



A review on dynamics in micro-milling

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Abstract

This paper is a review of all recent and most relevant research in the field of dynamics in micro-milling processes. It associates the recent research works, future trends, and thoughts in the field of dynamics and revises the dynamics in machining definition, the mathematical notions applied for micro-milling with the consideration of the size effect and common phenomenon impacting the dynamic model, and the common methods of detection of the vibration and chatter as well as its suppression methods. It also combines all the remaining challenges and difficulties. Many researchers have published papers on conventional machining and have studied the dynamic characteristics and behavior. However, there is no relevant review paper in the field of dynamics in micro-milling. To conclude, this paper reviews relevant research work achieved in dynamics regarding the theories, detection, application, surface quality, and tool life. The research work and results presented in this paper allow a better understanding of micro-milling operations for the production of high-quality micro-components.

Keywords Chatter · Dynamics · Micro-milling · Stability · Vibration

1 Introduction

Micro-machining processes are the most common operations required for the machining of high-precision micro-components [1, 2]. It has been confirmed by the technological needs of our society and the rapid advancement of the technology, new challenges in major fields such as aerospace, aeronautics, electronics, medicine, and luxury. Such parts can be obtained depending on the precision of the operation, which in the case of micro-milling consists of tolerance of few microns. In all fields, this range of tolerance is vital for the development of new technological devices and high-quality components [3, 4].

In the field of machining, the dynamic is often associated with the forces and vibration [5]. Dynamic performs key influence on machined surface quality, accuracy, and tool life. Micro-scale machining dynamics are very challenging, as the mathematical theories of macro-milling processes cannot

fully determine the actual micro-milling effects, due to the tiny material removal, the vibration is likely to unmatch tolerance requirement, therefore ineffective machining, resulting in material, time, and energy costs which in the actual manufacturing competition has to be avoided [6, 7]. Machining can operate by the law of dynamics representing the base of the process of metal removal, created by the contact between the tool and the workpiece. Tool runout, deflection, size effect, vibration, chatter, surface quality, and tool life extension in micro-cutting operations are the main focus studies of the researchers. The runout can lead to unstable periodic variations in the chip load and forces [8, 9]. The deflection in micro-milling can be implemented in the theoretical model using the Timoshenko beam model, which contains the shear forces of the beam contrary to the Euler Bernoulli model which neglects it [10]. In milling processes, the Euler Bernoulli model can be sufficient [11]. In micro-machining operations, the size effect has to be incorporated into the theoretical investigation due to the high tolerance requirement, inversely macro-operation can neglect those effects [2, 12, 13]. Moreover, the prediction of micro-milling processes highly depends on the consideration of the size effect, as well as the gyroscopic and rotary effect of the tool model [14, 15], and this is also true in micro-drilling and micro-turning operations [16–18]. Vibrations accompanied all machining operations and can, unfortunately, damage the

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equipment involved in the process. Persistent problems in micro-milling such as the machining accuracy and the vibration have to be solved; those problems lead to inefficient micro-milling operation [19, 20]. The vibration monitoring process in micro-machining is challenging due to the small size of the tool, and the displacement is of an order of a few microns; therefore, the recording process used for high accuracy often uses a laser displacement sensor to collect the displacement of the micro-tool during the machining [21]. In the last decade, novel monitoring methodologies have emerged; one of them is the machine learning processing methodology which presents enthusiasm in the research community [22]. The chatter is a special vibration behavior that regenerates vibration and increases its amplitude over time, and it can lead to tool wear or tool breakage and poor workpiece surface quality [23]. Those negative effects lead to extra costs for the manufacturer [24]. The chatter vibration in micro-milling has to be avoided; studies have presented some methods of monitoring the chatter using acoustic emission (AE) sensor, and this method has shown a good in-process detection of the chatter [25]. The use of the wavelet coherence functions can also provide information on the chatter occurrence; it is a powerful method to prevent the chatter to fully develop [26]. Another detection of the chatter could be achieved using AE sensors combined with machine learning classifiers [27].

The chatter lives chatter marks on the workpiece surface, which lowers its surface quality and decreases the machining performance. Plenty of methods are available to reduce, avoid, or suppress the chatter. The detection of the chatter is essential for the application of these methods and the simplest method leading to stable cutting operation is usually the change in the spindle speed parameter [28]. Micro-milling operations require the study of complex dynamics, which involves several multiphysics parameters and characteristics; the current trends focus on the tool, the microstructure, and the temperature [29]. The tool wear can affect the stability of the micro-milling operation; a study has shown that the wear formed on the micro-tool increases the tool edge radius, and larger edge radius are more likely to improve the stability and reliability of the machining [30]. In order to capture the wear on the tool, different techniques can be used; the most common is the use of a scanning electron microscope (SEM) which provides information on the tools life, and from the observation, the wears can be quantified. The tool wears can also be detected using the time-frequency analysis of the cutting force and vibrations signals resulting in the prediction of the tool breakage [31]. Novel methodology can be used such as the support vector machine model combined with recursive feature elimination which is based on the vibration and sound signals resulting in the micro-tool wear classification [32]. In the recent decades, the number of publications in the micro-machining field of research has increased, the

importance of this review paper is then justified and essential for the understanding of the actual problem related to the dynamics and the current methods applied to improve the machining output parameter, as the surface, quality, and tool life. This paper is a review of the dynamics in micro-milling operations, the structure can be seen in Fig. 1. This paper is limited to the relevant research expressed in the following parts: the dynamic model which expressed all-important relations in dynamics and the principal theories applied in the field of micro-milling with regard to other micro-machining processes; vibration monitoring and detection methods of the chatter including the relevant techniques involved in the experimental process; the chatter reduction and suppression methods which represents the essential point of research; afterward the application and benefits regarding the chatter suppression; the conclusion is the summary of all parts seen in this review paper; the further studies expected are expressed in the last part, which gives a suggestion for future research direction in the field of micro-milling dynamics.

2 Dynamic theories in micro-milling

According to the CIRP encyclopedia of production engineering, dynamics is defined as the connection between the motion of bodies and the forces acting on them [33]. Still, today machining dynamics are considered as driven by Newtonians law. The dynamics in the field of macro and micro machining can be classified into two different categories, macro-dynamics which deal with the vibration which appears as small motions of deformable bodies, and the large motions of rigid bodies. The vibration can be

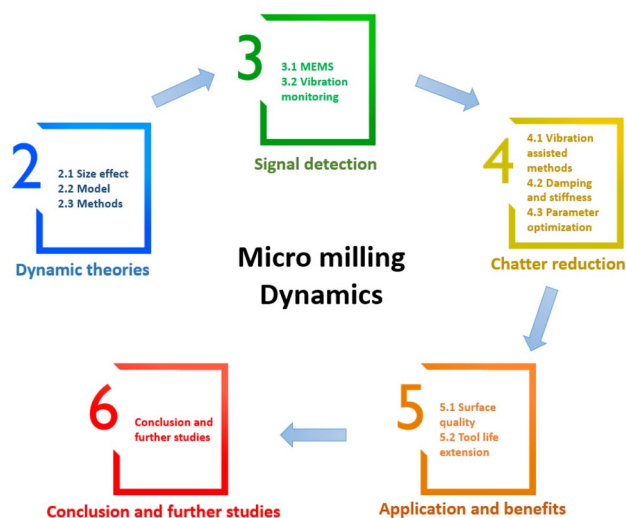


Fig. 1 Review paper structural flow of the chapter in a circular representation

classified as free vibrations, forced vibrations, self-excited vibrations, and parametrically excited vibrations. The rigid body motions deal with the cutting mechanisms, such as the cutting forces during the process. In this review paper, the large definition of the dynamics is bounded to micro-milling regarding the cutting mechanisms, the dynamic methods, the vibration monitoring, the chatter reduction methods, and their benefits and application on the surface and tool life extension, and those points cover most of the research. In micro-milling, the cutting forces are complex and involve several theories in order to predict accurately the reality, one of the complex phenomena is the size effect which involves the elastic recovery of the material, and this effect is present in the following subsection.

2.1 Size effect

The chip formation mechanism in micro-milling can be decomposed into three regions. In the plowing-dominant regime, where the deformation is only elastic, in this case, the uncut chip thickness is lower than the critical uncut chip thickness. In the mix plowing-shearing-dominant region, where the deformation is elastic-plastic, in this situation, the uncut chip thickness is equal to the critical uncut chip thickness. In the shearing-dominant regime, where the chip can be fully generated and the material is in its plastic deformation region, in this regime, the uncut chip thickness is higher than the critical uncut chip thickness due to the accumulation of the chip. These three regimes can be seen in Fig. 2, where types I, II, and III are the plowing, mix plowing-shearing, and shearing regimes, respectively [34]. The size effect occurs during the plowing; in this case, the material can enter its elastic and plastic deformation without

chip formation which appears in the plowing and mix plowing-shearing-dominant regime (type I and type II). Jin and Xie have concluded on the importance of the chip thickness in micro-milling, and an uncut chip thickness exceeding the critical value of the transition stage between brittle and ductile material causes poor machined surface, as seen in the micro-machining of glass material [35]. Researchers have investigated the plowing force in micro-milling of soft crystals, and they have shown that the plowing force induced by the size effect decreases at smaller cutting edge radius [36]. Due to the size of the micro-milling operation, it is likely for the critical chip thickness to be reached and so the workpiece material behavior is likely to enter the plowing region, where the cutting operation is less likely to perform a high-quality component, as it decreases the surface quality and reduces the tool life [37].

An important point that has been pointed out is the size effect in the dynamic modeling of micro-machining operations. Due to the micro-scale, parameters previously neglected must be considered, as the micro-structure of the workpiece affects the cutting process. Fig. 3 shows the different actors that create the size effect and their consequences and parameters that affect the micro-cutting process.

