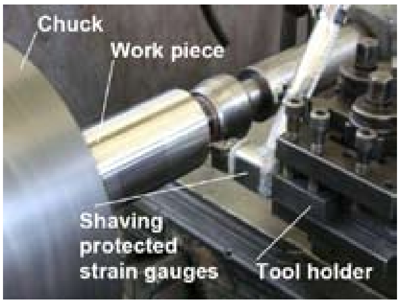
Because of the fact that the control system is specifically devised to handle the non-stationary random vibrations, it is not necessary to model the structural dynamics of the work piece. The influence of the work piece is properly accounted for through feedback of the measured vibration response of the tool at the actuator position. This signal is passed through the adaptive filter and then used as a command signal to drive the piezo-electric actuator.

Simulated response

To date, the active vibration control system has not been built yet, but it has been modelled mathematically and this model has been implemented in a MATLAB Simulink™ computer program. The program is used to simulate the whole dynamic process of vibration and control, and allows the engineer to evaluate the performance of the proposed control system before it is built. In order to perform a simulation, a realistic driving function is required. For this purpose, a comprehensive set of vibration measurements was made when turning on a lathe. This measurement did not involve any vibration control, because the purpose was to determine typical tool tip vibration during normal, conventional turning.

The vibration measurements were performed with a tool holder instrumented with strain gauges. The strain gauges were connected in three bridge configurations to measure the feed direction, the cutting direction and the axial direction dynamic forces at the tool tip. Prior to measurement, the three measuring channels were calibrated by applying known forces to the tool tip and measuring the corresponding bridge outputs.

The instrumented tool holder is shown in Figure 2. This photograph was taken during the vibration measurement exercise. The strain gauges were covered with a sheath to protect them from shavings and cutting fluid. The output of the three measurement channels were recorded by computer. Using a finite element model of the tool holder, the tool tip displacement time history could



→ *2. A strain gauge instrumented tool holder being used for measuring cutting forces during lathe turning*

be mathematically reconstructed from these measurements.

The reconstructed tool tip vibration signal was used in the simulation of the active control system, and the simulation results were very promising: it indicated that a 93% attenuation of the tool tip vibration is possible with the proposed active control system, employing the self-sensing actuator. The simulations also accentuated that the infinite impulse response filter approximation in the control system of the structural dynamics of the tool holder must be reasonably accurate in order to obtain good vibration attenuation. Sufficiently accurate models are, however, considered practically feasible.

Tool condition monitoring

The fact that the tool vibration is measured during active control of vibration additionally allows for monitoring of the tool condition, with the purpose of establishing an optimised tool replacement strategy. The current practice is to replace tools at fixed production intervals. This has been shown not to be optimal, as tool life varies significantly from one tool to the next.

The replacement intervals are determined by the life of the poorest tools, which results in many tools often being replaced prematurely. Previous work done by the Dynamic Systems Group on tool condition monitoring has shown significant benefit in using neural network techniques to interpret tool vibration measurements in order to determine the best time to replace a machine tool. Tool condition monitoring can lead to significant savings in tool replacement costs, but was not yet embraced by the machining industry, because of, among others, the additional complexity of the measuring system in the vicinity of the cutting surface.

The combination of active vibration control and tool condition monitoring has a multitude of benefits that may lead to implementation in industry. Additional work still needs to be done on the neural network techniques for vibration interpretation under active vibration control conditions. However, the importance of keeping the additional instrumentation surrounding the tool holder to a minimum is well understood and is the main motivation for pursuing the successful implementation of a self-sensing actuator.

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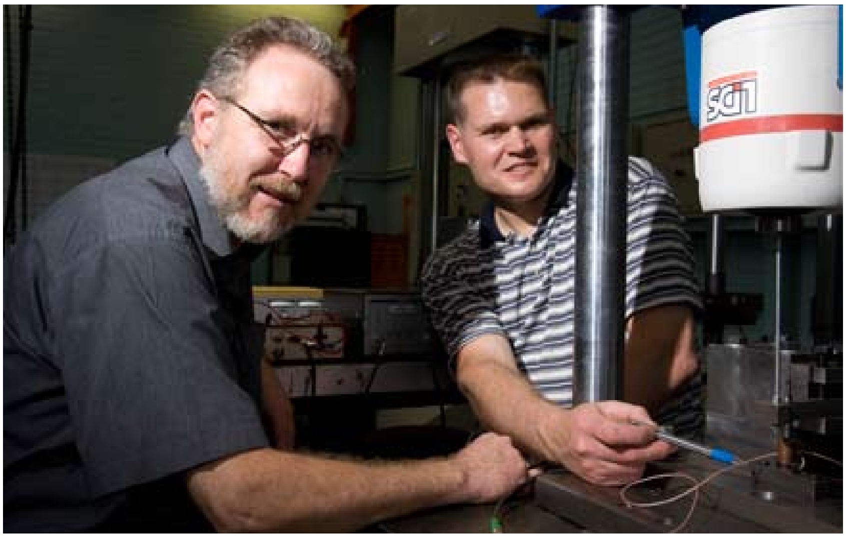
→ *Doctoral student Burkhard Freyer (right) discussing his research in self-sensing actuators for active tool vibration control and tool condition monitoring with Professor Nico Theron.*



Water-Drop Lens

How it works: The motors that zoom and focus the lens on a camera phone are bulky and drain the battery. But a process called electrowetting will replace the lens with a droplet manipulated within a glass cylinder. A zap of voltage will turn the surface concave, allowing you to focus or zoom in.
Who's working on it: Philips, Samsung
Due out: Not before 2013

[future gadgets]