Development of Langevin Piezoelectric Transducer-based Two Dimensional Ultrasonic Vibration Assisted Machining (2D UVAM) on 5-axis Micro-milling Machine

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Abstract. The purpose of this study is to design and develop a Two-Dimensional Ultrasonic Vibration Assisted Micro-milling (2D UVAMM) system. Two-dimensional ultrasonic vibrations produced by 2D UVAMM are used to vibrate the workpiece in the micro-milling process. The system is developed using the principle of two Langevin piezoelectric transducers which have the ability to produce ultrasonic vibrations with small vibration amplitude. Process of 2D UVAMM design optimization was done by modal simulation using Finite Element Analysis method. Both Langevin piezoelectric transducers are designed to have symmetrical and asymmetrical vibration modes with the same natural frequency, so that elliptical pattern vibrations can be generated on the workpiece. The 2D UVAMM system operates at a natural frequency of 24 kHz and has an estimated total displacement on the normal and tangential axes respectively 0.766 µm and 0.382 µm. Two power sources with frequency of 24 kHz, phase difference of 90 degrees, and peak-peak voltage of 212 volt were supplied by an ultrasonic generator to excite both of the Langevin piezoelectric transducers. To confirm the developed 2D UVAMM system, experiments were conducted to compare the surface roughness of Aluminum 6061-T6 through micro-milling with conventional method and with additional of the 2D UVAMM system.

1. Introduction
In the current era, almost all tools used by humans are minimalist and portable devices, due to the miniaturization of components or parts. For example, the automotive industry, aerospace industry, medical field and energy industry have conditioned the need for parts with relatively small dimensions [1]. Increasing demand for components and micro-products requires the improvement and development of existing manufacturing technologies so as to enable faster and more reliable micro components production. To overcome this problem, now micro components can be easily produced through a machining process known as micro-machining.

Nowadays there are many micro-machining techniques that have been applied in industries, but among them the micro-milling technique is one that is widely used. Micro-milling is a machining technique for producing micro components using a sharp cutting tool that rotates to cut or scrape the material clamped on the workbench with material disposal in the form of chips [2]. Micro-milling enables industries to produce micro components with complex shapes and patterns.
However, the industries mentioned above have used a lot of hard and brittle materials, such as ceramics and glass, and conventional micro-machining processes are not enough to obtain machining results with high-quality tolerance and surface roughness. Various efforts have been made to improve the quality of the micro-machining process, until a method is found where the machining process is equipped with a vibration generating device [3]. In the machining process, giving vibrations can increase machining results when applied with the correct method and parameter [4]. Vibration-assisted machining (VAM) is a cutting method in which vibrations with a certain frequency and amplitude are given to the cutting tool or to the workpiece, in addition to the relative motion between the cutting tool and workpiece, to obtain better cutting performance. The basic principle of vibration-assisted machining (VAM) is the occurrence of contacts separation between the cutting tool and workpiece periodically [5].

In vibration-assisted machining (VAM) process, a small amplitude and high-frequency vibration source is used [6]. This can be achieved by using an actuator called piezoelectric actuator. Piezoelectric actuators are composed of a ceramic material that can contract and expand when an electrical voltage is applied. Because of its ability, the piezoelectric actuator is used to produce small displacements with high frequency and response speed. Compared to other types of actuators, piezoelectric actuators also generate high force or strength relative to their small size [7].

The micro-milling process can also be equipped with an additional vibration device, so it is called vibration-assisted micro-milling (VAMM). In VAMM process, vibration motion can be given linearly in one direction (1D VAMM) or elliptically in two directions (2D VAMM) [6]. Several 2D VAMM systems have been developed previously using linear piezoelectric actuators with frequency ranges that were still below ultrasonic [5,8]. Chen et al. [3] states that to date the 2D VAMM system in the micro-milling process is limited to frequencies below 3 kHz, which is not suitable for the micro-milling process. It was also stated that in order to achieve proper periodic chip separation in one workpiece engagement cycle, ultrasonic frequencies with range above 20 kHz are needed. Therefore, the development of the Two Dimensional Ultrasonic Vibration Assisted Micro-milling (2D UVAMM) system is a challenge nowadays.