Cheng and Huo have linked the size effect to the comparison between the material grain size, the cutting edge radius, and the depth of cut, and due to the small depth of cut, depending on the material, the difference of size between the grain size and the uncut chip thickness is getting smaller, which causes plastic deformation on the tool edge [9]. The size effect is closely related to the ratio between the uncut chip thickness and the cutting edge radius, and during the micro-milling of hardened steel, it has been shown that a ratio lower than a unit shows an increase in the size effect phenomena [38, 39]. Thus, a smaller cutting edge radius is more likely to reduce the size effect and at the same time decrease, the maximum compressive residual stress along the depth of penetration [40–42]. Other researchers have confirmed this phenomenon [43, 44]. As presented in Fig. 2,

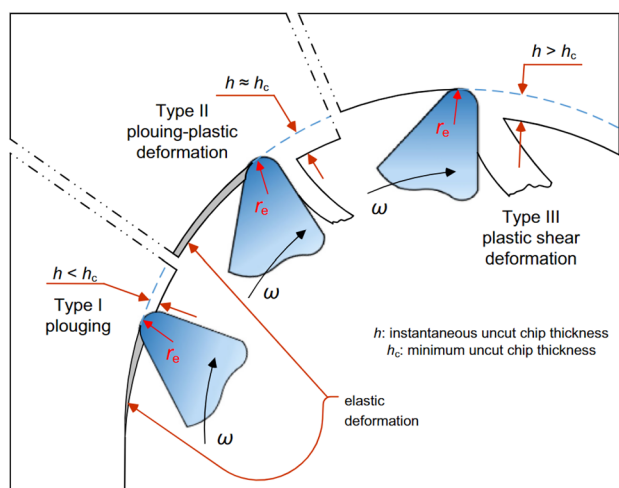


Fig. 2 Three types of material removal mechanisms in micro-milling [34]

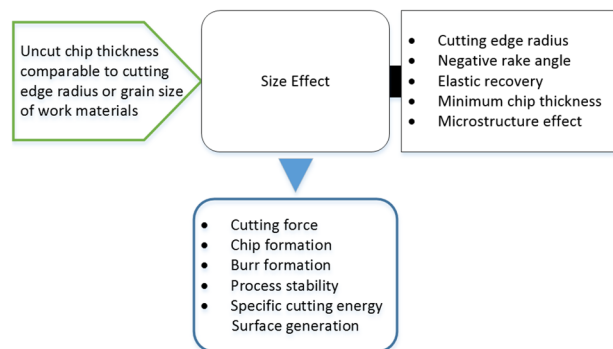


Fig. 3 Size effect in micro-scale cutting [9]

the size effect strongly affects the specific cutting energy for the material removal. In addition, when the specific shear energy increases, the uncut chip thickness decreases [45]. Common methods applied in macro-machining cannot be applied for microscale machining, and due to the size of the operation, all the parameters can have a big impact on the results. Mokhtari et al. have investigated the size effect in the study of the vibration of the tool; according to the results, the size effect has a non-negligible influence on the chatter prediction in micro-milling operation [14]. However, the size effect is able to improve the micro-milling tool stiffness resulting in lower experimental vibration results compared to the theoretical results [46].

It is important to understand the difficulty of the simulation at the micro-scale, due to the complex governing effects that result in a combination of several theories which cannot be neglected. Multi-scale model implementation into simulation studies grants high accuracy and agreement in the comparison with experimental results [47].

2.2 Dynamic model establishment

The dynamic model in micro-machining similarly to all mechanical system follows the equation of motion presented in Eq. (1),

$$m\ddot{x} + c\dot{x} + kx = F \quad (1)$$

where m is the mass, k is the stiffness, c is the damping and F is the force. The parameters \ddot{x} , \dot{x} , and x are the acceleration, velocity, and displacement of the micro-tool respectively [48–50]. The equation of motion is obtained by the decomposition of the force in three terms, the acceleration, the damping, and the stiffness. The challenge in micro-milling is to determine the total force. However, the current knowledge in the dynamic properties remains rudimentary [51]. Most researchers investigating dynamics in micro-milling are using the mathematical principles cited in this part, and in common studies, the investigation starts with the differential equations describing the mechanical system. A similar dynamic model can be constructed in micro-turning considering the tool and the workpiece as a three-dimensional mass-spring-damping system [52]. The complexity of the model in micro-machining often results in the use of complex phenomena such as the gyroscopic effect, process damping, runout, and nonlinearities [53]. Wang et al. have investigated the axial and radial runout, showing the influence of the geometrical parameters on the surface roughness [54]. Therefore, the implementation of complex phenomena in the dynamic model increased the number of variables leading to a diminution of the errors between the theoretical and experimental results. However, the runout is difficult to measure using conventional

measuring equipment. Researchers used laser Doppler vibrometry to measure the runout with high accuracy during the rotary motion of the tool. It has been shown that the radial and tilt motion of the spindle speed can be significant regarding the runout [55]. The method was adapted for the axial and radial measurement of the runout leading to low uncertainty levels [56]. At ultra-high speeds up to 150 krpm, the measuring error motions can be characterized using an arbitrary angle multi-orientation error separation technique by isolating the spindle error motions [57]. Assuming a consistent dynamic component of the radial throw over the spindle speed variation and negligible tool-dominant modes over the spindle operating speed, then a quasi-static model of the tool-collet-spindle in the radial and tangential directions can be used for an accurate prediction of the dynamic changes in radial throw [58].

The uncut chip thickness is a very important point in the study of the dynamic in micro-milling; its investigation can be very useful in order to obtain the boundary between the plowing-dominant regime and shearing-dominant regime, which will determine if the micro-machining process is removing materials. The material removal mechanism is differentiated by the shearing and the plowing, and the theoretical approaches are different; therefore, knowing the transitional cutting conditions is essential [59, 60]. Determining the uncut chip thickness allows the study of the cutting force and allows the establishment of a dynamic model [61]. The uncut chip thickness can be expressed by the addition of the static uncut chip thickness t_{sc} and dynamic uncut chip thickness t_{dc} [62]. In order to obtain the uncut chip thickness, it is important to look at the geometrical aspect of the cutting process. The cutting mechanism can be represented in a two-degree of freedom system as shown in Fig. 4, and points A and B represent the trajectory of the $(j-1)^{th}$ cutting flute and the trajectory of the j^{th} cutting flute respectively. The implementation of the tool runout effect in the trajectory model is essential in micro-milling [63].

The cutting contact can be verified numerically by the condition Eq. (2).

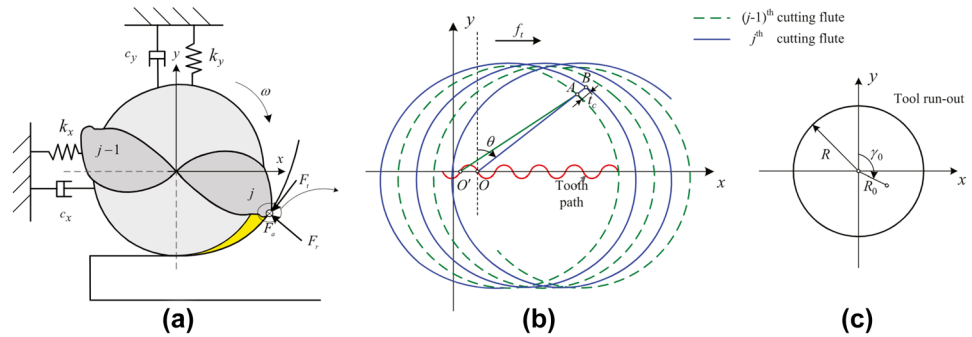
$$\begin{cases} \frac{x_{k,t}^2 + y_{k,t}^2}{x_{k'}^2 + y_{k'}^2} \leq 1, & \text{contact} \\ \frac{x_{k,t}^2 + y_{k,t}^2}{x_{k'}^2 + y_{k'}^2} > 1, & \text{no contact} \end{cases} \quad (2)$$

If the contact between the tool and the workpiece is verified, the static uncut chip thickness can be calculated as expressed in Eq. (3).

$$h = \sqrt{(x_{k,t} - x_{k'})^2 + (y_{k,t} - y_{k'})^2} \quad (3)$$

The positions in the x -axis for points A and B are respectively x_A and x_B , and the position in the y -axis is noted as y_A and y_B . The coordinates of points A and B are expressed in Equation (4),

Fig. 4 **a** Two-degree freedom system of micro-end milling operations, **b** trajectory of the $(j - 1)^{th}$ and j^{th} cutting flutes in x and y coordinate system, (c) micro-end mill center with tool runout [62]



$$\begin{cases} x_A = x_{O'} + f_i t' + R \sin(\omega t' - \frac{2\pi(j-1)}{N_z}) + R_0 \sin(\omega t' + \gamma_0) \\ y_A = x_{O'} + f_i t' + R \sin(\omega t' - \frac{2\pi(j-1)}{N_z}) + R_0 \sin(\omega t' + \gamma_0) \\ x_B = x_O + f_i t + R \sin(\omega t - \frac{2\pi j}{N_z}) + R_0 \sin(\omega t + \gamma_0) \\ y_B = x_O + f_i t + R \sin(\omega t - \frac{2\pi j}{N_z}) + R_0 \sin(\omega t + \gamma_0) \end{cases} \quad (4)$$

where $x_{O'}$ and $y_{O'}$ are the coordinate of the point O, f_i is the feed rate (mm/s). t is the time of the j^{th} cutting flute, t' is the time of the $(j - 1)^{th}$ cutting flute, N_z is the number of cutting flutes, R_0 is the runout offset (mm), γ_0 is the angle of the runout (rad) as shown in Fig. 4. The substitution of Eq. (4) into Eq. (3) forms the developed expression of the static uncut chip thickness as presented in Eq. (5).

$$\begin{aligned} t_{SC} = & ((2f_i(t - t') + R \sin(\omega t - \frac{2\pi j}{N_z}) \\ & - R \sin(\omega t' - \frac{2\pi(j-1)}{N_z}) + R_0 \sin(\omega t' + \gamma_0) \\ & - R_0 \sin(\omega t' + \gamma_0)^2 + (R \cos(\omega t - \frac{2\pi j}{N_z}) \\ & - R \cos(\omega t' - \frac{2\pi(j-1)}{N_z}) + R_0 \cos(\omega t' + \gamma_0) \\ & - R_0 \cos(\omega t' + \gamma_0)^2)^{\frac{1}{2}} \end{aligned} \quad (5)$$

The main issue in the dynamic uncut chip thickness is the reliability of the vibration function $v(t)$, which at any time t is variable and can be subjected to change depending on the environment conditions, reliability of the micro-machining process including the tool, workpiece, machining center, and measure equipment. The application of the model in the experimental process will lead to small differences, and similar conclusions have pointed out these reliability issues [64]. It is important to note that in high-precision components, depending on the material properties, at a depth of cut lower than the critical uncut chip thickness, no chip will be formed, and the material will be in the plowing regime rather than the shearing regime. This effect is common in micro-milling operations for depth of cut below a few microns, which makes the finishing processes very challenging. The cutting forces represent the most relevant parameter in the study of the dynamics; in a second position, the acceleration is an important parameter to consider, and it provides information on the vibration behavior and is the base of

the study of the natural frequency for the investigation of the chatter, in conventional machining as well as in micro-machining. However, a large-scale gap is spacing those fields and it is important in the micro-field to consider a wider area of parameters. Common researchers have defined a milling operation as a micro-milling operation when its tool diameter is lower than 1mm, which includes most of the micro-milling research and provides relevant results on the dynamic model. Accurate prediction of the forces and vibration in micro-milling can be performed using the tool geometry, gyroscopic effect, inertia, and error factors [65]. Recent research investigates the damping, non-linearities, tool runout, and the size effect [14, 62, 66, 67]. Moreover, the tool deflection has an influence on the cutting force model; its consideration can result in an improvement of the cutting force prediction [68]. The deflection of the micro-tool increases linearly according to the spindle speed, creating an unbalance and therefore an increase in the dynamic runout [69]. Researchers have shown the importance of the cutting forces in the creation of the dynamic model, and this statement is true for conventional milling and micro-milling [70, 71], but also for machining such as micro-drilling, drilling, micro-turning, and turning [72–74]. The forces communicate plenty of information on the cutting process, such as the chip formation, removal mechanism, the dynamic behavior, and the tool wear. Modeling the cutting force is essential for the study of the chatter, and as a part of the model dynamics output parameters, the cutting forces in micro-milling systems can describe the displacement of the system [66]. In milling processes, the main forces are mostly presented on the x -axis and y -axis; therefore, the general principle of the motion can be expressed as a two-degree of freedom system [62]. At a unit volume, the material removed from the cutting operation and the energy consumed are noted as dV and e respectively and are expressed in Eq. (6),

