Vibration Assisted Machining: Modelling, Simulation, Optimization, Control and Applications

A thesis submitted for the degree of

Doctor of Philosophy

by

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Abstract

Increasing demand for precision components made of hard and brittle materials such as glasses, steel alloys and advanced ceramics, is such that conventional grinding and polishing techniques can no longer meet the requirements of today's precision manufacturing engineering. Particularly, in order to undertake micro-milling of optical glasses or other hard-machining materials, vibration assisted machining techniques have been adopted. However, it is essential and much needed to undertake such processes based on a scientific approach, i.e. the process to be quantitatively controlled and optimized rather than carried out with a trial-and-error manner.

In this research, theoretical modelling and instrumental implementation issues for vibration assisted micro-milling are presented and explored in depth. The modelling is focused on establishing the scientific relationship between the process variables such as vibration frequency, vibration amplitude, feedrate and spindle speed while taking into account machine dynamics effect and the outcomes such as surface roughness generated, tool wear and material removal rate in the process.

The machine dynamics has been investigated including a static analysis, machine tool-loop stiffness, modal analysis, frequency response function, etc, carried out for both the machine structure and the piezo-actuator device. The instrumentation implementation mainly includes the design of the desktop vibration assisted machining system and its control system. The machining system consists of a piezo-driven XY stage, air bearing spindle, jig, workpiece holder, PI slideway, manual slideway and solid metal table to improve the system stability. The control system is developed using LabVIEW 7.1 programming. The control algorithms are developed based on theoretical models developed by the author.

The process optimisation of vibration assisted micro-milling has been studied by using design and analysis of experiment (DOE) approach. Regression analysis, analysis of variance (ANOVA), Taguchi method and Response Surface Methodology (RSM) have been chosen to perform this study. The effects of cutting parameters are evaluated and the optimal cutting conditions are determined. The interaction of cutting parameters is established to illustrate the intrinsic relationship between cutting parameters and surface roughness, tool wear and material removal rate. The predicted results are confirmed by validation experimental cutting trials.

This research project has led to the following contribution to knowledge:

(1) Development of a prototype desktop vibration assisted micro-milling machine.

(2) Development of theoretical models that can predict the surface finish, tool wear and material removal rate quantitatively.

(3) Establishing in depth knowledge on the use of vibration assisted machining principles.

(4) Optimisation of cutting process parameters and conditions through simulations and machining trials for through investigation of vibration assisted machining.

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Chapter 1 Introduction

1.1 Background of the research

1.1.1 Overview of vibration assisted machining

Vibration provides a lot of benefits in our life, such as in manufacturing, medical, communications, transport, industries, etc. In the machining process, vibration can lead to improvements when applied in the correct manner. The same occurs in manufacturing technology. Vibration assisted machining is a cutting technique in which a certain frequency of vibration is applied to the cutting tool or the workpiece (besides the original relative motion between these two) to achieve better cutting performance (Shamoto et al, 1990). There are a number of different experiments setup to simplify the process, but the tendency is to give a wide range of machining processes to machine hard and brittle materials. Matsumura (2005) developed a vibration machine using micro a end mill to machine glass in the ductile mode. However, this method of machining is not suitable for mass production. The design of the cutting tool, holder and machine resulted in the cutting process effect of tool wear, cutting angle and limited profile. If they are not concerned about this problem, the productivity in the area will be seriously affected.

Many researchers try to machine hard and brittle materials such as glass, ceramic, stainless steel, and steel alloys to a mirror surface finish in different types of machining applications. There are number of machines equipped with vibration devices for cutting purposes. However, the existing vibration machining process does not efficiently cut on hard and brittle materials because of excessive wear of the diamond cutting tool due to high chemical activity with iron (Bonifacio et al. 1994). Due to this phenomenon, researchers have explored a number of ways using ultrasonic and vibration to improve the design, frequency, cutting tools and equipment devices. It also to improve the efficiency with some basic experimental concepts carried over from conventional machines.

This project and research intends to review the various research experiments carried out in the past decade involving the ultrasonic and vibration assisted machining process. Even though this fundamental technique is still an ongoing investigation, the widely accepted principle based on vibration frequency and vibration amplitude is presented together with applications. The research review identifies the capability of vibration assisted machining technology in ultrasonic technology. Furthermore, this research discusses the future directions for 2 dimensional vibration assisted micro-milling research and applications.

Chern and Lee (2005) designed and developed a vibrating worktable in their drilling machine to create a vibration during the drilling process. The design was named the ultra-precision micro-drilling worktable. It was attached to a conventional drilling machine. They machined aluminium alloy (A1 6061-T6) and structure steel (SS41) investigated the effect of vibration assisted drilling. They found that the uniform distance between drilled holes center was greatly reduced with an increase of frequency. High frequency of vibration helped to align to the desired position. Hole roundness and oversize were also improved when high vibrating frequency was imposed. However, displacement of the hole centre and surface roughness of the drilled wall could be improved by increasing frequency of vibrating and amplitude. On the other hand, from their experimental setup, vibrating frequency has a negative effect on the drill life and there is a decrease in the number of holes produced because of the increased cutting speed, causing more collision with and rubbing of the edge of the workpiece. Therefore, this could be improved by applying additional axis of vibration.

The efficiency of the drilling process in reducing hole oversize was enhanced when frequency was increasing from 2 kHz to 10 kHz and hole oversize improved from 0.027 μm to 0.004 μm. The differences at the entrance of the hole produced without vibration are obvious when entering the workpiece surface. During the drilling cutting process, the drill bit rubbing the workpiece makes the uncut material at the edge at the hole, however when the vibration is applied, a nearly perfect circular shape can be obtained.

Chern and Chang (2005) presented another design for a vibrating worktable using a piezo-actuator affixed to a milling machine centre (model: MC- 1050P). The vibrating worktable used a piezo-actuator, two dimensional XY axis, a maximum operating frequency of 16 kHz and maximum travelling distance was 10 μm. It operated with a 2 channel high power amplifier to create the desired vibration to cut a slot of aluminium alloy Al 6061-T6. Through this experiment, they found that slot oversize about 20 μm, displacement of slot centre and slot surface roughness could be improved: employment of vibration cutting increases the number of slots produced within tolerance when high amplitude and proper frequency were imposed. However, higher frequencies have a negative effect on tool life according to a previous study (Chern et al, 2005). Even though higher frequencies affected tool life, the amplitude in vibration cutting had the highest influence on the interaction between the cutting tool and workpiece.

In vibration assisted machining, vibration amplitude (normally sine wave) lead to an intermittent gap during cutting and was identified as an important mechanism in vibration cutting. Increasing the vibration amplitude means an enlargement in the gap that allows more cutting fluid to extract the heat during the cutting process, thus enhancing the tool's life and reducing production cost.

