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DESIGN AND EVALUATION OF A PIEZO-DRIVEN TURNING TOOL FOR MACHINING NON-CIRCULAR GEOMETRIES

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Abstract

Conventional turning processes are inherently limited to the generation of rotationally symmetric geometries due to the fixed kinematics between the cutting tool and the rotating workpiece. To overcome this limitation and enable the fabrication of non-circular profiles, a superimposed radial oscillation of the cutting tool can be introduced. This additional degree of freedom allows for the controlled deviation from circular paths, thereby enabling the machining of a broad spectrum of arbitrary geometries, constrained primarily by the actuator's stroke amplitude. Precise synchronisation between the oscillatory motion of the tool and the angular position of the workpiece is essential to ensure contour fidelity and surface quality. In this context, a piezo-actuated turning tool was developed and experimentally evaluated. The system is capable of generating a sinusoidal radial displacement with a maximum amplitude of 85 µm. Experimental results demonstrate the tool's ability to consistently and accurately reproduce non-circular profiles, confirming the feasibility and repeatability of piezo-assisted turning for advanced shape generation. The approach offers a promising solution for applications requiring high-precision non-rotationally symmetric components.

Keywords: Non-circular turning; Piezoelectric actuation; Shape control

1. Introduction

Various methods exist to produce non-circular profiles in turning operations. One of these approaches is polygon or non-circular-rotary-turning, where a defined oscillatory motion is superimposed on the cutting tool while the workpiece rotates. This technique enables the direct machining of geometries like polygons, lobes or cam shapes on conventional lathes [1]. Another method of manufacturing non-round geometries on a lathe is equipping the tool with a feed in one or multiple axes. These systems are called Fast Tool Servos (FTS) and can be realised with a voice coil drive, a linear synchronous motor, a reluctance-based drive [2] or a piezoelectric actuator [3].

A practical application of non-circular profile machining is the production of engine pistons. During combustion, the pistons are subjected to thermal and mechanical loads that cause deformation resulting in reduced performance and efficiency. This issue can be mitigated by designing the piston geometry with a middle-convex, varying elliptical (MCVE) profile to better accommodate distortions and maintain optimal guidance [4].

Fig. 1. shows the characteristic geometry of a MCVE piston: the cross-section of the piston is an ellipse with a varying degree of ellipticity along the axial direction ("varying ellipse") while the axial profile has a cam-like, "middle-convex" shape [5].

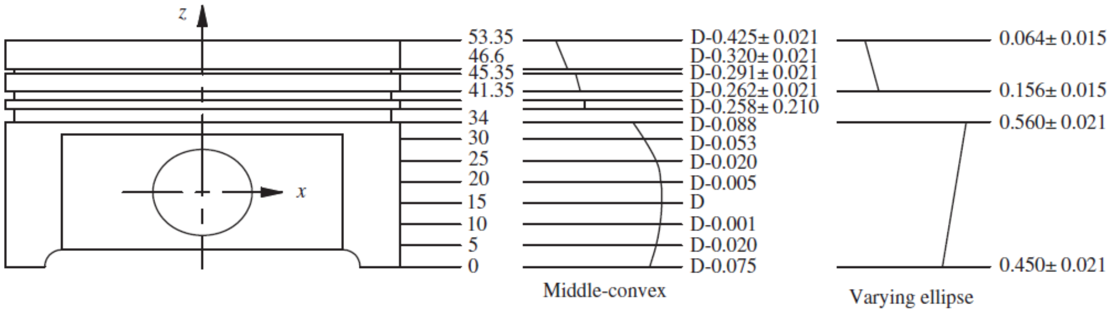

Fig. 1. Geometry of a MCVE piston [5]

Although surface roughness is typically regarded as detrimental, particularly due to its negative influence on friction and the functional performance of sliding interfaces [6], intentionally engineered surface features can provide significant advantages in specific tribological applications. A practical application of piezo-assisted machining is surface texturing, as tribological research has demonstrated its effectiveness in reducing friction in mechanical components [7]. Kurniawan et al. [8] used a piezoelectric actuator to drive a tool holder on a standard CNC lathe, allowing the tool to create surface textures directly during the machining process through controlled vibration. Ali et al. [9] examined the tribological properties of cylindrical surfaces textured with micro-dimples under starved lubrication. Comparing the resulting Stribeck curves of the textured surfaces to their non-textured control group, the authors found that the textured surfaces have a lower coefficient of friction in regions of high contact pressure.

This study presents the development and design of a piezo-actuated turning tool intended for machining defined non-circular geometries. The primary objectives are to investigate the tool's capability to accurately reproduce specified geometrical features and to systematically assess its performance in terms of precision, repeatability and surface quality. In addition, the influence of actuation parameters on machining outcomes is evaluated to verify the suitability of the approach for advanced manufacturing applications.