$$\begin{cases} dV = v dt R \cot(\beta) \int_{\theta_{ent}}^{\theta_{ext}} h(\theta_i(z)) d\theta \\ e = \frac{F v dt}{dV} = F \frac{\tan(\beta)}{R \int_{\theta_{ent}}^{\theta_{ext}} h(\theta_i(z)) d\theta} \end{cases} \quad (6)$$

where v is the volume, t the time point, R the tool radius, β the helix angle of cutting tools, θ_{ext} the tool exit angle, θ_{int} the tool entry angle, $h(\theta_i(z)) d\theta$ the uncut chip thickness, and F the cutting force [75]. The general cutting forces model consists of three components, the flute, the dynamic cutting forces due to regenerative chip thickness ($v(t) - v(t')$), and the process damping forces generated by the contact between the micro-tool and the workpiece surface. The interference volume between the workpiece and the tool is expressed in Equation (7),

$$V_p = A_p * dz \tag{7}$$

where A_p is the plowing area and dz is the height element which correspond to the normal axis of the workpiece surface. The force in the x -axis and y -axis can be expressed as shown in Eq. (8),

$$\begin{cases} F_{ij}(\theta) = \begin{bmatrix} K_{ip} \\ K_{rp} \end{bmatrix} A_p dz \\ F_{rj}(\theta) = \begin{bmatrix} K_{re} \\ K_{te} \end{bmatrix} dz \end{cases} \tag{8}$$

where F_{ij} and F_{rj} are the tangential and radial cutting forces, respectively. K_{re} and K_{te} are the radial and tangential edge coefficients, respectively. K_{ip} and K_{rp} are the tangential and radial plowing coefficients, respectively. The regenerative vibration can be expressed with the difference in the position coordinates in the x -axis and y -axis as shown in Eq. (9),

$$\begin{cases} \Delta x = x(t) - x(t - T_p) \\ \Delta y = y(t) - y(t - T_p) \end{cases} \tag{9}$$

where T_p is the period of time between successive flute engagements and $\dot{\mathbf{d}} = [\Delta \dot{x} \ \Delta \dot{y}]^T$ is the vibration velocity vector. $\mathbf{d} = [\Delta x \ \Delta y]^T$ is the regenerative vibration vector.

The 2×1 matrix \mathbf{F}_1 can be introduce for the composition of the static force and the 2×2 matrix \mathbf{F}_2 and \mathbf{F}_3 for the dynamic force and process damping force respectively as shown in Eqs. (10), (11) and (12).

$$\mathbf{F}_1(\theta) = \begin{bmatrix} -(K_{tc} a_p t_{SC} \cos(\theta) + K_{rc} a_p \sin(\theta)) \\ -(K_{te} \cos(\theta) + K_{re} \sin(\theta)) \\ K_{tc} a_p t_{SC} \sin(\theta) - K_{rc} a_p t_{SC} \cos(\theta) \\ +(K_{te} \sin(\theta) - K_{re} \cos(\theta)) \end{bmatrix} \tag{10}$$

$$\mathbf{F}_2(\theta) = \begin{bmatrix} -(K_{tc} a_p t_{SC} \cos(\theta) + K_{rc} a_p \sin(\theta)) \\ -(K_{te} \cos(\theta) + K_{re} \sin(\theta)) \\ K_{tc} a_p t_{SC} \sin(\theta) - K_{rc} a_p t_{SC} \cos(\theta) \\ +(K_{te} \sin(\theta) - K_{re} \cos(\theta)) \end{bmatrix} \tag{11}$$

$$\mathbf{F}_3(\theta) = \begin{bmatrix} C_t a_p \sin(\theta) \cos(\theta) & C_t a_p \cos(\theta)^2 \\ +C_r a_p \sin(\theta)^2 & +C_r \sin(\theta) \cos(\theta) \\ -C_t a_p \sin(\theta)^2 & -C_t a_p \sin(\theta) \cos(\theta) \\ +C_r a_p \sin(\theta) \cos(\theta) & +C_r a_p \cos(\theta)^2 \end{bmatrix} \tag{12}$$

The static force, dynamic force, and process damping force are expressed in Eqs. (13), (14) and (15) respectively,

$$F_s(t) = \frac{-R}{\tan(\lambda_s)} \sum_{j=1}^{N_z} \int_{\theta_{ent}}^{\theta_{ext}} \mathbf{F}_1(\theta) d\theta \tag{13}$$

$$F_d(t) = \frac{R}{\tan(\lambda_s)} \sum_{j=1}^{N_z} \int_{\theta_{ent}}^{\theta_{ext}} \mathbf{F}_2(\theta) \mathbf{d} d\theta \tag{14}$$

$$F_{pd}(t) = \frac{R}{V_c \tan(\lambda_s)} \sum_{j=1}^{N_z} \int_{\theta_{ent}}^{\theta_{ext}} \mathbf{F}_3(\theta) \mathbf{d} d\theta \tag{15}$$

where N_z is the number of flutes, λ_s is the helix angle, R is the tool radius, θ_{ent} and θ_{ex} are the entry and exit angle of tool respectively, K_{rc} and K_{tc} the radial and tangential cutting coefficients respectively, and K_{ipc} and K_{rpc} are the tangential and radial plowing coefficients respectively. The transition between the plowing- and shearing-dominant regime follows the rules states in Eq. (16) which expressed the forces relationships for the three orthogonal axis according to the uncut chip thickness h and the critical uncut chip thickness h_c as shown in Eq. (16),

$$\begin{cases} dF_t = \begin{cases} (K_{tc} h + K_{te}) dz, h \geq h_c (shearing) \\ (K_{ip} A_p + K_{te}) dz, h < h_c (ploughing) \end{cases} \\ dF_r = \begin{cases} (K_{rc} h + K_{re}) dz, h \geq h_c (shearing) \\ (K_{rp} A_p + K_{re}) dz, h < h_c (ploughing) \end{cases} \\ dF_a = \begin{cases} (K_{ac} h + K_{ae}) dz, h \geq h_c (shearing) \\ (K_{ap} A_p + K_{ae}) dz, h < h_c (ploughing) \end{cases} \end{cases} \tag{16}$$

where dF_t , dF_r , and dF_a , are the tangential, radial, and axial force, respectively. K_{ae} is the axial edge coefficient, K_{ac} is axial cutting coefficient, and K_{ap} is the axial plowing coefficient.

Researchers have found a similar dynamic model of the cutting forces in the plowing and the shear regime [76]. Chen et al. have proposed an improved model for the cutting force regarding the magnitude and frequency. The study involves the dynamic regenerative effect as a multiple time delays function. In his study, the cutting parameters (feed per tooth, cutting depth, and spindle speed), the tool parameters (tool diameter, teeth number, and edge radius), and the machine system parameters (runout, mass matrix, stiffness matrix, and damping matrix) were considered as the input parameters. His proposed

model for cutting force generation follows the schematic shown in Fig. 5 [34].

Researchers have incorporated the force variation in the dynamic cutting force model, a study applied on metal matrix where the shearing force and the particle fracture force were expressed analytically and the model was numerically validated resulting on a significant effect of the feed rate, radial depth of cut, axial depth of cut, particle size, and the volume fraction on the prediction of the cutting force variation [77]. Further experiments must be conducted for the validation of both analytical and simulation results. The study results conducted by Chen et al. have shown an error of 36% and 35% on the x -axis and y -axis respectively for a $1\text{-}\mu\text{m}$ feed per tooth and for the same cutting conditions, where the conventional simulation method using only milling principles and theories has an error of 76% and 68% for the x -axis and y -axis respectively [34]. This confirms the importance of the consideration of the dynamics in the cutting force model in micro-milling operations and the net gap between micro and macro milling operations.

The position between the tool and the workpiece can be expressed as shown in Eq. (17),

$$\begin{cases} x_{tw}(t) = x_t(t) - x_w(t) \\ y_{tw}(t) = y_t(t) - y_w(t) \end{cases} \quad (17)$$

where x_{tw} and y_{tw} are the position of the distance between the tool and the workpiece in the x - and y -axis respectively, $x_t(t)$ and $y_t(t)$ are the tool position in the x - and y -axis, respectively, and $x_w(t)$ and $y_w(t)$ are the workpiece position in the x - and y -axis, respectively. Researchers have considered the chip accumulation on the cutting force prediction in micro end milling, due to the elastic behavior of the machined material, the chip thickness is likely to affect the next tooth pass depending on the ratio between the critical uncut chip thickness h_{min} and the feed per tooth f_z , noted as h_{min}/f_z . In the case of $h_{min}/f_z < 1$, the chip is formed; otherwise, the uncut chip thickness is being increased. The

developed model has shown better results regarding the experimental forces measured compared to the traditional model considering the micro-tool as a rigid body. In addition, non-linear behavior of the cutting forces in the transitional area between the shearing and plowing regime can be observed when the uncut chip thickness gets close to the critical uncut chip thickness [78].

2.3 Dynamic methods

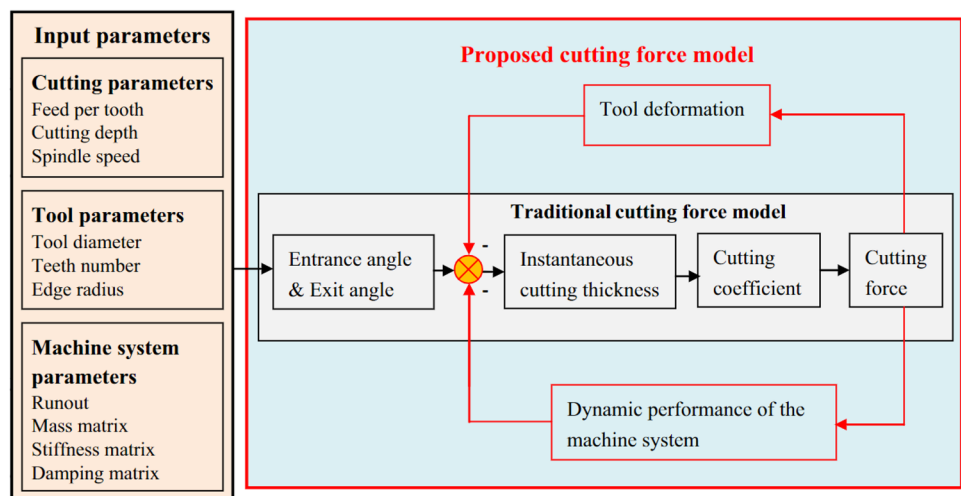
2.3.1 Dynamic stiffness method

The dynamic stiffness method (DS) is used for the characterization of the vibration behavior of the structure. Researchers have highlighted this method based on the free vibration behavior of beams structure [79]. The DS method is based on the frequency of the shape functions leading to the exact solution for the governing differential equations of the system. This method can be used in all types of frequency ranges, rather than the finite element method that is inaccurate at high vibration frequencies. The derivative of the governing differential equation is expressed in Eq. (18),

$$\begin{cases} F = \frac{1}{L}(A_1\phi' - A_0V') \\ = \frac{1}{L}(A_1 \sum_{j=1}^6 r_j - A_0 \sum_{j=1}^6 \alpha_j r_j)R_j e^{r_j \epsilon} \\ S = \frac{A_3}{L}(-W' + L\Phi) \\ = \frac{A_3}{L}(L - \sum_{j=1}^6 \beta_j r_j)R_j e^{r_j \epsilon} \\ M = \frac{1}{L}(A_1V' - A_2\Phi') \\ = \frac{1}{L}(A_1 \sum_{j=1}^6 (\alpha_j r_j - A_2 \sum_{j=1}^6 r_j)R_j e^{r_j \epsilon} \end{cases} \quad (18)$$

where F is the axial force, S is the shear force, and M is the bending moment. Note that F , S , and M are