In order to maintain its stability and precision, the vibrations within the machining system need to be monitored and controlled so as to achieve the optimum vibration displacement between the tool and a workpiece.

1.1.2 The current needs in industry

The development of precision metal cutting in recent years has not only been focused on better surface finishes, but also on expanding the sphere of applications. The machining of micro-scale parts is one such application. With the miniaturisation and increasing complexity of audio/visual products, the demand for high-precision micro machining is going to increase (Liu and Cheng, 2005).

Vibration assisted machining was introduced at early 1950s and has now become widely accepted in precision metal cutting industries. It has become a well known method, and many researchers have developed various kinds of design that suit their applications. For example, cutting hard and brittle material has now become popular with the help of vibratory cutting. Some factories have multi-function components such as Fresnel lenses or other varying profile optics requiring higher forms of accuracy and lower cutting forces that can be achieved with the help of vibration cutting. Workpiece deformation, chatter, built-up-edge (BUE) and burrs become major challenges at this micro scale (Isaev et al, 1961).

Many companies associated with aerospace or optical components production are considering diamond turning so as to achieve greater performance. Vibration assisted diamond turning is a process that uses a precision ground diamond cutter capable of nanometer positioning to produce nearly error free shapes (within micrometers of those desired) with high quality surface finishes (roughness at the nanometer scale). With the help of vibration assisted turning, the high modulus and fracture toughness of diamond make for a tool that retains a uniform, sharp edge over the extended cutting distance up to kilometers (Ikawa et al, 1991).

The new achievement in the material removal process is vibration micro-milling of steel using diamond tools, which has been under intensive investigation since the early 1990s (Brinksmeier et al, 1999). Carbon containing materials such as steel do not lend themselves to being machined with diamond tools. It is theorized that the carbon in the material either diffuse or mechanically weakens the carbon bonds in the diamond to produce rapid wear. If a surface finish of the same magnitude common on materials such as copper and aluminum (< 50 nm) could be realized in the machining one step on steel parts, such as valve seats, higher performance as well as tremendous time and money savings could be realized.

1.1.3 History of vibration assisted machining

Precision metal cutting is defined as a cutting technique, which enables the production of optical, mechanical and electronic components with micrometer or sub-micrometer form accuracy and surface roughness within a few tens of nanometers (Brehl, 2008). Starting with the United States in the mid 1960s, research into precision metal cutting was driven by the technological demands mainly from the defense and aerospace industries. While still very important to the military complex, precision metal cutting has expanded its field of application to touch almost every aspect of manufacturing, including moulds for contact lens production and non-spherical mirror arrays used in the most advanced scientific research satellites.

Vibration assisted machining was founded in the early 1960s when this technology achieved great things in drilling wood. The hydrostatic bearing with its sub-micrometer rotational accuracy was the first component of precision metal cutting to benefit from the research push. Along with the refinement of conventional machine components (spindles, metrology frames, etc.), the development of linear motors in the late 1970s and piezoelectric driven stages in the 1980s allowed for tool positioning and control on the nanometer scale. Not to be left out, materials research and the development of the monocrystalline diamond tool with its nanometric edge sharpness enable the levels of form error and surface roughness lowered even further (Brehl, 2008).

The technology discovered and/or refined over the past 40 years has found its way into one of three primary machining techniques: turning, planing or milling. Of these, turning has established itself as the relevant method due to its combination of relatively short machining time and high quality surface finish. Regardless of which manufacturing process is used, an additional polishing step is sometimes required to meet the ever increasing demand of industry for better surface finish and higher form accuracy.

1.2 Aim and objectives of the research

Aim of the research

The research aims to get a scientific understanding of the vibration assisted machining process against the material removal rate, surface roughness generation and tool wear. The research includes the machining system development, process modelling, simulation and optimization, and application of case studies.

The research uses a systematic approach based on the desktop vibration assisted micro-milling machine designed and built by the author.

Objectives of the research

The distinct objectives of the research are as follows:

- To develop a micro-milling test rig using a piezo-actuator as the vibration actuator.
- To model the vibration assisted machining process to predict the surface finish, tool wear and material removal rate.
- To design a program for user interface on LabView to control the piezo-driven device vibration mode options including vibration frequency, vibration amplitude, spindle speed and feed rate online during the cutting process.
- To develop algorithm on Ansys, Workbench, MatLab to investigate the 2D VAM cutting.
- To investigate the optimization and control of the vibration assisted machining process for selected application case studies.

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1.3 Scope of the thesis

The thesis contents are planned and structured based on the research findings as grouped consecutively. This dissertation is divided into eight chapters as shown in Figure 1.1.

