Title:
**Framework for Determination of Surface Topography Generated Through Elliptical Vibration Assisted Single Point Cutting**

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## Introduction:

Recent years have shown an increased demand for single point cutting methods that are capable to generate surfaces that are characterized by a broad range of functionalities such as wettability [5], enhanced aerodynamics [1], paintless coloring [9], improved optical and retroreflective properties [3],[4],[7]. While these functionalities could be attained, certain technological limitations continue to hinder further developments. Among them, the dimensional barrier (i.e., the capability to produce precise micro/nano geometries) as well as the ability to machine ferrous or other hard-to-cut materials by means of diamond tools continue to remain the most important ones.

To address these known challenges, one possibility is represented by the use of elliptical vibration cutting (EVC) as a technology capable to augment the previously proposed ultraprecise single point cutting method (USPC) [6]. Along these lines, elliptical vibration assisted single-point cutting (EVASPC) essentially represents a combination between a *slow* and *fast* cutting motion associated with USPC and EVC, respectively. In this context, the multi-axis stage of the five-axis machine used to generate USPC kinematics is responsible for the generation of the slow motions. By contrast, the fast motion is controlled externally by the EVC equipment that generates the elliptical motion with micron-scale amplitudes and KHz-scale frequency. The main role of the fast EVC motion is to introduce discontinuities in the tool/workpiece contact and thereby convert the continuous cutting into a discontinuous one. The intermittent tool/workpiece contact ultimately leads to smaller cutting forces, reduced tool wear and cutting temperature, all factors that extent the applicability of EVC to ferrous and/or hard-to-cut materials.

The controllability of EVASPC relies on several user-set cutting parameters that ultimately formulate a description of the EVC trajectory. These parameters represent the key contributors to the geometry of the EVASPC-generated surface. Since no EVC-specific CAD/CAM system has been developed so far, the main objective of this study is to develop a framework that can be used to predict the final geometry to be generated through the complex EVASPC kinematics.

## Theoretical Framework:

Generation of CAD models to constitute surface structures follows a consistent methodology and - as suggested by Fig. 1 - each topological model will depend on EVC kinematics. Due to the combination between slow and fast motions as well as the relative positioning between the planes in which they


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occur, the tip of the cutting tool follows a trochoid that can be mathematically modeled through the summation of harmonics:

$$
\begin{aligned}
x(t) &= Vt\sin(\theta) \\
y(t) &= Vt\cos(\theta) + A_y\cos(2\pi\omega t + \phi) \\
z(t) &= DoC + A_z\sin(2\pi\omega t)
\end{aligned}
\tag{1}
$$

where $V$ and $DoC$ represent the feed rate and depth of cut for the slow USPC process. By contrast, the augmenting fast EVC motion is defined by the longitudinal and transversal amplitudes ($A_y, A_z$), motion frequency ($\omega$) and phase angle ($\phi$). Finally, $\theta$ represents the angle between the direction of the slow feed ($V$) and that of the plane containing the EVC motion. While $\theta$ will be assumed as null for the current work ($x(t) = 0$), its nonzero values might represent a future extension direction. Evidently, $t$ represents time in Eq. 1.

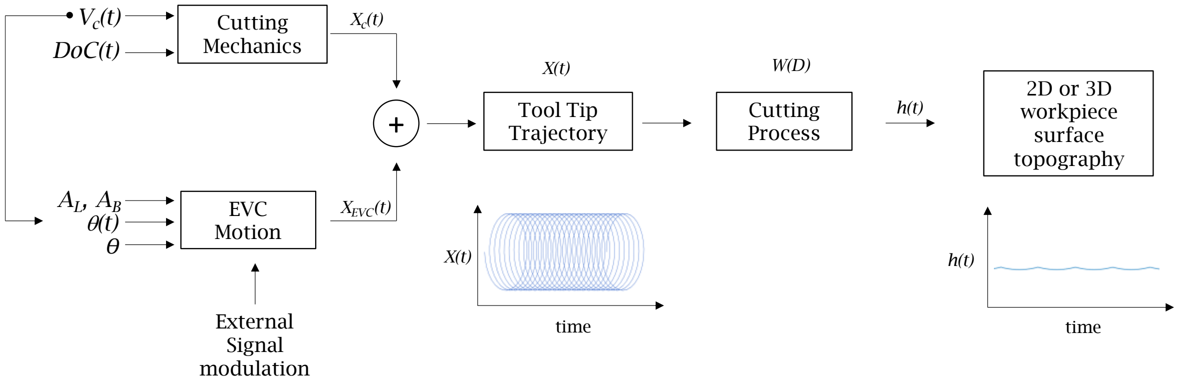


Fig. 1: Theoretical framework for modeling EVASPC-generated topography.

The combination between the two primary motions (slow and fast) determines the tip of the tool to follow the planar trochoidal trajectory shown in Fig. 1 ($Y(t), Z(t)$). As the tip of the tool immerses in the flat workpiece according to the $DoC$ variable (assumed constant), the surface topography yields as the Boolean subtraction of the swept trochoidal envelope of the tool from workpiece volume ($h(t)$).