Fig. 5 Schematic of the cutting force generation [34]



frequency-dependent, due to the term α_j and β_j which depend on the frequency ω [80]. Researchers have investigated the DS method for rotating tapered beams covering a large number of practical cases and have developed its dynamic stiffness matrix [81]. Liu et al. have proposed a FEM analysis method for the determination of the dynamic properties of the micro-end mill, and the analysis was conducted on single-phase ferrite and pearlite workpiece material with a spindle speed of 84,000 rpm and several feed rates from 0.25 up to 3.0 $\mu\text{m}/\text{flute}$, resulting on modal parameters [82]. For the first bending mode of the micro-tool, in X and Y directions, the natural frequency is found at 10.4 kHz with stiffness of $1.6 \times 10^6 \text{ N/m}$, which deviate from 12% from the experimental process. Tajalli et al. have analyzed the chatter instability of the micro-end mill using the semi-discretization (SD) method and involving the process damping effect resulting in the dynamics of the system using the Galerkin approach coupled with the dynamic stiffness (DS) method [83]. In addition, the gyroscopic effect was incorporated into the governing equations, resulting in an improvement of the stability prediction as shown Fig. 6. The study has shown the non-negligible influence of the gyroscopic effect and better results compared with the finite element method of analysis.

The DS method has been utilized by Damjanovic et al. in order to predict the natural frequencies of a stiffened composite plate; the results have shown an average difference of 0.13% with the finite element model computed by ABAQUS [84]. Su and Banerjee have confirmed the reliability of this method and concluded their study on exact results [80]. In the field of machining, the DS method is used as an analytical method for the determination of the natural frequency, and researchers have been using this method in order to characterize the micro-tool vibration behavior. Wittrick-Williams

(W-W) algorithm is often combined with the DS method; it presents an effective way of incorporating all-natural frequencies into the dynamic stiffness matrix. W-W algorithm has been used by many researchers in the analytical investigation of the DS method for the field of machining and other fields [79–81, 85].

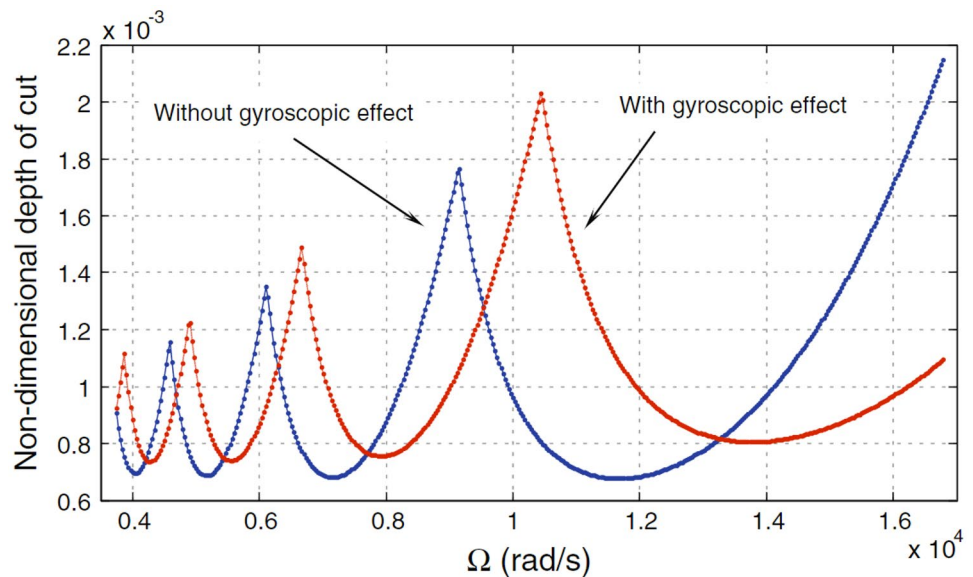
2.3.2 Beam dynamic theories

The Euler-Bernoulli approach is used to simplify the calculation of the beam dynamic model by not considering the transverse shear deformation [86]. This neglected parameter can be assumed if the deformation of the beam is neglected; thus, the beam is considered rigid and unreformable. In the study by Uhlmann and Mahr conducted in micro-milling, due to the small diameter of the micro-tool, the gyroscopic effects were neglected and so the Euler-Bernoulli theory was applied for the calculation of the tool dynamics [87]. Later in the research conducted by Mokhtari et al. on the impact of the size effect in micro-milling, the neglected gyroscopic parameter was shown as an important parameter to include in the investigation of the dynamic, as it increases the error [14]. The dynamic Timoshenko beam (TB) theory in machining processes is principally used in the representation of the machining tool. It is considering the tool as a rectangular or cylindrical beam with the damping effects and axial effects as expressed in Eq. (19),

$$\begin{cases} \rho A \frac{\delta^2 \omega}{\delta t^2} + \nabla(x) \frac{\delta \omega}{\delta t} = \frac{\delta}{\delta x} [\kappa A G (\frac{\delta \omega}{\delta x} - \Phi)] + q(x, t) \\ \rho I \frac{\delta^2 \Phi}{\delta t^2} = N(x, t) \frac{\delta \omega}{\delta x} + \frac{\delta}{\delta x} (E * I * \frac{\delta \phi}{\delta x}) + \kappa A G \frac{\delta \omega}{\delta x} - \phi \end{cases} \quad (19)$$

where ρ is the density, A is the cross-section area, E is the elastic modulus, G is the shear modulus, κ is the

Fig. 6 The effect of gyroscopic terms on stability lobe diagrams [83]



Timoshenko shear coefficient, I is the second moment of area, $q(x,t)$ is the disturbed load, $N(x,t)$ is the axial force, and $\nabla(x)$ is the damping force. The TB theory is taking into account the transverse shear deformation effects which leads to a non-perpendicular shape at the end of the beam, whereas in the Euler-Bernoulli theory the transverse shear deformation is neglected, resulting in a perpendicular shape at the beams end [87]. Thus, Euler-Bernoulli beam theory will lead to less precise results compared to the TB theory. TB theory is applied in an orthogonal coordinate system (x,y,z) , and is used to calculate the dynamic characteristic of the tool. It has been used in micro-milling, conventional macro-milling, and other machining processes. Due to the small diameter of the micro-tool (less than 0.5mm), the use of TB theory is more common in the micro-milling field compared to the Euler-Bernoulli theory. The gyroscopic effect as well as the rotary inertia effects and the shear deformation can be implemented into the TB equations leading to the governing equation of the system. Hamiltons principle is used for the derivation of the governing equation leading to the dynamic characteristics of the tool [88–90]. The tool geometry has an important influence on the dynamic characteristics in micro-milling, and the geometry can be evaluated using analytical models. The model investigated by Filiz et al. uses the Timoshenko beam theory (TB) to accurately describe the shear and rotary inertia effect of the tool, the spectral Tchebychev solution applied to the model can predict with high accuracy the dynamics of the micro-end mills [91]. The spectral Tchebychev technique is used to solve the boundary value problems, in the case of micro-milling, this technique simplifies the common finite element method and has shown great accuracy for the description of the micro-end mill dynamics [92]. The error related to the micro-milling process setup directly impacts the runout of the tool, amplifying the tool-tip vibration. Using the same model, this increase in the runout can be analyzed [91]. The spectral Tchebychev technique has been validated experimentally with a difference of less than 1% compared to a finite element model for the natural frequencies and mode shapes of the micro-tool [69]. A similar study has been conducted and extended to micro-drills, where the spectral Tchebychev technique applied in a single dimension can describe the rotary dynamics of the micro-end mill and micro-drill [93]. Researchers have investigated the dynamic behavior of the micro-tool using the TB theory considering the size effect, gyroscopic moments, and rotary inertia of the tool resulting in higher accuracy of the stability prediction [14]. The micro-milling cutting tool was considered as a 3D flexible nonlinear rotating cantilever Timoshenko beam coupled with the gradient theory for the system stability prediction, resulting in a complete model of the governing equations of the system.

2.3.3 Receptance coupling method

The receptance coupling (RC) method is an analytical method that permits to couple the dynamical behavior of two joint systems. The receptance coupling method is a very efficient method to obtain the tool dynamics of a micro-mill. It is a useful and powerful mathematical method that has shown good results in the study of tool-tip dynamics [94]. In micro-milling and milling processes, the tool structure can be separated into two substructures A and B, represented in Fig. 7.

Substructure A represents the tool tip and substructure B represents the machining tool structure, the spindle, the holder, and the shank of the tool. Both substructures dynamics are calculated separately from the experimental and simulation data. The RC method has been used for determination of the assembled dynamics of the micro-milling system, which was afterwards implemented in the chatter suppression algorithm [95]. The RC equation for coupling the structures A and B is expressed in Eq. (20),

$$G_{11} = \frac{X_1}{F_1} = H_{11} - H_1(H_{22} + H_{23})^{(-1)}H_{21} \tag{20}$$

where G is the assembled dynamics and H is the substructure dynamics. In addition to the use of the RC method, the Timoshenko beam theory can be combined with the finite element model for the determination of the tool-tip dynamics. More methods can be applied for the study of the dynamics in micro-milling such as the flight dynamic theory (FDT) is applied for the motion of a floating rigid body, considering the gyroscopic effects. In the study conducted by Huang et al., the choice of an appropriate FDT of the rotor dynamical behavior has been investigated [96]. The RC method was used in macro machining operation leading to an accurate the tool point FRF prediction. The authors' results show that the receptance coupling of the tool with the spindle can predict the systems dynamic response [97]. The RC method can be combined with other theories such as the active control of active magnetic bearings (AMBs) which have shown good results in the suppression of the chatter in milling processes. However, studies on AMBs in micro-machining are still very limited [98, 99].