Based on the problems mentioned above, the aim of this research is to develop a 2D UVAMM system in order to produce ultrasonic vibrations for micro-milling process using Langevin piezoelectric transducer which have the ability to produce vibrations with higher frequencies compared to linear piezoelectric actuator. From the results of the development, an experiment will be conducted to compare the surface roughness of machined products from conventional micro-milling and micro-milling equipped with the developed 2D UVAMM system.

2. Langevin Piezoelectric Transducer

Ultrasonic wave applications have been developed over the past few decades and piezoelectric ceramic materials have been commonly used as the source of these waves [9]. One example of the application of piezoelectric material in this field is the Langevin piezoelectric transducer. This type of transducer has a construction consisting of one or more piezoelectric elements which are clamped between two pieces of metal. Both pieces of metal are often known as mass or end mass.

![Figure 1. Construction and cross section of Langevin piezoelectric transducer](image-url)
The illustration shown in Figure 1 above is a general construction and the cross section of the Langevin piezoelectric transducer. Both piezoelectric elements are compressed between the two end masses which are separated by electrodes using a bolt through the middle part of the two masses. End mass 2 is usually made of lightweight metal and end mass 1 is made of heavy metal to ensure that the energy produced by the piezoelectric elements can be maximally transferred to the cross section associated with end mass 2 [10].

After being connected to a power source with a certain frequency, the transducer will then resonate. A Langevin piezoelectric transducer will resonate at a certain resonance frequency and amplitude. By changing the dimensions and geometries of the end mass on the transducer, the transducer can be adjusted for applications with the desired frequency and amplitude [10-11]. Abdullah et al. [9] stated that designing the Langevin piezoelectric transducer was not easy, because there was no valid information and equation to design and analyse the dynamic behaviour of the ultrasonic transducer. Therefore the Finite Element Analysis (FEA) method is one of the reliable analysis methods for analysing ultrasonic transducer.

3. Design and Optimization of 2D UVAMM System

3.1. Design Limitation

In designing the 2D UVAMM system, attention needs to be paid to the working envelope dimensions of the micro-milling machine. The dimensions of the 2D UVAMM system must be proportional so as not to disturb the movement of the machine. The micro-milling machine used in this study is Hadia Micromill-5X, a miniaturized table/spindle tilting type micro-milling machine shown in Figure 2. It consists of five axes of movement, with three XYZ linear axes and two AC rotation axes. Each axis is driven by a stepper motor stage which is controlled by DS102 Suruga Seiki stepper motor driver. A Nakanishi HES 810-ST32 electric motor spindle is used to rotate the cutting tool to a maximum speed of 80,000 RPM. The 2D UVAMM system developed in this study was then used to produce vibrations that oscillate on two axes that are level with the planar surface of the workpiece, it will then be placed on the C axis motor stage as shown in Figure 3.

3.2. Design of 2D UVAMM

The design of the 2D UVAMM system was developed using the Langevin piezoelectric transducer principle. This design was made based on a reference from Kurniawan et al. [12], a surface texturing device using two-dimensional ultrasonic vibrations. This system consists of two bolt-clamped Langevin piezoelectric transducers which are installed with a 90 degree angle difference. The reason for choosing this type of transducer is because of its ability to produce ultrasonic vibrations with small amplitude that is still within the micrometer range. Each Langevin piezoelectric transducer used is composed of four piezoelectric ring actuators. The piezoelectric ring used in study is produced by Soar Piezo, with an outer diameter of 15 mm, inner diameter of 6 mm, thickness of 3 mm, and it is made of PZT4 material. Detailed specifications of the piezoelectric ring used are shown in Table 1.
Previously, the design of Kurniawan’s Langevin piezoelectric transducer [12] was used to vibrate the head block installed with a Polycrystalline Diamond (PCD) cutting tool. Whereas in the purpose of this study, a 2D UVAMM system was developed to generate vibrations for the workpiece in micromilling process, therefore the head block needs to be modified into a workpiece clamp which can simultaneously receive vibrations produced by both Langevin piezoelectric transducers.