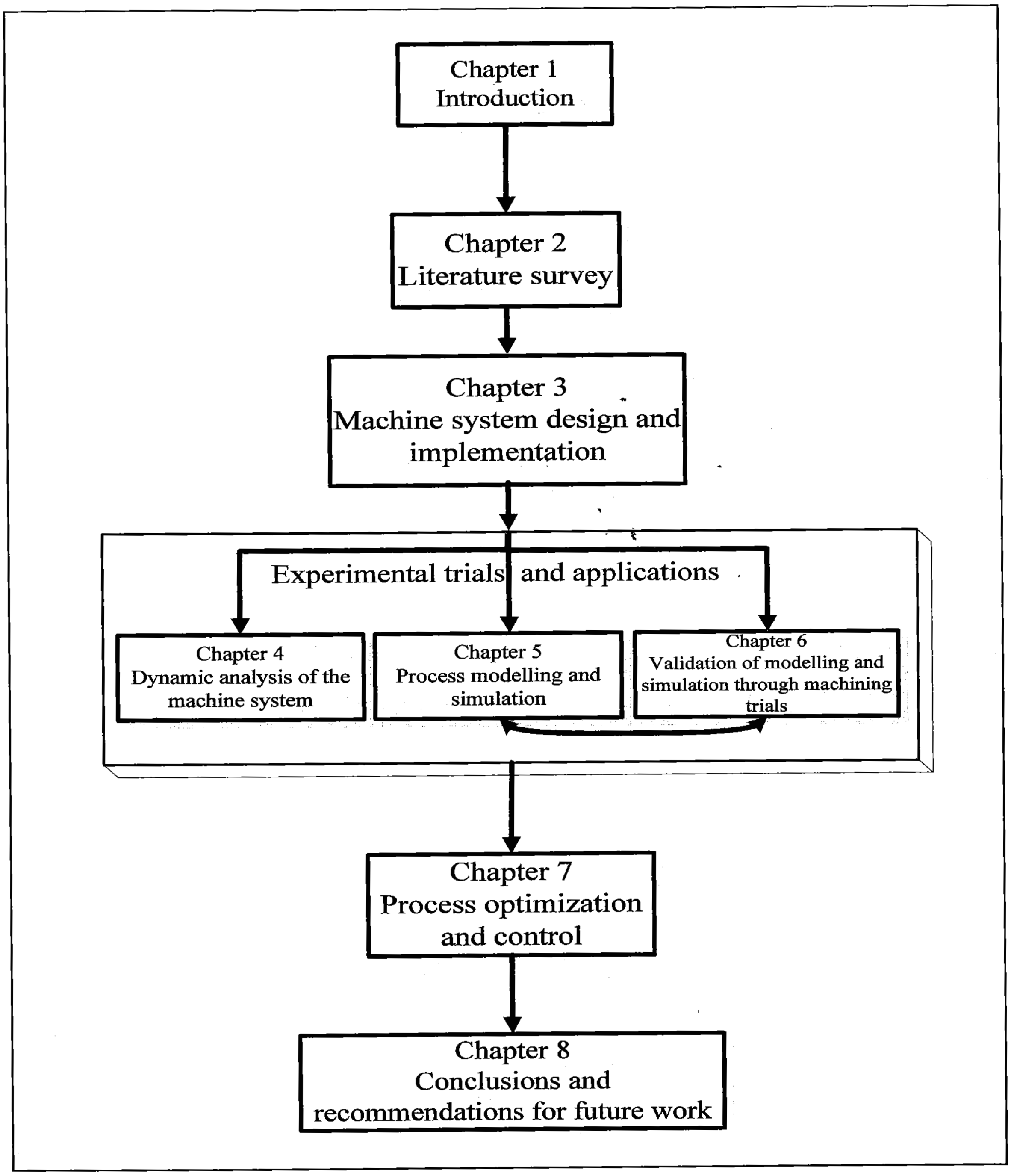

Figure 1.1: Structure of the thesis

Chapter 1 explains the historical background of the state of the art vibration assisted machining. It also consists of the current need of industries and a brief history of vibration assisted machining. The aim and objectives of the research have also been explained. Based on the objectives, the structure of this thesis is built and presented here.

Chapter 2 critically reviews the related ideas for the preparation of the research findings. The literature survey is responsible for the investigations of relevant and effective research to identify the related works that have been implemented on the vibration assisted machining based technology. Initially vibration assisted machining systems based on cutting process method were studied. A survey of recent developments in vibration assisted machining with their achievements is explained in this chapter. The discussion of machine design factors for test bed and piezo-actuator toward a response parameter system is carried out to highlight the errors of this system in this research area. With implementation of measurement on surface roughness, the tool wear and material removal rate are analysed.

Chapter 3 describes the system development design and implementation. This presents descriptions of software and hardware, focusing on the development and component assembly. The software and controller have been used, such as LabView 7.1 and MATLAB simulink, Ansys 11.0, Workbench and Mechanical Dekstop V2007 application software packages. Hardware devices took a part for these researches are piezo- electric XY stage, air bearing spindle with brushless motor, Physik Instrumente DC motor controlled X linear stage, data acquisition (DAQ) card, piezo-actuator amplifier and are also presented. Surface roughness measurement with equipment, such as the 3D Zygo Surface profiler explained in this chapter.

Chapter 4 focuses on investigating the machine dynamics of test bed. It includes the piezo-actuator analysis and machine dynamic behaviour by using Ansys and Ansys Workbench. These include all the dynamic simulation models, which are static structural, modal analysis, harmonic analysis, frequency response, etc. These investigations will be validated using hammer testing and modelling simulation. The limitation of the piezo-actuator in electrical and thermal failure will be described with different types of parameter condition. For piezo side, the driving response and electric capacitive response towards the synoptic of a driving system has been discussed by presenting the modelling and controller using the, LabView and Physik Intrumente software.

Chapter 5 presents a process modelling approach which will elaborate the simulation of the cutting process, modelling and surface generation and the motivation to use MatLab programming in the research. The discussion of modelling is focused on the cutting force, cutting tool trajectory, cutting mechanics and machine dynamics which is adopted from conventional machining. The related factors in 2D VAM are discussed and in depth investigation of tool temperature, chip thickness and chip formation presented. The comparative investigation between conventional and 2D VAM for its potential is discussed in great detail.

Chapter 6 reports the validations of the modelling through machining trials. These include the experimental plan, facilities and workpiece material and the condition monitoring of machine. The cutting forces, surface roughness, tool wear and material removal rate have been evaluated and validated between the simulation with 2D VAM and without 2D VAM. In addition, the effect of significant variables and machining parameters on the responses is further analyzed with the results from both the machining trials and the simulation.

Chapter 7 presents a discussion of the machining results, evaluation and optimum condition of the 2D VAM cutting process. The interactions between the each key parameter have been outlined for further future analysis.

Chapter 8 highlights the conclusions drawn from the research work and recommendations for future work.

Chapter 2 Literature survey

2.1 Introduction

Vibration assisted cutting is a cutting method in which periodic or oscillating cycles are imposed on the cutting tool or the workpiece, besides the original relative motion between these two, so as to get improvements in cutting performance. The fundamental feature of vibration assisted cutting is that the tool face is separated from the workpiece repeatedly. Historically, this technique was first employed in the precision drilling of wood and low carbon steel (Cerniway, 2005).

Vibration cutting started in the mid 1970s. It was reported in the beginning when this technique was used that the cutting tool underwent a circular distance of displacement towards the individual axis (X or Y or Z). Early experiments were primarily carried out at frequencies greater than 20 kHz. These "ultrasonic" frequencies were greater than 20 kHz. However, it showed vibration machining to have little practical value. It took nearly two decades of slow growth before this technology started to show promise.

Finally, in the early 1990s, research into vibration cutting at both low and high frequency produced results sufficient for industrial applications (Shamoto, 1991). This mature class of machining is called Vibration Assisted Machining (VAM).

It has been reported by Adachi and Arai (1997) that, unlike ultrasonic vibration cutting, low frequency vibration cutting has been found to prolong tool life and help reduce burr sizes in drilling. They developed an electro-hydraulic servo system to generate vibrations of 1,000 Hz in the spindle of an NC machine. Through their experimental studies on drilling aluminium, they found that burr size could be reduced considerably with the assistance of vibration in low frequency, especially 1,000 Hz.

The literature survey in this research covers all relevant as shown in Figure 2.1. The main element is the building up of the vibration assisted machining test rig where the applications and various investigations can be carried out to analyse improvement, which is critical and essential in this research.