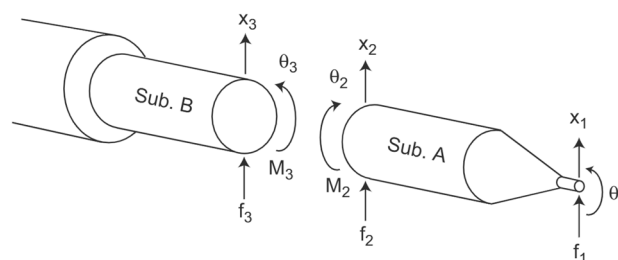


Fig. 7 Receptance coupling of a spindle and an arbitrary end mill [94]

2.3.4 Machine learning method

The fuzzy logic (FL) can also be called neuro-fuzzy or fuzzy neural, and it is an analysis method of the signal during the machining. It is a powerful method for the combination of multiple parameters and has mostly been used for sensor monitoring [7, 64]. Malekian et al. have used the FL method in order to obtain feedback on the micro-tool integrity with regard to the shape and the wear [100]. In his study, he proposed a schematic of the neuro-fuzzy method for tool condition monitoring and he fuses the acceleration, acoustic emission, and the forces signals. The results show a good correlation between the actual tool wear and the simulation results. The FL mathematical principle is shown in Eq. (21), with $x_1=A_1 I$, $x_2=A_2 I$, $x_n=A_{n1}$.

$$f_1 = p_{11}x_1 + \dots + p_{1n}x_n + r_1 \quad (21)$$

where f_1 is the first-order Sugeno fuzzy model, p and r are the coefficients of a linear relationship, and A is a nonlinear function that results from primary experimental process. An adaptive neuro-fuzzy interference system has been developed used by many researchers, and the composition of the structure is shown in Fig. 8.

The structure is composed of different nodes (adaptive and fixed) that will process the information from the sensors signals in order to return the corresponding fuzzy model as expressed in Eq. (21). The Fig. 9 shows the schematic of the neuro-fuzzy method for the tool-condition monitoring, which in micro-milling gives a good alternative comparing with the traditional experimental investigation on the tool dynamic mechanism monitoring.

The regression and FL method in micro-milling can successfully predict the tool wear, cutting forces, and surface roughness resulting in a good correlation with the experimental process as confirmed in the study of E. Kuram; the authors have combined the Tagushi method with their FL

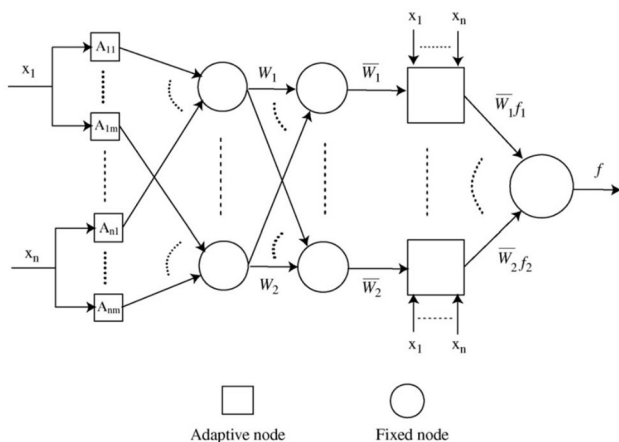


Fig. 8 Adaptive neuro-fuzzy interference system structure [101]

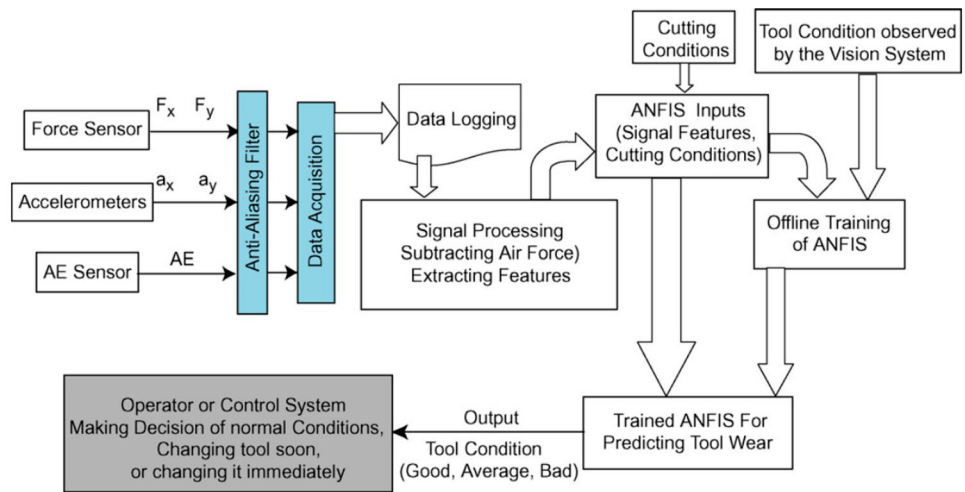
model and they successfully established the relationship between the dependent and independent variables in micro-milling [102]. Like fuzzy logic, the Back-Propagation Neural Network (BPNN) is another prediction method; however, it is mostly used for the prediction of the output parameters, such as the burrs generated by the cutting operation [103]. In addition, the BPNN can be used as a real-time adaptive control method. Furthermore, the surface can also be predicted in micro-milling with the use of BPNN [104]. In recent research, the BPNN method was used for the prediction of the vibration, resulting in a good prediction of the vibration displacement [21]. An artificial neural networks model can validate the relationship between the feed rate increase and the increase of the static deflection and the dynamic displacement [89].

3 Signal detection

3.1 Micro-electronic mechanical system

Production of high-quality micro-electronic mechanical systems (MEMS) is of great importance. The requirement for relative MEMS accuracy of micro-components is in order from 10⁻³ to 10⁻⁵, and they are necessary for the study of micro-scale phenomenon and reliable micro-sensors seeing as the foundation of the data consistency [9]. It is important to understand the difference between macro-machining and micro-milling; indeed, the theories involved in that field are not reciprocal. The reliability and consistency of experimental investigation define numerous problems in the field of micro-machining [105]. The use of micro-electronic mechanical systems (MEMS) in the experimental process of vibration recording is fundamental. MEMS is essentially designed through finite element simulations in order to evaluate the performance of the system [106]. In the case of force recording using a dynamometer, Table 1 shows the range of forces obtained respectively by different researchers during the micro-milling experimental process, and it shows a net difference regarding the maximal force between a micro-tool of 0.2 mm and 0.8 mm of diameter corresponding to 0.4 N and 6 N, respectively. Therefore, due to the micro-scale, it is mandatory to develop or use the correct sensitivity sensor for the corresponding parameters involved in the experimental process. Most researchers have shown the great application of piezoelectric sensors in the measurement of the dynamic force [51]. Piezoelectric sensors have great characteristics due to their passive behavior requiring no external power to generate a charge output. Therefore, the investigation of the dynamics in machining processes is likely to involve this sensing technology. Researchers have shown the necessity of the MEMS, at a micro-scale operation the forces are very small and the noise might be a

Fig. 9 Schematic of the neuro-fuzzy method for tool condition monitoring [100]



source of error, the force amplitude depends on the material removal rate which can be obtained through the geometry and machine inputs, and Table 1 presents some researchers results in forces at different input parameters.

The effect of the vibration in terms of displacement has been estimated to 0.002 μm during a micro-milling at a feed rate, spindle speed, axial, and radial depth of cut of 1 $\mu\text{m}/\text{tooth}$, 10,000 rpm, 10 μm , and 12 μm respectively [46]. The challenge in micro-milling is the size of the sensor, especially for accelerometers, which requires to be attached to the investigated surface. It can change the corresponding variable of the dynamics of the system, due to its non-negligible weight compared to the system. In macro-operations, the size of the accelerometer is small in comparison of the whole milling process, so it can be neglected. Researchers have developed a 1 mm \times 1 mm accelerometer sensor, reducing parasitic capacitor and increasing sensitivity, and the simulation results have shown a mechanical sensitivity of 29.8 nm/g and a capacitive sensitivity of 15.5 fFm/g [108]. An ideal sensor has a large bandwidth and a high sensitivity. However, it is difficult to combine these two advantages. Large bandwidth can be obtained by increasing the stiffness or the rigidity of

the system, where these parameters will lower the sensitivity. Optical force sensor can also be used in the processes of dynamics recording; researchers have shown an error of 0.775 N and 0.511 N for the static force in the x -axis and y -axis, respectively [109]. In the development of sensors, further research must be accomplished in the enhancement of the bandwidth during the machining processes. The importance of accurate sensors is justified, and it allows adaptive control system to optimize the machining process by enhancing the material removal rate and by avoiding unwanted wears simultaneously. Moreover, the force signal is very useful in the evaluation of the machining performance, as well as the chatter detection and dynamic model improvement.

3.2 Vibration monitoring

The real-time experimental process of vibration monitoring mainly requires an accelerometer or a dynamometer [110]. The use of both sensors can lead to better results in terms of vibration recording. Moreover, the orthogonal acceleration signals recorded by the accelerometer can be injected into wavelet coherence functions in order to effectively detect the chatter [26]. AE devices are also used in chatter detection. Indeed, it has been shown that unstable cuts are more likely to appear at a high root mean square level acoustic emission, due to the larger amount of energy produced [25]. The union of the sound signal with the acceleration has shown higher effectiveness compared to their separate use [32]. Therefore, the combination of multiple sensors for the measurement of the acceleration, forces, and sound can provide a significant amount of data that enhance the vibration capture, and examples of the experimental setup can be seen in Fig. 10.

Recent research has shown the use of high-precision laser displacement sensors in the vibration monitoring process; it describes a safe and high-precision monitoring approach to collecting vibration data. The laser displacement sensor

Table 1 Results on the force signal amplitude in micro-milling

Tool diameter (mm)	0.2	0.2	0.8	0.01
Spindle speed (rpm)	10,000	20,000	10,000	10,000
Feed rate ($\mu\text{m}/\text{tooth}$)	3	3	4	1
Depth of cut (μm)	50	50	50	18
Maximal amplitude of the force in the x -axis (N)	1.15	1.5	6	0.135
Maximal amplitude (N) of the force in Y -axis (N)	1.3	1.35	6	0.28
Reference	[107]	[107]	[102]	[46]

provides high accuracy results, which makes it beneficial for high-speed micro-machining [111–114]. The development of a new holder for the setup of a laser displacement can lead to a higher control in the rotational angle of the device and therefore contribute to the enhancement of the experimental performance on the vibration measurement with the laser displacement sensor [21].

3.2.1 Frequency response determination

The frequency response function (FRF) is used in machining processes for the identification of the dynamics of the system, and it is used for the generation of the stability lobes diagram and therefore the identification of the chatter occurrence and machining stability. The FRF curve gives precious information on the modal dynamics equation of motion, as it provides the natural frequency, the damping, and stiffness coefficient [115]. Those parameters are essential in the design of chatter reduction or suppression methods. In the literature, modal testing is mainly performed on the stationary tool; however in micro-machining due to the gyroscopic effects, the modal tests should be performed while the system is rotating to catch the rotational dynamics of the system. In Fig. 10, they showed an experimental setup however with a capacitance sensor the frequency range will be limited. Also, with this setup, only the response is measured, and no information is given in terms of excitation. The common measurement of the FRF involves impact test on non-rotating tool, in case of micro-machining processes this process is challenging

due to the small diameter of the tool, and it is presumed to be damaged during the dynamical hammer test [94]. Therefore, the macro impulse hammer does not show an accurate measurement of the tool-tip dynamics [95]. One of the solution is the use of a micro-impulse hammer on the micro-mill and a laser displacement sensor has been investigated and presents a solution for the recording of the modal parameters. While performing modal testing on the tool, the impact point should be chosen to be rigid enough on the tool shank to distribute the energy along the tools structure, in that case, a good measurement can be performed [116]. An experimental result of the FRF is shown in Fig. 11 where the real part and imaginary part of the FRF and the first three modes at 3574 Hz, 4707 Hz, and 5645 Hz are shown, respectively [110].