The analytical tool motions depicted in Fig.1 apply to the physical cutting process during which tool tip trajectory - responsible for the formation of surface topography – is generated as an overlap between slow kinematic cutting motions (supplied by a multi-axis CNC controller) and two additional EVC motions (supplied by an external EV unit). As a result, two overlapped cutting motions are responsible for the final tool path trajectory.

The inherent assumption behind the considerations above is that the trochoidal swept envelope of the tool is replicated identically in the workpiece. Nonetheless, when the attack angle of the tool into the workpiece is larger than the clearance angle, undesirable interferences will be present [10]. However, this situation was averted in the current work through an appropriate design of the cutting tool.

Implementation:

Two parametric modeling tools were developed to enable the graphical representation of the surface topography yielded by means of EVASPC. The first tool relies on a commercial CAD software (NX) and was primarily developed to enable the visualization of the 3D geometry generated through EVASPC. The tool relies on the framework presented in Fig. 1 in order to generate the 3D model of the surface structures resulted as a result of EVASPC motions. For this purpose, a total of five consecutive phases have to be executed (Fig. 2).

The core of the graphic modeling module is constituted by an expression table that was used to define the cutting parameters and the motion equations for the three principal axes. The motion of the


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tool was then represented by means of a law-defined spline and confined to travel for one half of an elliptical revolution for which a swept extrusion was used to follow the length of tool's cutting edge. A patterned feature was then used to linearly repeat this extrusion by means of a 'pitch and span' option. Because of this approach, the pattern spanned over a chosen distance while the pitch distance – essentially separating each pattern feature - was chosen to mimic the spatial frequency determined by feed rate and vibrational frequency ($V/\omega$) [2]. As indicated above, the final operation consists of the Boolean subtraction between the swept tool envelope and workpiece.

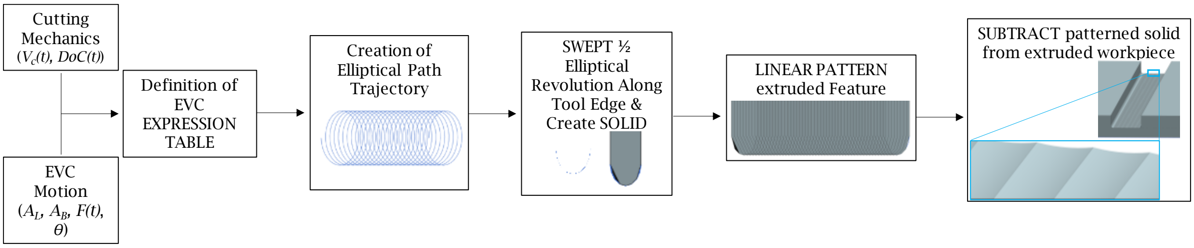


Fig. 2: CAD-based modeling framework for modeling EVASPC-generated topography.

While extremely descriptive and clear from a graphical standpoint, the CAD-based modeling tool is typically unable to appropriately handle surface geometries that encompass features that are different by two-three orders of magnitude. More specifically, while the geometric features of the functional surface are usually in the hundreds of microns domain, the controlled surface finish to be generated by means of EVASPC typically falls under the 20 nm range. Because of this, it is often preferable to rely on a 'pure' numerical tool that might have limited 2D profile plotting capabilities, but is capable of handling a broad range of range of input EVASPC parameters.

For this purpose, a Matlab-based tool was developed (Fig. 3). The computational tool was designed to generate three primary outcomes: tool trajectory, duty cycle and surface topography. Evidently, the tool trajectory represents nothing but the trochoid determined by the formulas in Eq. 1. By contrast, duty cycle represents the ratio between the length of the trajectory when the tool is engaged with the workpiece material (red portion of the curve) and the total length of the tool trajectory. Both tool trajectory and duty cycle are known to play an important role on cutting forces, tool-wear rate, and the surface profile [8]. The third important output of the tool, namely the predicted machined profile offers an important metric that can be validated by means of physical cutting trials. In the current context, the most appropriate metric to be used for comparison purposes between numerical and physical profiles is constituted by the theoretical average roughness $R_a$. Of note, the theoretical $R_a$ represents the lowest roughness attainable through the EVASPC process whereas the disturbances unique to physical cutting – tool geometry, wear, chatter, tool-workpiece chemical reactions, etc. – can only increase the physical surface roughness. Thus, $R_a$ simulation is merely the result of analytical tool trajectory considerations.

Application:

It is anticipated that the developed framework will be capable to generate theoretical predictions of the surface topography to be generated through EVASPC to become the baseline for future experimental trials. While the term computer-aided manufacturing (CAM) might be somewhat of a misnomer in this particular context, it is perhaps worth emphasizing that a certain amount of overlap exists between the tasks fulfilled by of a conventional CAM system and those of the developed framework. Nonetheless, the intricacy of the geometry/surface topography to be generated by means of EVASPC surpasses by several levels of complexity the one that can be fabricated by means of more or less traditional machining/micromachining methods. To elaborate a bit further on this idea, it should be emphasized here that whereas in case of conventional machining/micromachining, the shape of the workpiece is almost never a concern since the goal of the fabrication process is in fact to replicate – as accurately as possible – the idealized CAD geometry, it is almost impossible to estimate the final topography to be


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produced through a certain combination of EVASPC parameters. Because of this, the aforementioned framework represents somewhat of a combined CAD-CAM system that is capable of simultaneously model/represent/predict the geometry to be generated as well as to control the tool path trajectory.