2. System design

The respective piezo turning tool is a prototype setup designed for producing non-circular geometries in the micrometer range. The schematic structure is depicted in Fig. 2. Two piezoelectric actuators excite the tool holder, which is mounted in the housing by two membranes. A return spring counteracts the force of the actuators and pushes the tool back into its initial position. The moving part is also equipped with a linear encoder that measures the stroke of the tool. The piezo-actuators can be powered with a voltage of up to 200 V and a maximum frequency of 300 Hz. The geometry generated during the turning process is influenced by the applied actuation frequency, enabling the production of varying profile shapes depending on the excitation conditions.

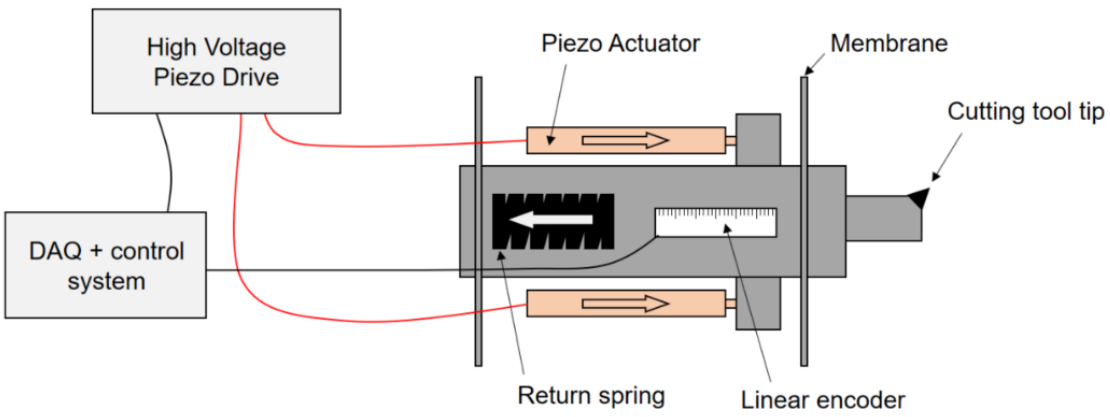

Fig. 2. Schematic of the piezo-driven tool

The piezo drive is a PD200X4 from Scientific Instruments with a maximum output voltage of 150 V and a peak current of 2 A per channel. The DAQ and control unit is realised with a National Instruments USB-6343 X-Series featuring analog and digital I/O ports.

3. Experimental Evaluation

3.1. Determination of the characteristic map of motion

To characterise the dynamic behaviour of the tool, experiments were performed to determine the amplitude response as a function of the excitation voltage and frequency. The objective was to construct a characteristic map representing the peak-to-peak values of the stroke (in micrometers) as a function of the applied sinusoidal voltage and its corresponding frequency. The piezoelectric actuators were driven by a sinusoidal input signal ranging from 10 V to 150 V peak-to-peak in increments of 10 V, centered on a DC offset of 75 V. Excitation frequencies varied from 10 Hz to 300 Hz in steps of 10 Hz. Each test configuration was held for five seconds, followed by a two-second idle period to prevent thermal drift and actuator saturation. Following completion of the full parameter sweep, the displacement data recorded via a high-resolution linear encoder was post-processed using fast Fourier transformation (FFT). This frequency-domain analysis enabled automated extraction of the dominant frequency component and its corresponding amplitude, facilitating the accurate quantification of peak-to-peak displacement for each excitation condition.

The resulting characteristic curve is presented in Fig. 3. The actuator displacement exhibits a predominantly linear dependence on the applied voltage amplitude. Frequency-dependent effects on stroke amplitude were observed to be minimal, although a slight increase at higher frequencies was detected. Beyond a critical voltage-frequency threshold, the actuator power supply entered an overload protection mode, limiting the system's operational envelope and preventing further displacement amplification.