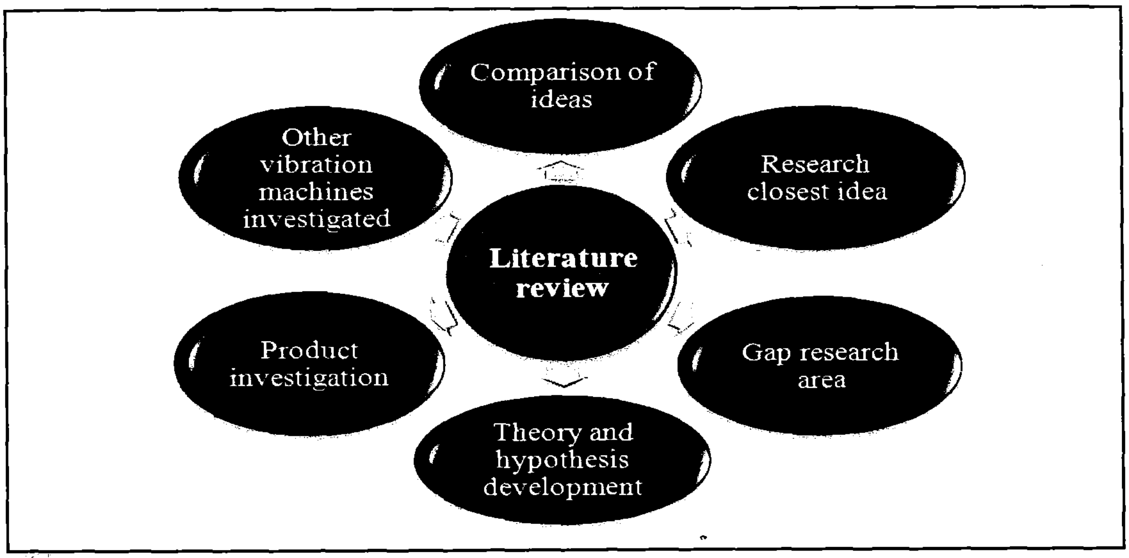

Figure 2.1: The aspect of literature survey

2.2 Vibration assisted machining

Vibration assisted machining techniques are becoming very demanding in many recent engineering developments, especially in relation to material removal rate, surface finish and tool wear. Generally, all vibration cutting has a common and different background. All the principal research has focused on the vibration itself. The main component used in the vibration cutting was the vibration generator. Figure 2.2 shows the fundamentals of vibration assisted machining in a wide range of applications.

The very basic component of vibration assisted machining is a piezo-actuator. Taking this stage as a starting point, many designs of the piezo-actuator have been developed into various application requirements, such as vibration assisted turning, milling, drilling, grinding, electric discharge machining (EDM) and, recently, the combination of electric discharge micro-milling with vibration assisted machining has been reported (Endo et al. 2008).

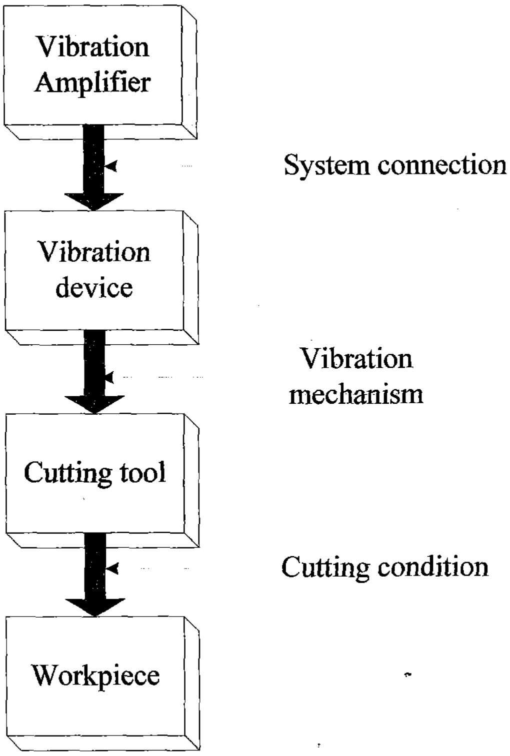

Figure 2.2: Block diagram of a VAM system

Vibration assisted machining technology has been studied by many cited references. All of these studies analyze in different ways the concept, design dynamics, characteristics and behaviours of vibrations by looking at surface generation, tool life and material removal rate.

Chern and Lee (2005) developed a milling machine with a vibration table, which vibrates the table holding a workpiece. They found that hole oversize, displacement of the hole centre and surface roughness of the drilled wall could be improved with the increase of vibrating frequency and amplitude. The results have demonstrated the potential of the vibration technique to be developed into a useful tool for enhancing the drilling technology.

Adachi and Arai (1997) found how to prolong tool life and help reduce burr sizes in drilling. They developed an electronic servo that vibrates in low frequency up to 1,000 Hz. Through their experimental studies on drilling of aluminum, they found that burr size could be reduced considerably with the assistance of VC. They built their servo machine on the spindle of the NC milling machine. An advantage of this design is the ease with which it can be modified for different applications. The purpose of their work was to develop a technique applicable to the drilling process for surface-roughness measurement in the wall paths.

Wang and Zhou (2002) proved by their experiments they could cut hard and brittle materials in high critical depth of cut. By applying an ultrasonic diamond tool tip a surface roughness of 100 nm was achieved. The material cut was a fused silica with cutting conditions: vibration amplitude 3 μm, vibration frequency 40 kHz, spindle speed 90 rpm and feedrate 5 μm/rev. They also proposed the fundamental principles and material removal mechanism of ultrasonic machining, which is developed to measure both dimensions and surface roughness simultaneously. The principle of the developed vibration is based on the displacement curve of the tool tip through a cycle of the vibrations on the tool tip.

Wu and Fan (2003) developed a centreless grinding technique called the ultrasonic elliptic-vibration shoe centreless grinding. This new method employs an ultrasonic elliptic-vibration shoe to support the workpiece and control the workpiece rotational motion instead of using a regulating wheel such as that employed in conventional centreless grinding. The vibration ellipse is applied into the shoe or bed of the workpiece with frequency of 20 kHz. The shoe is given an intermittent force in micron scale to push the cylindrical workpiece towards a spot between the bed and the grinding wheel. They discovered the rotation of the workpiece was controlled by the friction force between the workpiece and the shoe so that the peripheral speed of the workpiece is the same as the bending vibration speed on the shoe end-face. On the other hand, the geometry or roundness of the workpiece can be controlled by tilting the two angles γ for shoe and ϕ for bed piezo.

Vibration assisted machining technology based on the piezo-electric actuator method is improving year by year. In the article by Brehl (2008), the objective was to assess the potential of applying vibration in machining understanding of zero burrs. From his finding, the process does not allow a complex shape to be made without grinding and polishing. Surface roughness and tool life are very important in the metal removal processes focused on diamond cutting of ferrous materials. It was found that tool life is extended by 1D and 2D vibration assisted machining. From another point of view, vibration assisted machining experiments in steel, glass, and brittle ceramics confirmed that diamond tool life could be extended to allow economic machining of such materials and also demonstrated improvements in surface finish and ductile cutting when compared to conventional machining. The use of 1D vibration assisted machining led to significantly greater interest in 2D vibration assisted machining, starting in the mid-1980s (Brehl, 2008).