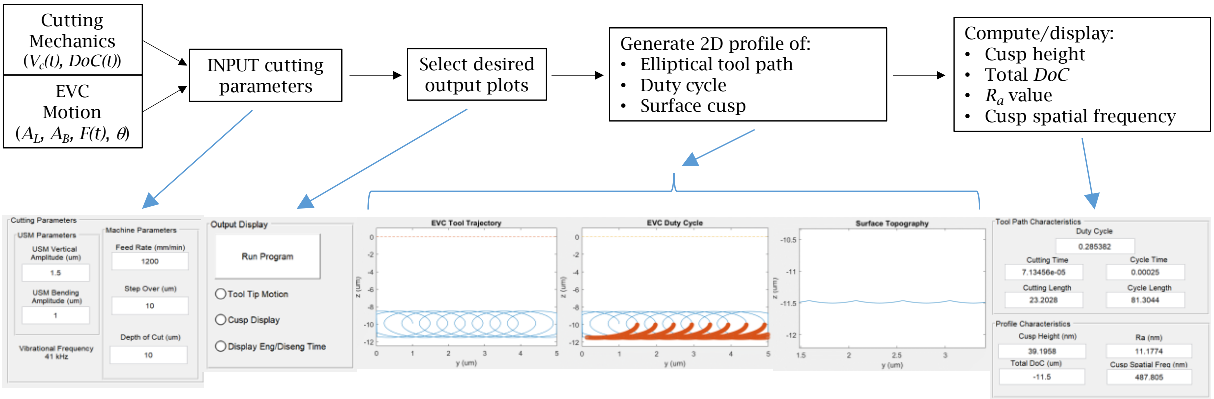
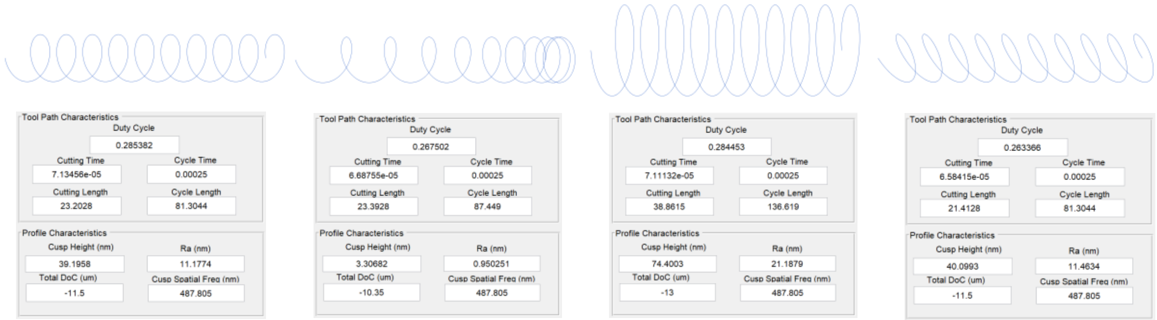



Fig. 3: Matlab-based modeling framework for modeling EVASPC-generated topography.

To demonstrate the versatility of the developed framework, four different surface topographies have been exemplified in Fig. 4. While the geometric differences between them are rather evident, it can be mentioned here that they are all a direct consequence of the chosen process parameters.



(a) (b) (c) (d)

Fig. 4: EVASPC framework output examples: (a) constant parameters, (b) variable feed rate, (c) altered EV amplitude, and (d) altered phase shift.

More specifically, while the tool path in Fig. 4a is the result of a set of constant process parameters, Fig. 4b suggests the effect of a linearly variable feed rate $V$. This supplementary 'degree of freedom' of the framework enables the possibility to really-control the distribution of a periodical structure. Furthermore, Fig. 4c implies that the ability to independently control the two vibrational amplitudes allows changes in $DoC$ and in turn this is equivalent with the capability to generate a 2½D surface topography. Finally, the fourth example – and arguably the most advanced one – is an effect of tuning/altering the orientation of the ellipse itself (Fig. 4d). The key parameter for the latter strategy is represented by the phase shift between bending and longitudinal components of the elliptical vibrations ($\phi$) that can modify the elliptical locus between forward-tilted, vertically oriented, and back-tilted.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Conclusions:

The framework proposed in this study represents one of the first attempts made to integrate various EVC strategies that were previously reported in the surveyed literature. The integrated CAD/CAM system presented above can be used for both design and fabrication purposes and one of the immediate extensions of this work will be constituted by side-to-side comparisons between the topography predicted by this framework and physical samples yielded as a result of physical cutting trials. Beyond that, it will be interesting to explore in the future the functional characteristics of different designs that can be produced through EVASPC because at this time, while many of them can be fabricated accurately even in the nano-domain, their practical significance remains rather unclear.

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