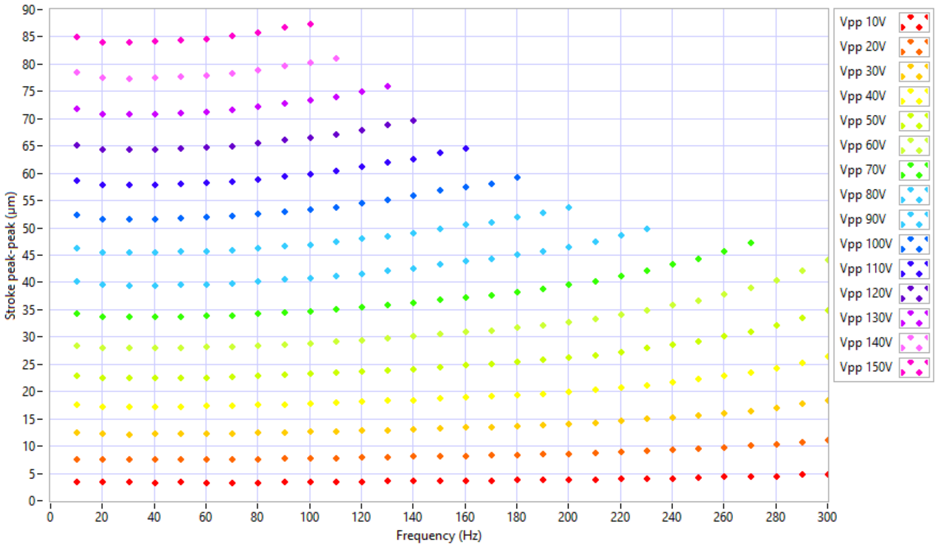

Fig. 3. Characteristic map of the tool

3.2. Machining tests

For the cutting experiments, the piezo-actuated tool was mounted on the machine table of a CNC machining center as shown in Fig. 4. The specimen is an aluminium rod with a raw diameter of $D = 25$ mm, which is mounted in the machine's tool holder. An inductive proximity switch is mounted next to the tool holder and generates a pulse once per spindle revolution, which is subsequently used as a trigger signal for the control of the actuating system.

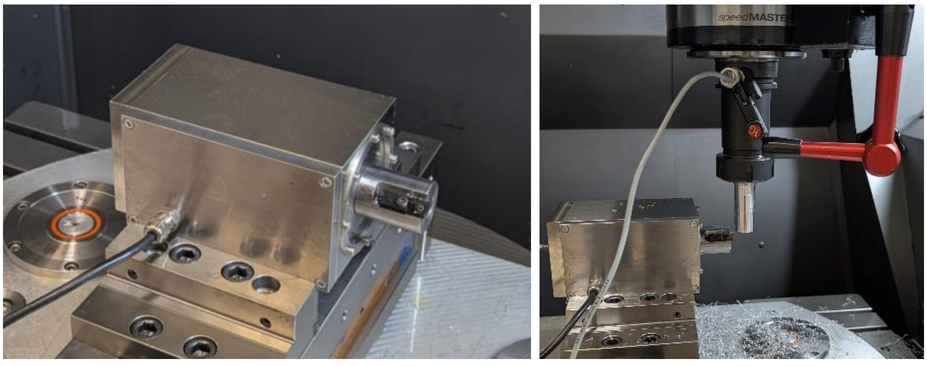

Fig. 4. Experimental setup

Table 1 lists the machining parameters corresponding to the various specimens depicted in Fig. 5. The rotational speed of the spindle was set to 1500 rpm which results in a cutting speed of v_c = 118 m/min for the given workpiece diameter of 25 mm, suitable for turning aluminum alloys.

Test run	Waveform	n (s^{-1})	Freq (Hz)	V_{pp} (V)	Offset (V)	Stroke peak-peak (µm)
a)	Sine	25	50	140	80	72
b)	Sine	25	100	140	80	76
c)	Sine	25	100	80	80	40
d)	Sine	25	75,2	140	80	74
e)	Triangle	25	75,2	140	80	74
f)	Sawtooth	25	75,2	140	80	98

Table 1. Parameters and results of the cutting tests

Following the machining experiments conducted under these systematically varied process parameters, the resulting workpiece geometries were characterised using a high-precision coordinate measuring machine (CMM) to quantify dimensional accuracy and assess surface characteristics. The experimental results are depicted in Fig. 5.

A comparative analysis between four-fold sinusoidal oscillations per spindle revolution at excitation levels of 140 V_{pp} (b) and 80 V_{pp} (c) reveals an approximately linear correlation between the peak-to-peak stroke amplitude and the magnitude of the applied voltage. Specifically, at an excitation amplitude of 140 V_{pp}, two oscillations per revolution (a) result in a stroke of 72 µm, while three (d) and four oscillations (b) yield strokes of 74 µm and 76 µm, respectively. This moderate stroke amplification with increasing frequency is consistent with the previously discussed actuator response behaviour shown in the characteristic map in Fig. 3. Furthermore, an investigation of the influence of waveform shape on tool displacement - while maintaining constant frequency and amplitude - demonstrates that sinusoidal (d) and triangular (e) excitation signals produce nearly identical stroke amplitudes. In contrast, a sawtooth waveform (f) induces a higher peak displacement. However, the surface profile generated by a sawtooth input exhibits superimposed oscillations along the ramp section of the geometry. These undesired oscillations are absent in the triangular waveform, which yields a smooth and continuous contour. The disturbance observed in the sawtooth case is attributed to the abrupt phase discontinuity inherent in the waveform, which induces dynamic perturbations in the actuator's mechanical support system, comprising a compliant suspension mechanism formed by a spring and membrane. This excitation of structural resonances compromises the kinematic fidelity of the actuator’s motion, thus adversely affecting surface integrity.