In their investigation of cutting aerospace materials, Babitsky and Kalanishikov (2003) made an experiment with a turning machine. The ultrasonic vibration process has a common problem when the load applied to the cutting tip and in results the loss of cutting efficiency. Through their experiment, the reduction of tip velocity also occurs during the cutting process due to the cutting tip's interaction with the workpiece, so the upper limit on surface speed is further reduced.

However, it can be eliminated with an auto-resonant control system. Efficient vibration cutting comes from the vibration design structure itself. They used bolted Langevin type transducers with maximum displacement of 20 μm and with maximum frequency of 20 kHz can improving the displacement efficiency. The reason for all of the improvements was a change in the nature of the cutting process, which was transformed into a multi-impact high frequency interaction between the tool and workpiece, giving a decrease in cutting force up to several times. The result has improved surface roughness by some 50% and noise reduction by 50%.

A simulation study to investigate vibration assisted machining was carried out by Cerniway (2005). This was achieved by using a computer technique which simulates the effect of Horizontal Speed Ratio (HSR) produced from kinematic tool tip surfaces, where a percentage of tool cycling between touched and untouched areas on the workpiece surface was calculated. The author proposed an initial attempt to evolve an application of the cycling or oscillating assessment technique by investigating how the frequency and amplitude of the machining tool tip location compared simulation.

2.3 Vibration assisted machining systems

The typical vibration assisted machining system consists of three main parts which are the data output (from desktop computer), data acquisition card (DAQ) and the vibration device (piezo actuator). The process involves the analogue and continuous time signals controlled by the LabView 7.1 software that transfers through signal conditioning circuitry in the data acquisition card and is amplified by an amplifier into the desired voltage and thus to the piezo actuator device.

Travis (1998) claims that DAQ is simply the process of measuring a real-world signal, such as the voltage or frequency, and bringing information into the computer for processing, analysis, storage, or other data manipulation. An overall system framework can be seen in Figure 2.3.

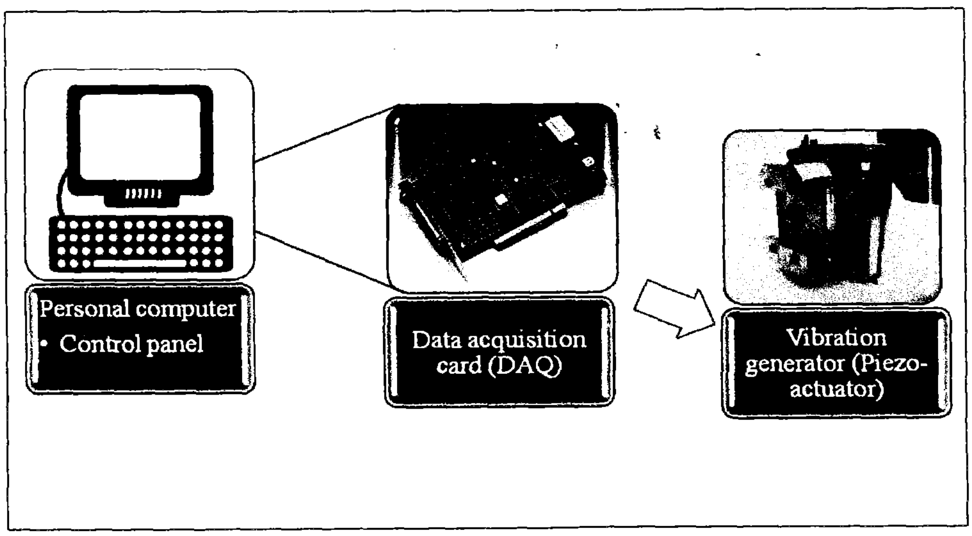

Figure 2.3: Basic system in 2D VAM

Suzuki and Nakamura (2003) constructed control systems by using data acquisition as a medium between the controller and actuator device. The acquisition is to keep and monitor the elliptical vibration to have a desired locus, where the amplitudes of the two directional vibrations and their phase shift are kept to the desired values, and the vibration frequency is locked to an average value of their resonant frequencies. Their idea was to locate the vibration control system which is mounted on the ultra-precision planing machine consisting of three feed tables with double hydrostatic oil guideways in XYZ axes, two rotary index tables in B, C axes and a five axis control system.

The development of the elliptical vibration cutting system is applied to ultra-precision diamond planing of hardened die steel, and a high quality mirror surface finish is obtained over a large area of the whole finished surface. The maximum roughness was 0.04 μm Ra, although the cutting distance reached 1,110 m. On the other hand, the surface finished by ordinary cutting without vibration was cloudy with maximum roughness of more than 0.52 μm Ra, within a cutting distance of 1 km. Based on this advantage, the elliptical vibration cutting system was successfully applied to ultra-precision micromachining of dies for manufacturing the front light panel of the LCD.

An optical quality surface with fine microgrooves over a large area of 122 × 91 mm^2 and with surface roughness of less than 0.04 μm Ra was obtained by the developed system. This is difficult for any conventional machining methods, including grinding, polishing and other ordinary cutting process.

2.3.1 Cutting mechanism in vibration assisted machining (VAM)

1D VAM

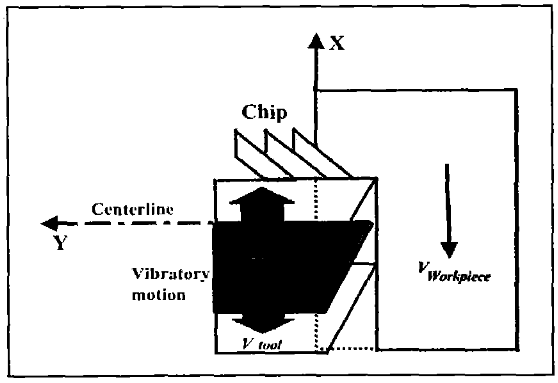

Figure 2.4: 1D vibration assisted cutting (Shamoto, 2004)

The 1D VAM moves in one plane parallel to the workpiece surfaces so as inline to the principal cutting force, as shown in Figure 2.4. By adding one more vibration motion a 2D

VAM system will be formed, moving the tool in elliptical tool motion (Figure 2.5). This can be observed when the major axis of the ellipse is inline with the cutting force and the minor axis is inline with the thrust force.