The FRF and the experimental process of tool-wear monitoring using an impact hammer test can serve as a calibration method for the force sensor, and using this process the researchers have found that the force sensor Kistler 9025B used for the force sensing has a bandwidth up to a frequency of 2000 Hz [100]. A similar experiment was conducted on the tool FRF determination [117]. Bediz and Ozdoganlar presented an experimental methodology to determine spindle dynamics up to 20 kHz while the system is rotating at different spindle speed up to 150 krpm; in order to perform such experiment, the setup is composed of an impact excitation system driven by an electromagnet capable of hitting the test structure with a defined impact force magnitude, and the measurements are performed using two independent fiber-optic laser Doppler vibrometers [118]. The use of

Fig. 10 Experimental setup for vibration recording in micro-milling: **a** using an accelerometer and a microphone [32]; **b** using an accelerometer, dynamometer, and AE sensor [26, 94]

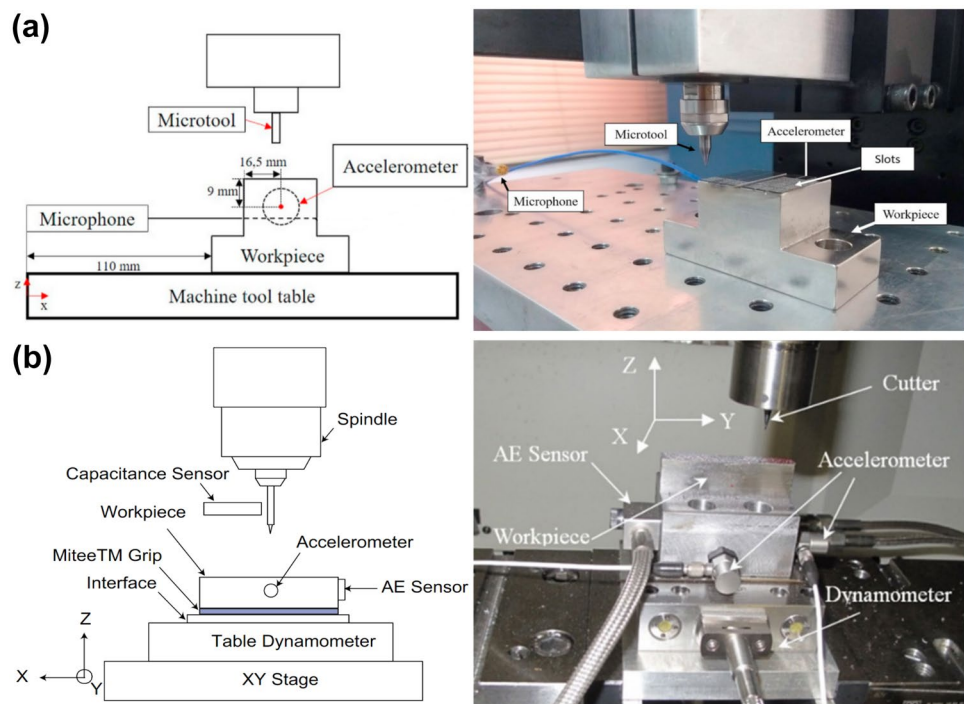
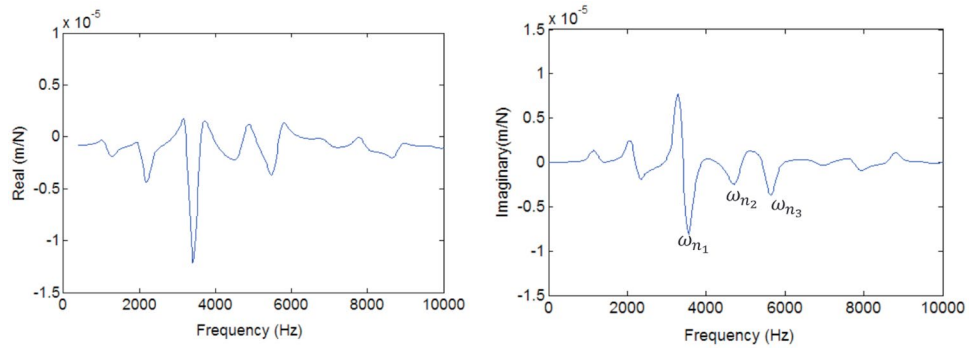


Fig. 11 Frequency response function of the tool with machine tool compliance. **a** Real part. **b** Imaginary part [110]



a high-precision laser displacement for the vibration monitoring can provide accurate results; the results of the synthesized tool tip frequency response function in the *x*- and *y*-axis can be seen represented in Fig. 12, where the four harmonic frequencies on the *x*-axis have been found at 2078 Hz, 2737 Hz, 4807 Hz, and 10971 Hz and their corresponding damping ratio is 4.12%, 3.24%, 2.47%, and 1.32% respectively. On the *y*-axis, the frequencies are closely like the *x*-axis, but the damping has a higher damping ratio, which explains its lower amplitude compared with the FRF on the *x*-axis. The research conducted showed that at a high feed rate the vibration was less likely to occur and at the given input parameters investigated the regenerative did not impact the vibration occurrence [119].

The spindle speed ramp-up is a method for the extraction of the chatter limits suitable for low-cost equipment, and their comparison with the FRFs obtained at the tool-tip through modal tests can provide accurate predictions of the stability lobes diagram in milling process [120].

3.2.2 Chatter detection and stability

Research has shown that the chatter can be detected by the surface topology, the displacement signal, or the force signal

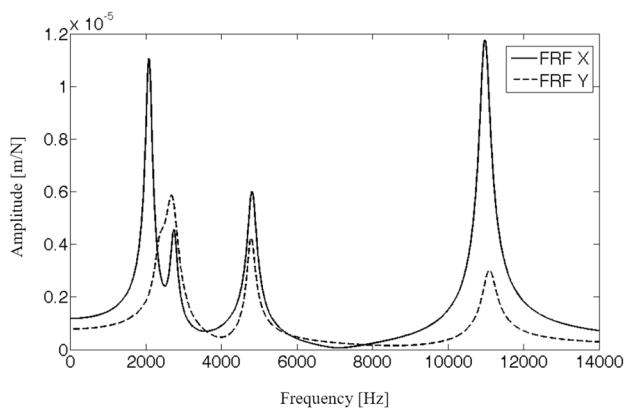
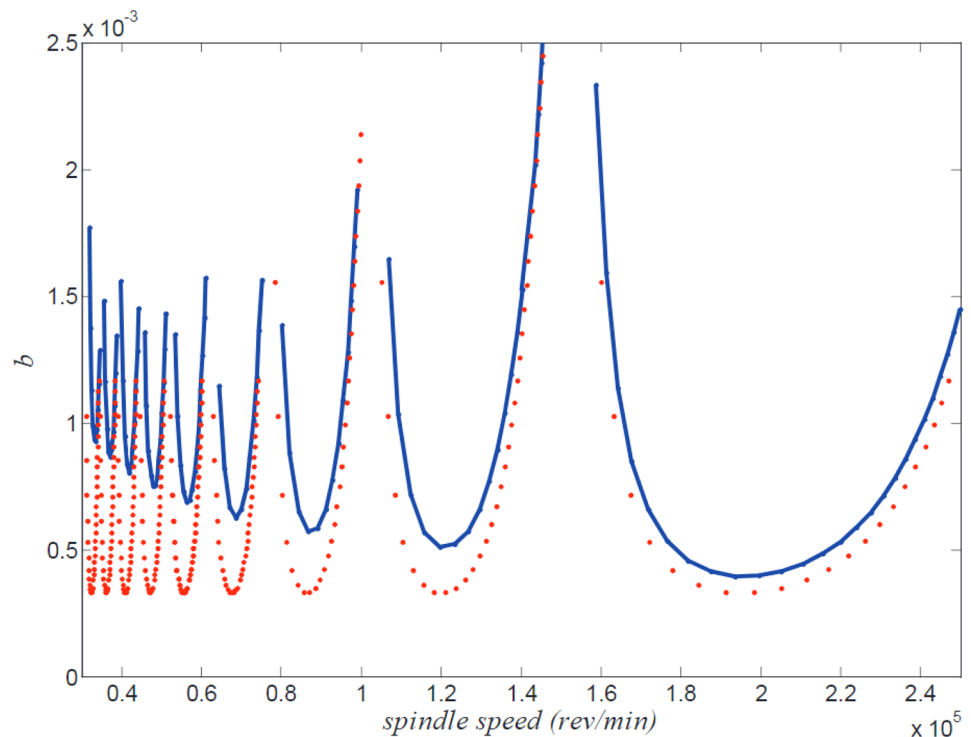


Fig. 12 Synthesized tool tip frequency response functions in X and Y directions [119]

[110]. The force signal is more likely to detect frequencies below 5000 Hz; therefore, the force signal is not suitable for large bandwidth micro-milling operations. The displacement sensor (accelerometer) is adapted for high frequencies and provides real-time information. However, it is more likely to generate noise. The surface topography method is very accurate to capture the chatter; however, it is a post-operation method. The consideration of the process damping in the study of the chatter cannot be neglected, on Fig. 13, the numerical results on the stability of the micro-milling show a net difference with the chatter stability without process damping. The continuous blue line and the non-continuous red line represent the machining with process damping and without process damping, respectively.

For all spindle speeds, the return value of the amplitude is much higher when the process damping is considered rather than neglected; therefore, the machining operation is more likely to be stable. Moreover, the critical depth of cut is larger at a lower spindle speed when the process damping is considered [90]. A similar study has also been conducted via a semi-discretization approach leading to the same conclusion on the importance of using the process damping. Moreover, it has been shown that the Floquet theory can analyze the boundaries of the chatter occurrence at a specific depth of cut [83]. The gyroscopic effect can be neglected for the inertial frame; however, it cannot be neglected for the rotating frame [53]. In the machining processes, at macro and micro scales, the stable depth of cut can be determined with the analysis of variance (ANOVA) method, and this method can be extended for other machining parameters [72, 111, 121, 122]. Considering the nonlinearities in the cutting forces model with runout integration can describe the stability of the operation and identify the chatter in micro-milling operations [66]. The use of the process damping in the dynamic model of the micro-milling operation can lead to an accurate prediction of the chatter stability [123]. The micro-tool natural frequencies are mostly obtained through a piezo-actuator. The cross FRF is able to predict the FRF at the tool-tip. The combination of the three parameters: cutting forces, damping coefficient, and FRF leads to a reliable

Fig. 13 Stability lobes calculated numerically: with process damping (continuous lines), without process damping (non-continuous lines) [90]



prediction of the chatter stability for the corresponding frequency domain. Xuewei et al. have implemented the process damping to chatter stability considering the nonlinearities, and the stability lobe diagram resulting from the experiment shows a larger stability area for all runout of $1.5 \mu\text{m}$, $2.0 \mu\text{m}$, and $2.5 \mu\text{m}$ with process damping compared to the corresponding runout without damping. The method considering the process nonlinearities, the process damping, and the tool runout effect has shown a better correlation between the cutting force and the surface quality of the workpiece [62]. Researchers have investigated the stability in micro-milling using the speed effect of aerostatic bearing, the stability lobe diagram is shifted to the low-speed range while considering the speed effect. The increase in the air pressure slightly shifts the lobes to the high-speed range, contrary to the increase in the air film thickness which shifts them to the low-speed range [124]. By confronting these results to the investigation of the nonlinearities [66], a common conclusion can be drawn: the stability of the chatter can be improved by the addition of various effects such as here the nonlinearities, runout, and the process damping.