Three-dimensional modeling software used in designing the 2D UVAMM system is Autodesk Inventor 2016. CAD design of the 2D UVAMM can be seen in Figure 4. The design consists of two Langevin piezoelectric transducers which are mounted perpendicular to each other on a holder block made of AISI 1045 medium carbon steel. Both end mass with diameter of 15 mm which function as bolts to tighten the system are made of the same material. Head block functions as a workpiece clamp and it is made of Aluminum Duralumin 2024 Alloy which is lighter than steel, thus the resulting vibrations produced can be channeled effectively to the workpiece. The workpiece material used in this study is Aluminum 6061-T6. The whole system is then connected to the C axis motor stage using an AISI 1045 medium carbon steel base plate, and an Aluminum Duralumin 7075 Alloy base block.

### Table 1. Piezoelectric Ring Specification

| E  | C  | Tc | Tg δ | Fr | Kp | Zr | Qm | d33 |
|----|----|----|------|----|----|----|----|-----|
| 1500 | 520 | 300 | 0.5  | 107 | 43 | 30 | 600 | 320\times10^{-12} |

**Figure 4. CAD Design of 2D UVAMM**

3.3. Modal Simulation of 2D UVAMM

CAD design that were previously made need to be evaluated to analyze its dynamic behavior. The evaluation process is done by modal simulation through the Finite Element Analysis (FEA) method. ANSYS Workbench 17.0 software is used to determine the natural frequency of each vibration mode formed from the 2D UVAMM. Two vibration modes that will be used are the symmetrical and asymmetrical modes. The following Figure 5 shows the illustration of the two vibration modes.

When the two Langevin piezoelectric transducers are in the same phase, the system will produce a symmetrical vibration mode, whereas when both of the Langevin piezoelectric transducers are not in phase, an asymmetrical vibration mode will occur. Vibration motion to the normal axis from the tip of the transducer is produced by symmetrical mode, while the vibration motion to the tangential axis is caused by asymmetrical mode. The process of optimizing the design of 2D UVAMM system is done so that vibrations can be generated with an elliptical motion, where the phenomenon can be achieved if both symmetrical and asymmetrical vibration modes have a natural frequency that is almost close or equal. Kurosawa et al. [11] stated that the natural frequency of symmetrical and asymmetrical vibration modes can be modified by changing the dimensions and geometries of the end mass. Therefore, several simulation processes with different end mass length variations need to be carried out to identify the appropriate natural frequency in order that both vibration modes can be formed simultaneously on 2D UVAMM system.
4. Experiments and Results

4.1. Modal Simulation Results
End mass with a diameter of 15 mm with variations in length of 12 mm, 13 mm, 13.5 mm, 14 mm, and 15 mm are used in the modal simulation process to determine its effect on the natural frequency of both symmetrical and asymmetrical vibration modes. From the modal simulation through ANSYS Workbench 17.0 software, three pairs of symmetrical and asymmetrical vibration modes with different natural frequency ranges are obtained. Symmetrical and asymmetrical vibration modes 1, 2 and 3 are sorted by their natural frequency, detailed information is shown in Table 2 and Figure 6.