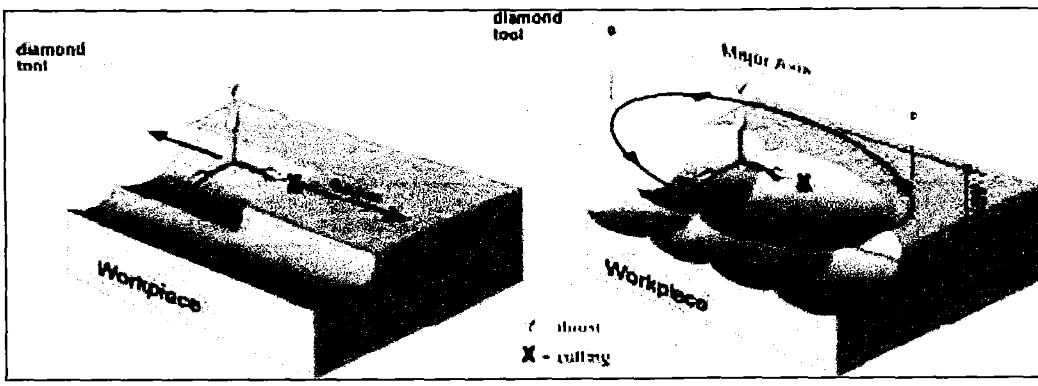

Figure 2.5: 1D and 2D elliptical vibration cutting (Cerniway, 2001)

Figure 2.6 shows the kinematic of 1D VAM where the tool is driven in a linear path subjected to the vibration frequency and vibration amplitude. It has been used by Shamoto, Moriwaki, Isaev, Kumbabe and Skelton, et. al. in their early investigations of vibration assisted machining. The intermittent contact of tool rake face relative to the workpiece is expressed as:

$$x(t) = A\sin(\omega) + Vt \tag{2.1}$$

$$\dot{x}(t) = \omega A\cos(\omega) + V \tag{2.2}$$

$x(t)$ and $\dot{x}(t)$ are the intermittent position and velocity at t, A is a amplitude, ω is vibration frequency equal to $2\pi f$ and V is a velocity. V is positive in 1 and 2, but negative in 3 and 4, this phenomenon is results because V is the relative velocity between tool and workpiece.

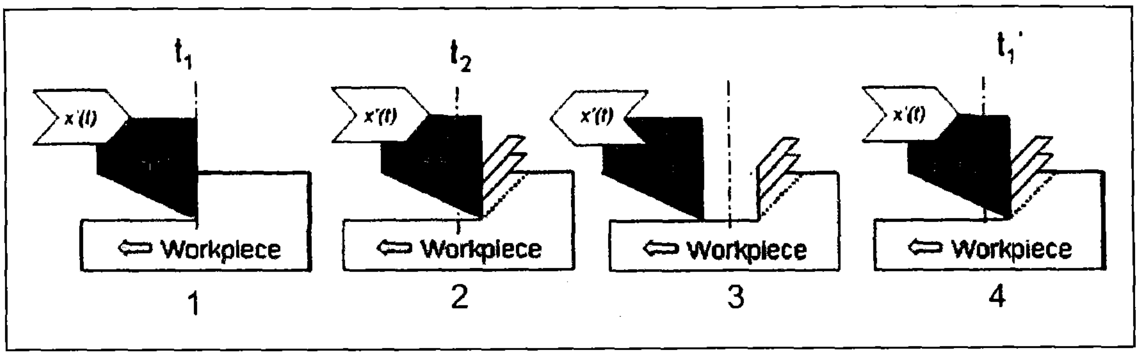

Figure 2.6: 1D vibration assisted machining (Dow, 2007)

2D VAM

Figure 2.7 shows the theory of reducing the cutting force in VAM which has been demonstrated experimentally by Shamoto and Moriwaki. Through their experimental study with low frequency systems operating at frequencies of 0 to 6 Hz they found that the instantaneous force (peak) cutting and thrust force are the same value as conventional cutting. But there is a zero time period when the tool has no cutting force at all. It is believed the zero cutting force condition came from the kinematic disengagement (tool separation) when there was a non-contact between the tool edge and the workpiece. Shamoto and Moriwaki have claimed that the reduction of cutting force was approximately 30% to 40% lower compared to conventional machining.

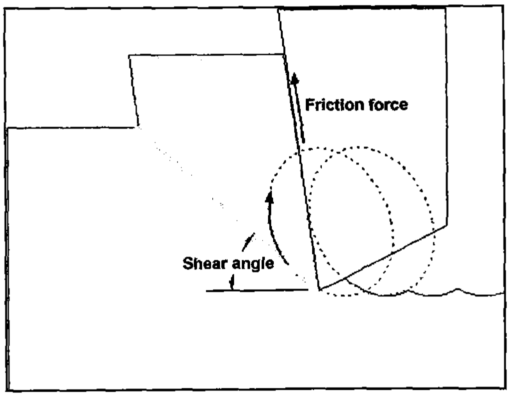

Figure 2.7: Shamoto and Moriwaki model for circular motion lifting phenomena

Ahmed (2007) claimed that the increase in the vibration amplitude leads to a 52% decrease in the average cutting force in vibration assisted machining. Again, it is because of an increase in part of a cycle of ultrasonic vibration without a contact between the tool and chip. An increase in the vibration frequency from 10 to 30 kHz results in a 47% drop in the level of average cutting forces, which could be attributed to an increased velocity of the tool vibration. Hence, an increase in either vibration frequency or amplitude leads to a decrease in cutting forces, which is beneficial to increasing accuracy and improving material removal rates.

2.3.2 Comparison between 1D and 2D VAM

Previous studies have shown that using one dimensional vibration assistance can extend tool life, lead to economies in machining, and also improvements in surface roughness compared to conventional machining (Wu and Fan, 2003). However, two dimensional vibrations assistance is much more effective, reliable and beneficial to the cutting process. The addition of vertical harmonic motion will bring the tool edge motion into a circle or ellipse that will impose an upfeed motion related to the workpiece. Experimental studies in previous research found the tool forces in two dimensional vibrations assistance are consistently smaller than one dimensional, even with the same tool geometry and machining conditions (Skelton and Wang, 2002). Average tool forces were reduced to 20% by one dimensional machining and by addition 2% more for two dimensional machining when compared with conventional machining.

Shamoto and Weber (1999, 1984) machined both ferrous and non-ferrous material using diamond and carbide tools. As shown by their experimental studies, longer tool life can be achieved by using two dimensional vibrations instead of one dimensional machining with the same condition of tool geometry, depth of cut and tool-workpiece material combination.

Figure 2.8 shows average thrust force versus cutting distance in meters in 1 D VAM (▲), conventional machining (♦) and 2D VAM (●). It is a major improvement when the thrust force drops to 20% of the conventional machining for 1D VAM and 2% more in 2D VAM.

The typical data were measured during cutting aluminium using carbide tools, but with no details about VAM conditions (Zhou, et al 2002).