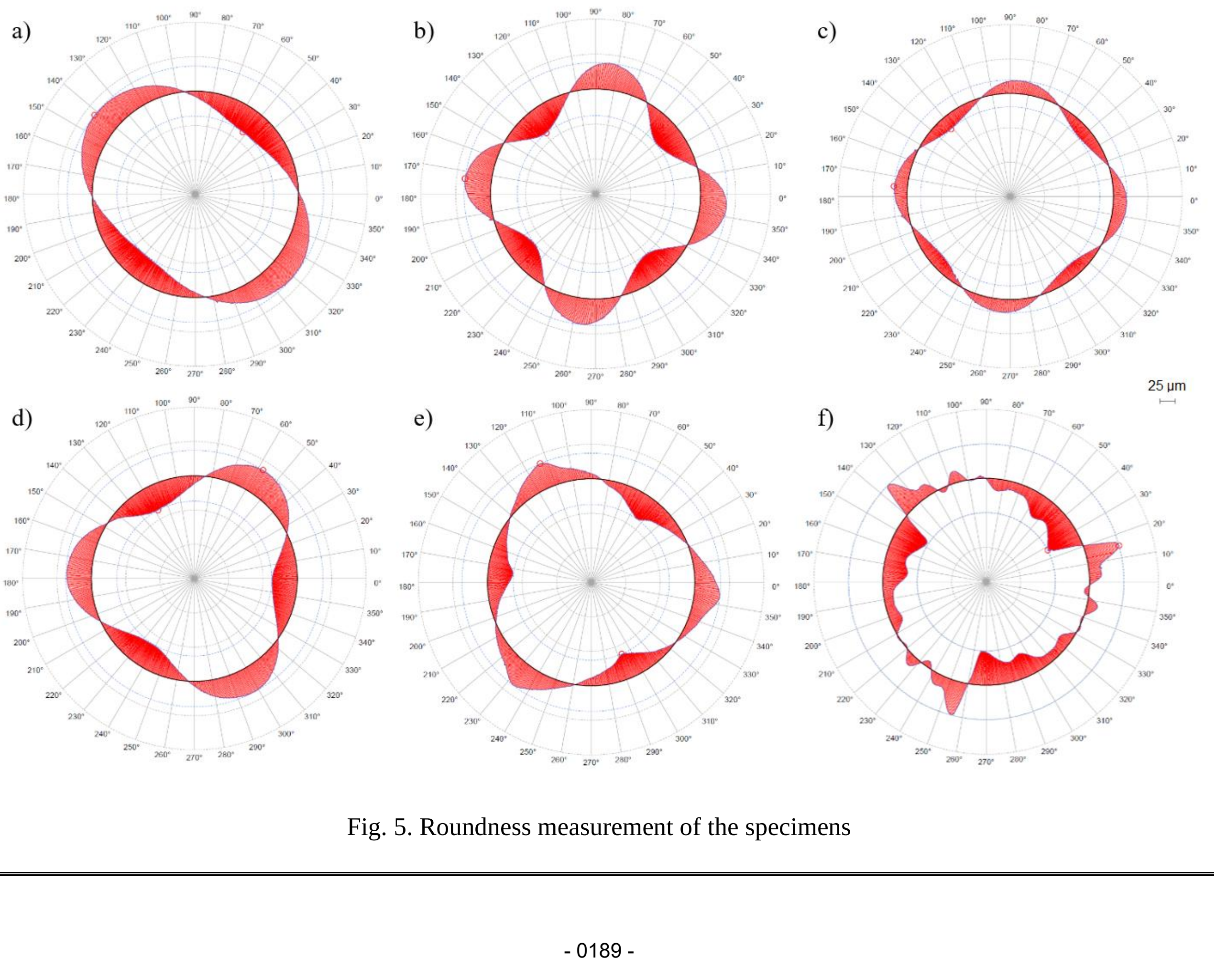

Fig. 5. Roundness measurement of the specimens

4. Conclusion and Outlook

This study has demonstrated the feasibility of using a piezo-actuated turning tool to machine non-circular geometries by superimposing controlled tool path modulations onto the cutting path. One key area for future investigation is the influence of waveform steepness on dynamic stability. Preliminary results indicate that excessively steep ramp transitions, such as those present in sawtooth waveforms, can induce unwanted oscillations due to the rapid retraction of the actuator and the resulting excitation of structural resonances. A more detailed analysis is needed to quantify the critical slope thresholds beyond such effects occur. Furthermore, the system's ability to produce controlled, periodic tool motions opens up opportunities for automated chip-breaking strategies where continuous chips are undesirable. Overall, the integration of programmable piezo actuation into turning processes represents a promising direction for achieving high-precision, flexible and functionally tailored surface geometries.

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