| End Mass Length mm | Natural Frequencies |
|--------------------|---------------------|
|                    | Symmetric Mode 1 (Hz) | Asymmetric Mode 1 (Hz) | Symmetric Mode 2 (Hz) | Asymmetric Mode 2 (Hz) | Symmetric Mode 3 (Hz) | Asymmetric Mode 3 (Hz) |
| 12                 | 6,573               | 4,052                | 15,577               | 19,106                | 25,470               | 25,103                |
| 13                 | 6,503               | 4,008                | 15,354               | 18,620                | 24,423               | 24,285                |
| 13.5               | 6,468               | 3,986                | 15,231               | 18,397                | 23,969               | 24,047                |
| 14                 | 6,432               | 3,963                | 15,090               | 18,138                | 23,570               | 23,836                |
| 15                 | 6,359               | 3,917                | 14,755               | 17,549                | 22,938               | 23,585                |

Figure 5. 2D UVAMM Vibration Modes (a) Symmetrical (b) Asymmetrical

Figure 6. Effect of end mass length on 2D UVAMM vibration modes
It can be seen in Table 2 with the end mass length ranging from 12 mm to 15 mm, the natural frequencies of symmetrical vibration modes 1 occur at 6,359 Hz to 6,573 Hz. While the asymmetrical vibration modes 1 has natural frequencies ranging from 3,917 Hz to 4,052 Hz. The pattern obtained is that the natural frequency of each vibration mode will decrease as the end mass length increases. Symmetrical and asymmetrical vibration modes 1 cannot be used in research because the natural frequencies are still below the ultrasonic. Moreover, the natural frequencies differences between the two vibration modes are quite large, ranging from 2,442 Hz to 2,521 Hz.

With the same variation of end mass length, natural frequencies of symmetrical vibration modes 2 are obtained at 14,755 Hz to 15,577 Hz, while the natural frequencies of asymmetrical vibration modes 2 occur at 17,549 Hz up to 19,106 Hz. The same pattern is obtained with the vibration modes 1, an increase in end mass length will decrease the natural frequencies of both symmetrical and asymmetrical vibration modes. Same as before, the natural frequencies of the vibration modes 2 are still below ultrasonic, thus it cannot be used in this study. Natural frequencies differences between symmetrical and asymmetrical modes ranging from 2,794 Hz to 3,529 Hz are still large, so it can be concluded that elliptical vibration will not be formed.

Unlike the pairs of vibration modes 1 and 2, symmetrical and asymmetrical vibration modes 3 occur in the ultrasonic range. Symmetrical vibration modes 3 are obtained in the range of 22,938 Hz up to 25,470 Hz, while the natural frequencies of asymmetrical vibration modes 3 turn up in the range of 23,585 Hz to 25,103 Hz. Similar pattern is obtained, the addition of end mass length will also reduce the natural frequencies. In vibration modes 3, the differences between the natural frequencies of the symmetrical and asymmetrical modes are quite small, which ranges from 78 Hz to 647 Hz. The smallest difference in natural frequency occurs at the end mass length of 13.5 mm.

From the results of the modal simulation, it can be concluded that the pair of symmetrical and asymmetrical vibration modes 3 with end mass length of 13.5 mm can be used in this study. With that, natural frequency of the symmetrical vibration mode occurs at 23,969 Hz, and the asymmetrical mode at 24,047 Hz. Both natural frequencies are close to 24,000 Hz, hence the natural frequency value is used in the developed 2D UVAMM. Both vibration modes only have differences of 31 Hz and 47 Hz with the operating frequency of 24,000 Hz. Therefore the 2D UVAMM can produce symmetrical and asymmetrical vibration modes simultaneously, thus elliptical trajectory vibrations can be formed.