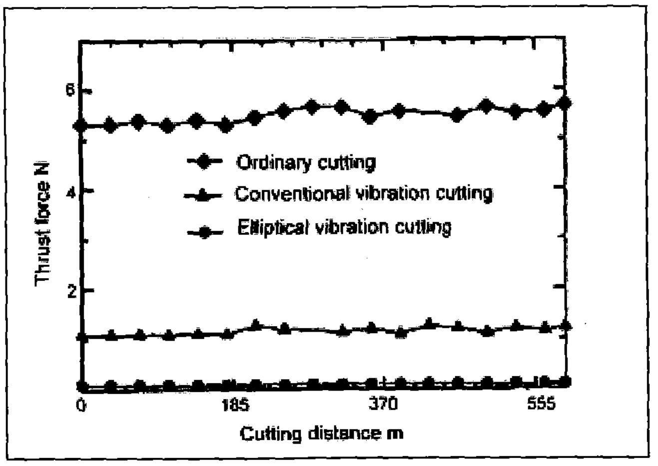

Figure 2.8: Comparison of thrust forces in 3 machining methods (Ma, 2004)

Significant improvements in accuracy have been achieved by two dimensional vibration assistance as measured by surface roughness and form, with reductions of up to 95% using two dimensional vibrations and 40% using one dimensional vibration (Brehl, 2007). Two dimensional vibrations also showed almost no burr formation, in comparison with the 60% to 80% reduction of burrs using one dimensional vibration, compared with conventional machining.

VAM actuator design

The evolution and market trending for vibration cutting changed rapidly when more researchers enhanced the piezo-actuator in their machine design on the shop floor. Circa, 1980-1990, developed a 1D actuation servo in his early research on a turning machine at the Frauhofer institute, as shown in Figure 2.9. His investigations focused on the vibration assisted turning using a diamond cutting tool on hard and brittle steel and glass (Klocke, 2004).

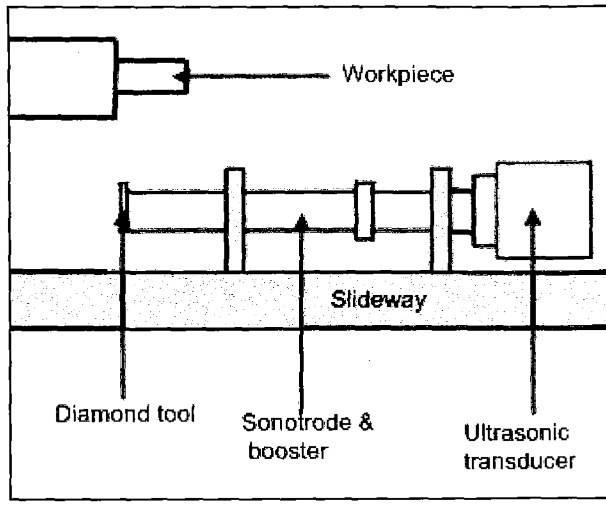

Figure 2.9: Fraunhofer servo design (Klocke, 2004)

Toh et al, 2004, developed a simple servo design. The operation of their servo design is similar to that of the Circa design, where the piezo-actuator transducer creates motion at longitudinal vibration and connected through a sonotrode to an amplification horn. Implementation of the non-amplifying resonator in his design brings the ultrasonic energy input and sets up a longitudinal resonance in the booster. The amplitude of the vibration is increased and this arrangement resulted in a ±5 μm sinusoidal displacement of the diamond tool.

Following the principle of mass weight designed in the diamond cutting tool where the longitudinal is off in the centreline, some of the investigators noticed that the elliptical motion was possibly produced automatically. A researcher at the University of Bremen, Germany designed and constructed the elliptical motion from the imbalance of mass position, similar to the Fraunhofer design. It has been successfully proved that the Bremen design generates at 40 kHz, 700W ultrasonic generator coupled to a piezoelectric converter to produce a tool ellipse motion. By optimizing the sonotrode/booster arrangement, vertical amplitude of 6 μm was produced. The elliptical tool path is slightly tilted due to the phase of bending motion. Within certain limits, the elliptical motion of this servo could be controlled with the addition of a counterweight. Figure 2.10 illustrates this elliptical motion due to system imbalance and the orientation of the tool servo to the workpiece.

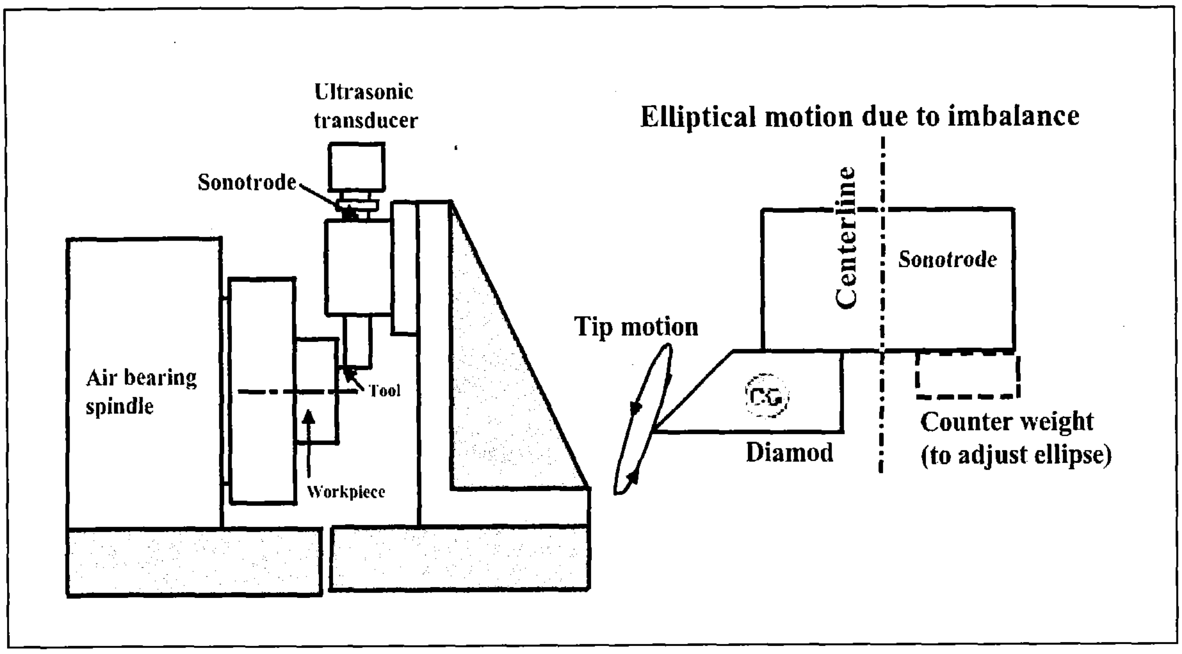

Figure 2.10: Servo design from Bremen University, Germany (Brinksmeir, 1999)

The success of the Bremen studies in servo design involving the diamond turning of steel shifted the focus away from 1D system to 2D system. As previously mentioned, aside from the dimension of cutting motion, servos operate either at or below resonance. The servos illustrated in Figures 2.9 and Figures 2.10 represent resonance and non-resonance designs respectively.