Song et al. have presented a method to simulate the cutting forces and to predict the cutting stability where the first initial parameter is the cutter geometry: diameter of the tool, number of teeth, helix angle of the flank edge, the normal rake angle of the cutting tooth, edge radius, and clearance angle; the second initial parameters are the cutting constants: proportionality constant, specific cutting energy, radial edge coefficient, tangential edge coefficients, radial

plowing coefficient, tangential plowing coefficient, friction coefficient, viscous damping coefficient, and minimum chip thickness, then the cutting conditions: radial depth of cut, axial depth of cut, spindle speed, feed per tooth, and down/up milling. And finally, the dynamics parameters are the masses, damping, and stiffness. The control variables are the axial depth of cut ap and the spindle speed n . The accuracy of the calculation is written as the variation delta of ap , n , t , and the axial position z . The initial parameters as well as the control variables and the accuracy of the calculation are added to the following algorithm as shown in Fig. 14 [76].

The stability in micro-milling processes was investigated by many researchers; in most cases, the stable cut appears in the stable region which is below the lobes and the unstable cut where the chatter occurs is present above the lobes [125, 126]. In the stable cut region, the prediction of the cutting mechanisms is accurate contrary to the unstable region which presents chatter. However, recent studies have shown an uncertain region near the stability boundaries as shown in Fig. 15 [115].

The sound spectrum analysis can be used for chatter monitoring, and the tool natural frequency can be obtained through the dynamic stiffness matrix method; in the study of Mokhtari et al., the tool first natural frequency was found at 6020.152 Hz. The authors have used a SONY dynamic microphone F-VJ22/C model with a frequency bandwidth of 12 kHz. The chatter occurs at the frequency range near 5900 Hz, which is close to the natural frequency of the micro-tool studied analytically, and Fig. 16 shows the results

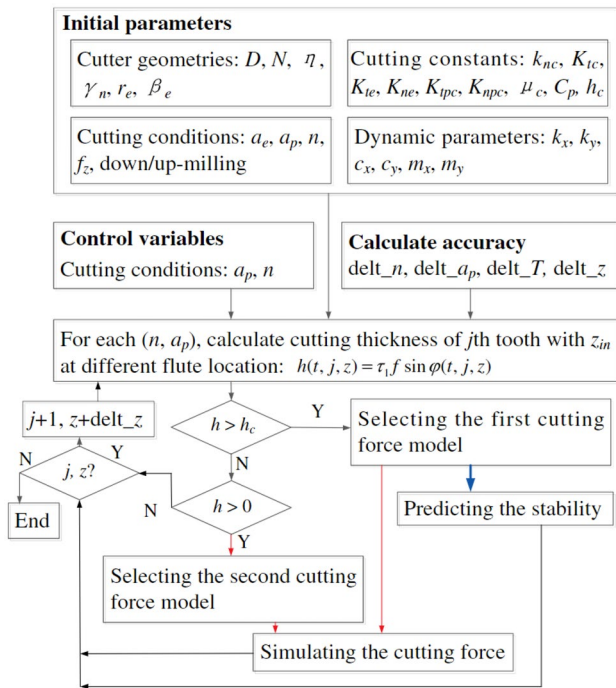


Fig. 14 Flow chart for simulating cutting forces and predicting the stability with blue and red lines representing a stable and unstable cutting operation respectively [76]

of an unstable cut with the fast Fourier transform (FFT) corresponding to the amplitude of the audio according to its frequency from 5000 to 6100 Hz [14].

Authors prediction model was compared with the model presented by Jin and Altintas, resulting in a relative error in a range between 0.069 and 16.45% depending on the corresponding spindle speed from 18.0976 to 36.1952e-2 Ω [123]. The detection of the chatter using common sound and vibration signals in micro-milling is complex and can

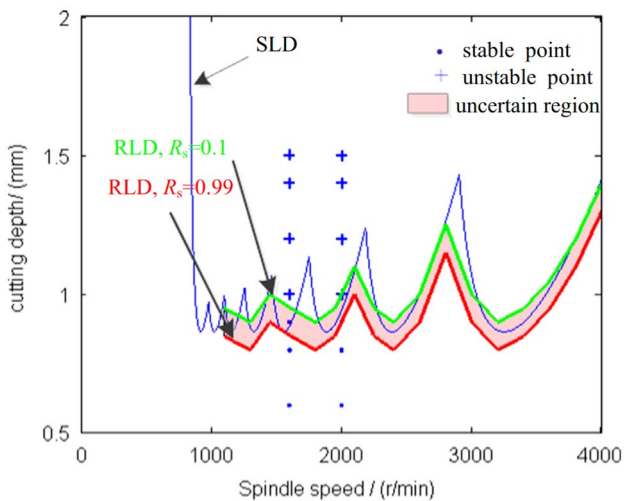


Fig. 15 Stability lobe diagram principle

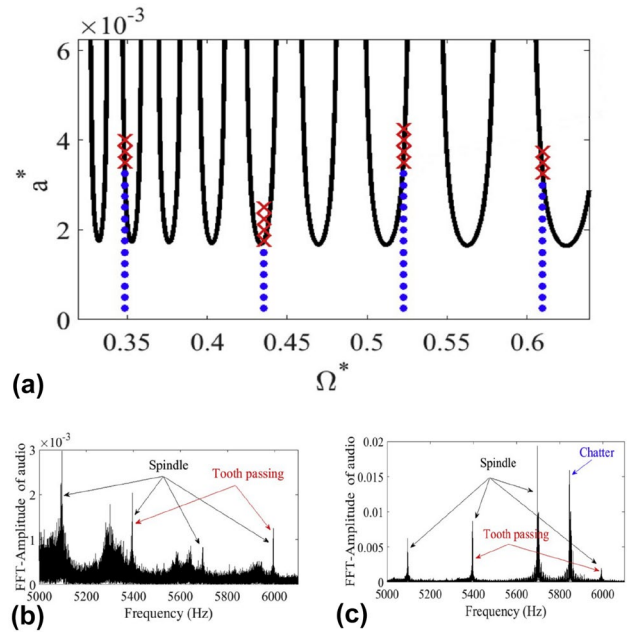


Fig. 16 Stability behavior in micro-milling of 1045 steel: **a** stability lobe diagram of the micro-milling operation using non-dimensional analysis regarding to the spindle speed and the axial depth of cut; **b** FFT representation of the audio at a stable cutting conditions $\Omega^*=0.5226$ and $a^*=3.25e^{-3}$; **c** FFT representation of the audio at an unstable cutting condition $\Omega^*=0.5226$ and $a^*=2.25e^{-3}$ [14]

lead to inconclusive results. Moreover, at high speed, the use of low-cost equipment such as a microphone is less likely to provide accurate information on the chatter limits due to the limited bandwidth. Researchers have compared the standard theoretical approach using the FRFs for the stability limit prediction and the experimental investigation using acoustic emission signal, and they have confirmed the difficulty of the chatter detection using micro-tool and the need for unconventional detection methods [116]. The combination of the acoustic signal and machine learning can be relevant for chatter detection using the root-mean-square value of the amplitude of the signal [27]. Short-time Fourier transform and support vector machine can be used in chatter detection, the comparison with complementary chatter detection methods has shown that image recognition using short-time Fourier transform offers better chatter detection compared to the time domain and continuous wavelet transform image features [127].

4 Chatter reduction methods

Chatter reduction, suppression, or avoidance have been investigated by many researchers, and the chatter is the principal source of quality reduction, so it is necessary to reduce it; the chatter is harmful to surface quality and leads

to non-efficient machining [26]. There are three groups of methods for chatter reduction: passive, semi-active, and active. Passive methods consist of the design of a robust structure regarding the optimization of the dynamic coefficients (mass, stiffness, and damping); the disadvantage of the passive methods is the non-capability of adaptation during the machining operation. In the semi-active methods, the dynamic characteristics can be adapted, and they do not need excessive energy for functioning. The last group is the active methods, which allow full control of the dynamic behavior of the system during the machining process, and it presents better results but also requires more power. This part will discuss the common methods used in the field of micro-milling in order to reduce the unwanted vibrations which can result in poor surface quality, imprecise tolerances, and therefore rising costs of the machined part.

4.1 Vibration-assisted methods

There are plenty of research studies related to chatter and its suppression methods by the use of active or passive methods. Active methods such as vibration-assisted micro-milling are a solution for the chatter reduction [128]. Results using those methods have shown an improvement in the surface quality, lower roughness, and extended tool life [129, 130]. Ultrasonic vibration-assisted turning (UAT) shows the same results [122]. However, inappropriate parameters of vibration frequency and amplitude can worsen machining quality. Vibration-assisted methods of chatter reduction involve forced vibration, such as vibration-assisted machining (VAM), ultrasonic vibration-assisted (UVAM) for high frequencies, and elliptical vibration-assisted machining (EVAM). Jin and Xie have investigated the vibration-assisted micro-milling of glass. Fig. 17 shows the setup of the 2D vibration-assisted stage. With the use of a piezoelectric actuator for a frequency range from 0 Hz up to 18 kHz, results show that the vibration assistance in the normal direction causes the indentation of the tool into

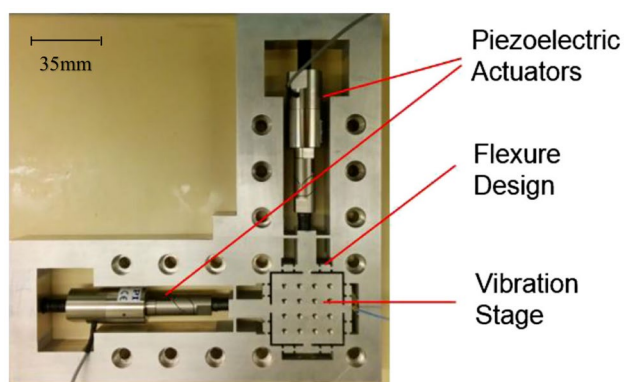


Fig. 17 2D vibration-assisted stage [35]

the workpiece, where the vibration assistance in the feed direction results in the burnishing effect on the surface. The vibration assistance designed was effective for a frequency range from 5 to 11 kHz and show an improvement of the surface quality due to the average surface roughness value decreasing by 45% [35].