4.2. Preliminary Machining Results

The fabricated 2D UVAMM is then mounted on the C axis motor stage of Hadia Micromill-5X machine. Conventional machining process and machining with the addition of 2D UVAMM system were carried out to compare the surface roughness between the two. The experimental setup of the machining process is shown in Figure 7. The two Langevin piezoelectric transducer are excited by an ultrasonic generator from Hybrid Precision. Ultrasonic generator USG-110 was tuned to a frequency of 24 kHz according to the natural frequency of both symmetrical and asymmetrical vibration modes from the 2D UVAMM. The magnitude of phase difference used in both vibration modes is 90 degrees, whereas the output peak-peak voltage used is 212 Volt.
Surface roughness verification was done by slot cutting process using DIXI 7242 two flutes uncoated carbide endmill cutting tool, with diameter of 1 mm. Because the developed 2D UVAMM is still a initial prototype, Aluminum 6061-T6 is suitable to be selected as the test material in this study with the reason of its relatively soft material properties. In addition, Aluminum 6061-T6 is also widely used in industry today for the process of making lightweight aircraft and aerospace components. Slot cutting of 1 mm width, 10 µm depth, and 8 mm length channels were carried out on Aluminium 6061-T6 workpiece with dimension of 18 mm × 18 mm × 3.3 mm. Both conventional and 2D UVAMM equipped machining processes were treated with the same cutting parameters, including 7,000 RPM spindle rotation speed, feed rate of 0.2 mm/s, and 10 µm depth of cut. Each machining process is then repeated three times. For the machining process with 2D UVAMM, Figure 8 shows the feed direction towards the motion of oscillation from the resulting elliptical vibrations.

\[ U = n \cdot d_{33} \cdot V_{p,p} \]  

(1)

The value of the elliptical amplitude generated by the 2D UVAMM can be estimated using the amplitude generated by the both piezoelectric actuators on the X and Y axes according to Equation (1). Where n is the amount of stacked piezoelectric rings layers, \( d_{33} \) is the piezoelectric ring coefficient and \( V_{p,p} \) is the supplied peak to peak voltage. Then by using the resultant and decomposition of vectors, it can be obtained the elliptical vibration amplitude against the normal and tangential axes. From the calculation results, the estimated total displacements produced by the 2D UVAMM on the normal and tangential axes are 0.766 µm and 0.382 µm, respectively.

Surfcom 2900SD3-12 measuring device was used to measure the surface roughness of the machined slots with a cut off value of 0.8 mm, measurement length of 4 mm, and measurement speed of 0.3 mm/s. From the measurement results, the average surface roughness in the conventional machining slots is equal to 0.1429 µm, whereas the average surface roughness in machined slots using 2D UVAMM drops to 0.1334 µm. The decrease in surface roughness is 6.626%. Ultrasonic vibrations produced by 2D UVAMM will create alternating oscillation movements on the workpiece, causing the cutting tool to re-cut the surface that has not been evenly cut before, thus improving surface quality. Shown in Figure 9, there are significant differences between the cutter marks of the two processes. Cutter mark produced through the 2D UVAMM machining process has a pattern like small scales.

**Figure 9.** Surface cutter marks (a) Conventional micro-milling (b) Micro-milling with 2D UVAMM
5. Conclusions
After developing a Two Dimensional Ultrasonic Vibration Assisted Machining (2D UVAM) system on 5-axis micromilling machine and then used for Aluminum 6061-T6 machining process, the following conclusions can be drawn.

- The 2D UVAMM was developed using the principle of two Langevin piezoelectric transducers. The reason for choosing this type of transducer is because of its ability to produce ultrasonic vibrations with micro scale amplitude.
- Two symmetrical and asymmetrical vibration modes were used on the 2D UVAMM, vibration motion to the normal axis from the tip of the transducer is produced by symmetrical mode, while the vibration motion to the tangential axis is caused by the asymmetrical mode.
- Natural frequencies of both vibration modes were optimized by modifying the end mass geometry, an increase in end mass length will decrease the natural frequencies of both vibrations modes.
- Proposed 2D UVAMM system operates at an ultrasonic frequency of 24,000 Hz with estimated total displacement on the normal and tangential axes respectively 0.766 µm and 0.382 µm. Natural frequencies from both vibration modes are almost equal, thus an elliptical trajectory vibrations can be formed on the workpiece.
- Based on micro-milling machining experiments, the elliptical ultrasonic vibrations produced by 2D UVAMM on Aluminum 6061-T6 workpiece helps improve surface quality.

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