The research effort in vibration assisted machining allowed the researcher from Pusan University to design a two stacked piezo-actuator integrated into the tool holder, as shown in Figure 2.11. It is a non-resonant design utilizing two piezoelectric actuators oriented 90° parallel to each other. The flexures design is to eliminate the shear stress on the tool holder. The design of the flexure eliminates shear stress in one stack by the motion of the other (Hwan, et al, 1999). The tool path is a summation of two arcs, which produces a quasi-ellipse. This research effort was aimed at improving the machining accuracy of micro-scale parts by using elliptical vibration cutting.

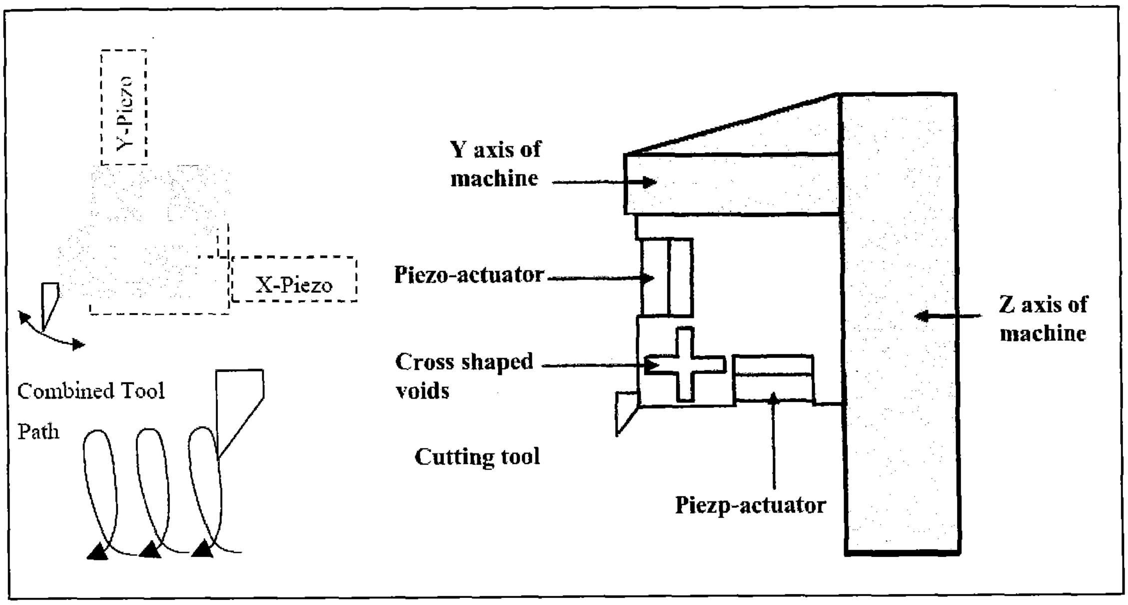

Figure 2.11: Servo design from Pusan National University, Korea

In 1999, Shamoto and Moriwaki developed a 2D servo using piezo stack in 2 directions to give ellipse tool motion, as shown in Figure 2.12. It efficiently operates at a resonance frequency of 20 kHz and produces an amplitude of 3.5 μm. The natural frequency of their machine was less than 5,000 Hz. Their investigation focused on the benefits of vibration diamond cutting of hardened steel towards the surface roughness and tool wear. This tool servo operated at the third resonant bending mode to produce a circular path.

Unlike previous designs where the actuators were in the same plane as the generated tool path, the actuators are perpendicular to the tool path. They found through their experiment using a single-crystal diamond tool-tip that cutting fused silica can be achieved even for 2 μm depth of cut. The increase in the critical depth of cut is significant and is a function of the ratio of vibration speed to cutting speed. A surface roughness Ra of 100 nm was obtained for up to 2 μm depth of cut.

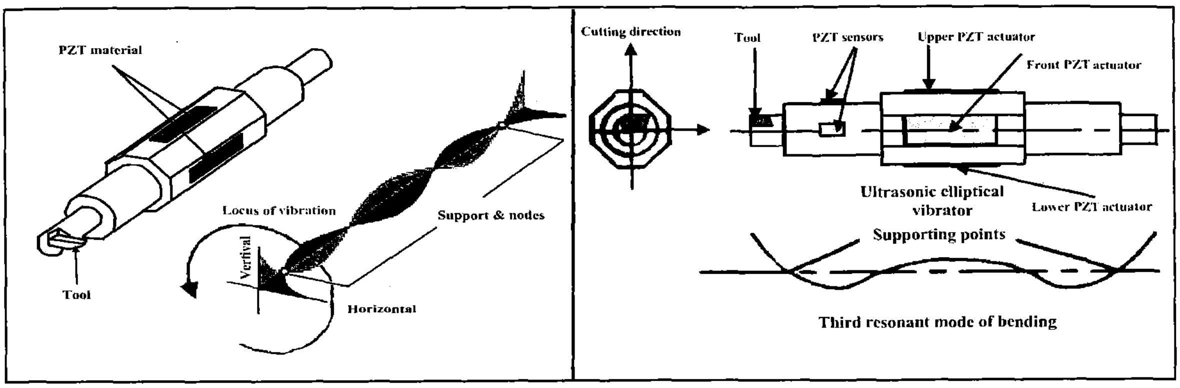

Figure 2.12: Resonant servo design by Kobe University, Japan (Moriwaki, 1999)

2.3.3 System specifications

In dealing with piezo-electric components, the tool servos on the VAM can be divided into two main categories:

i) Resonance

The vibration in an elliptical tool path at a resonant frequency in two directional tool motions is called the resonant system. Where the piezoelectric actuators are attached to the opposite side in 90° of the beam structure. The combination of the two bending vibrations makes the tool move in an elliptical path. Normally, it has advantages for tool vibration working at the greater frequency than 20 kHz. However, it is a limited service that can only operate at discrete frequencies and displacement amplitudes less than 6 μm (Figure 2.12).

ii) Non-resonance

Unlike resonant systems, non-resonance uses a mechanical linkage to convert the expansion and contraction of piezoelectric actuators into an elliptical tool path. The design of tool holder acts as the linkage. For a non-resonance system, the piezo-actuator component operates under the first natural frequency. This system can operate in a wide range of tool path. The huge working range in operating frequencies has been offered as well as amplitudes greater than ten times from the resonance servos. The disadvantage of this servo is that it required a large amount of electric energy to increase the performance in terms of displacement and frequency (Figure 2.11).

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