Another benefit of using VAM is the reduction of the burrs on the workpiece surface. In the micro-milling process of Ti6Al4V titanium alloy, results have shown a good correlation between simulation and experimental results leading to the reduction of the burr size on the down milling side in the feed direction [128]. The FEM has validated the contribution of vibration assistance. The overall studies have shown good results in the reduction of burrs with vibration-assisted micro-milling. Similar results have been found in the ultrasonic vibration-assisted method [130–132]. In VAM, the specific vibration can be unidirectional (1D) or bidirectional (2D). Where the 1D vibration assistance is commonly applied in the feed direction or in the cross-feed direction and the 2D vibration assistance is composed of both feed and cross-feed directions. Vibration assistance shows improvement in terms of surface quality, surface roughness, tool forces reduction, chatter marks reduction, and tool life [128, 133–135]. UVAM is the term given for the high-frequency vibration range (upper 20 kHz). The most suitable method for reaching such high-frequency is by the use of piezoelectric or magneto-strictive actuators [128]. The principle of both actuators is to use piezoelectric material properties to convert the electrical signal into mechanical displacement output leading to a vibration output according to the wave of the electrical signal on the input. For magneto-strictive actuation methods, the electrical signal must be converted into the intensity of the magnetic field which subsequently using magneto-strictive effect leads to mechanical output. Thus, a magneto-strictive actuator is less profitable due to the signal processing than the more straightforward piezoelectric actuator. Moreover, piezoelectric actuators have shown a high energy efficiency, high-precision, and fast response. In micro-turning, linear VAM shows a better surface roughness compared to an EVAM. However, in terms of cutting forces, the EVAM shows better results due to its low amplitude [136]. EVAM methods present good results in terms of surface roughness improvement. Shi et al. have investigated different models in order to determine the critical depth of cut for micro-cutting of brittle materials in ductile mode [137]. In VAM, loss of contact between the workpiece and the tool can be observed when the vibration assistance is applied due to the superposition of the vibration signals generated by the tool movement on the workpiece surface. The time delay between the tooth passing periods which is needed for the calculation of the dynamic chip thickness is therefore variable due to this unsteady contact between the workpiece and the tool. EVAM can suppress this unsteady contact due

to the material spring back and the sudden transition from ductile to brittle cutting mode.

4.2 Damping and stiffness

The damping coefficient in the dynamic system has an important impact on the chatter generation. Increasing the damping coefficient will lower the amplitude of the regenerative chatter, the chatter suppression can be performed by adjusting the damping, as well as the natural frequency of the machining system [115, 125]. The determination of the damping ratio can be performed by simulation and analytical investigation, the damping ratio ξ can be read at the peak of the dynamic compliance of the natural frequency and the two frequencies equidistant from the peak noted as f_a and f_b according to the frequency response function, and the dynamic compliance can be obtained by finite element analysis method using the FRF [138]. Eq. (22) expresses the relationship between the damping ratio and the calculated frequencies after getting the FRF.

$$\xi = (f_b - f_a)/(2f_n) \quad (22)$$

Many solutions have been found to achieve a high damping coefficient output parameter and consequently reduce the chatter effect. The use of active dampers leads to an improvement in the dynamic response of the system. Piezo actuators are employed in the active control method due to their fast response time, its high stiffness, and wide range of forces. It shows also good results in the dynamic force measurements. Combined with a suitable adaptive control strategy, the regenerative chatter can be suppressed. The active dynamic surface control can be investigated using the fuzzy neural network. Researchers have proven analytically its effectiveness in micro-milling. In addition, it presents a great regenerative chatter suppression capability [139]. The use of dampers increased the damping of the critical element. Passive dampers can be an additional solution, as the tuned mass dampers or eddy currents will lead to different dynamic characteristics of the system. Absorbers are also widely used in machining; it absorbs the energy released during the machining operation in order to reduce the remained energy that eventually can lead to regenerative chatter or unwanted vibration. It consists of an energy absorber, such as piezo-electric material, which will convert the energy generated during the vibration motion of the system into an electric signal that can be recorded for measurement purposes. Tuned mass dampers are used as a passive damping method for vibration suppression, it is physically composed of mechanical energy absorbance components such as springs. Its performance is limited to the accuracy

of its corresponding tuning, as it makes the link between the damper frequency and the structural model frequency. Alexander and Schilder have presented the principle of a nonlinear tuned mass damper composed of four springs reacting on two orthogonal axes in both directions [140].

The dynamic vibration absorber (DVA) is constructed to absorb a specific narrow frequency range, the goal is to determine the natural frequency in which the regenerative chatter will occur, and then center the range of absorption of the DVA on the natural frequency of the system. In micro-milling, the DVA has been used in order to suppress the regenerative chatter, thus improving the surface finish [141]. Researchers have investigated the linear and nonlinear DVAs operation and its results in the enhancement of the systems vibration behavior. The effectiveness of the DVA on the reduction of the vibration amplitude of the system in X and Y directions for a linear and non-linear absorber investigated by Shakeri and Samani has shown that on the x -axis, the amplitude keeps oscillating from $-1 \mu\text{m}$ and $1 \mu\text{m}$ over time, where without DVA the amplitude is increasing over the 4 ms of the recorded signal from an amplitude of $0 \mu\text{m}$ at 0 ms up to $17 \mu\text{m}$ (peak to peak). Therefore, the found corresponding study related to this optimized DVA has shown an estimated reduction of the regenerative chatter of 75% [141].

The stiffness coefficient in the dynamic system has to be maximized in order to reduce the regenerative chatter [142]. Indeed, increasing the stiffness and optimizing the tool path lead to better dynamic stability, thus can prevent machining errors and reducing the oscillation during machining [143]. The dynamic stiffness method (DSM) can be used to predict the regenerative chatter behavior, DSM was used for laminated composite stiffened plate assembly in terms of frequencies in a range from mid to high, resulting in high reliability and accurate method for chatter prediction and analysis [84].

4.3 Optimization of the parameters

The most common method for the reduction of the chatter effect and the improvement of the surface quality is the study of the dynamic parameters optimization [144]. Optimization of the machining process mostly depends on the study of the uncut chip thickness, especially in micro-milling where the plowing regime is more likely to be reached [71]. The optimal parameter can be obtained analytically or numerically by many methods that have been previously described in this review paper in Sect. 2.3.

Similarly, with mathematical optimization methods, experimental-based methods of optimization can be more suitable in some cases, due to the uncertainties in the dynamic prediction model. The study of the spindle speed parameter optimization can be easily obtained with the use of the stability lobe diagram, which represents the stable

and unstable area of the cutting operation in macro and micro-milling. However, in micro-milling, the process of creation of the stability lobe diagram is more challenging due to the difficulties in monitoring the micro-tool natural frequency. The spindle speed, depth of cut, feed rate, and the tooth path are common parameters investigated by most of the researchers in the field of chatter-free optimization and consequently, the surface quality [142, 145]. The chatter can easily be detected using the stability lobe diagram and so be avoided using the optimal spindle speed and depth of cut [125]. A multi-objective optimization using Taguchi methods has been investigated in micro-milling with a ball nose end mill considering the spindle speed, feed rate, and depth of cut as the input parameters, resulting in control of the output parameters such as the force components on the x - and y -axis and the surface roughness [146]. Moreover, the tool inclinations also play a role in the optimization of the machining, and it has been shown that it affects the vibration amplitude and the surface finish [147]. The use of optimized parameters for vibration absorber devices has shown good results in the development of a controlling regenerative chatter in micro-milling [148]. The use of the neural network method can be beneficial for the cutting force and vibration relationship establishment, which can lead to vibration suppression and parameter optimization [21]. In micro-drilling, artificial intelligence has been used for the prediction of the hole quality, and better hole quality prediction can be drawn using a combined model using all the concerned features contrary to considering them individually [149]. Sagris et al. have determined the influence of the cutting parameters and the dynamic characteristics on the vibration of the spindle and the tool in micro-milling, the authors support the use of the transient finite element model for the optimization of the cutting parameters in micro-milling operations [150]. The consequence of the parametric optimization can be seen in the refinement, energy consumption, machining cost, and machining time [151]. The study on lubrication has shown a reduction in frictional rubbing at the contact between the tool and workpiece; the use of KOH solution during the machining process results in a reduction of vibration and chatter contributing to lower surface roughness [152].

5 Application and benefits

5.1 Surface quality

Micro-milling operation leads to a small, detailed surface, with a tool diameter less than 0.5 mm in most of the studies. Therefore, it requires a high machining performance in order to obtain the high-precision components. The study of the dynamics in the field of micro-milling is of great importance, due to the sensible micro-tool that can easily be damaged on hard surface

material such as titanium. For soft materials such as copper, the burr generation is most likely to appear. The optimization of the machining parameters for the improvement of micro-milled surface quality can be conducted via surface generation modeling. Moreover, the surface generation modeling also predicts the surface topography [153]. The consideration of the tool wear in the prediction model of the surface roughness in micro-milling of Inconel 718 has been investigated using the BP neural network involving the Taguchi method for the determination of the relationship between the surface roughness and the tool wear. In fact, results have shown a poor prediction of the roughness due to the BP neural network that was not optimized [104]. Further research on the prediction of surface roughness can be made by increasing the number of neurons. Chen et al. have presented a micro-milling dynamic model based on the variation of the feed rate from 0.001 up to 0.008 mm/flute, the surface quality resulting from the experiments conducted on AL7075 permits to clearly identify the chatter occurrence from a spindle speed range of 8000 up to 70,000 rpm. The conducted micro-channels on the workpiece surface were getting wider and were decreasing the surface quality along with the slot. The researchers have proposed to focus future research on machining factors such as the effect of tool wear, types of material, and operation environment [154]. During micro-machining using MQL lubrication, the adhered chip quantity is reduced compared to the dry condition [155]. Therefore, the use of minimum quantity lubrication MQL cooling method extends the micro-tool life and enhances the surface roughness, as well as the use of smaller micro tool diameter (below 0.15 mm). Appropriate dynamic viscosity of coolant such as Isopart H ($V_p=1.8 \text{ mm}^2/\text{s}$) contributes to the improvement of the surface roughness [156]. The dynamic instability induced by lubrication in micro-milling of Ti6Al4V results shows a reduction in the cutting force going up to 38 % with lubrication compared with dry machining [112]. In addition, the use of lubricant during the micro-milling process has shown great results in the stability, and at 100,000 rpm an enhancement of 20 % has been observed. Further research can be achieved in the comparison of the MQL, air cooling, and cryogenic cooling techniques and their results on the integrity of the surface of the workpiece.

5.2 Tool life extension

As the geometric parameters of the micro-mill have a significant influence on the micro-machining process [157], inappropriate cutting parameters can lead to chatter and considerably reduce the tool life. Therefore, it is crucial to optimize the machining process and extend the tool life. The impact in macro-milling is less imperative due to less restrictive tolerance. Most of the studies in micro-tool dynamics have highlighted the kinematics, runout, deflection, wears, and geometry [158]. In most cases, an accurate prediction model for the tool wear is not achievable without capturing

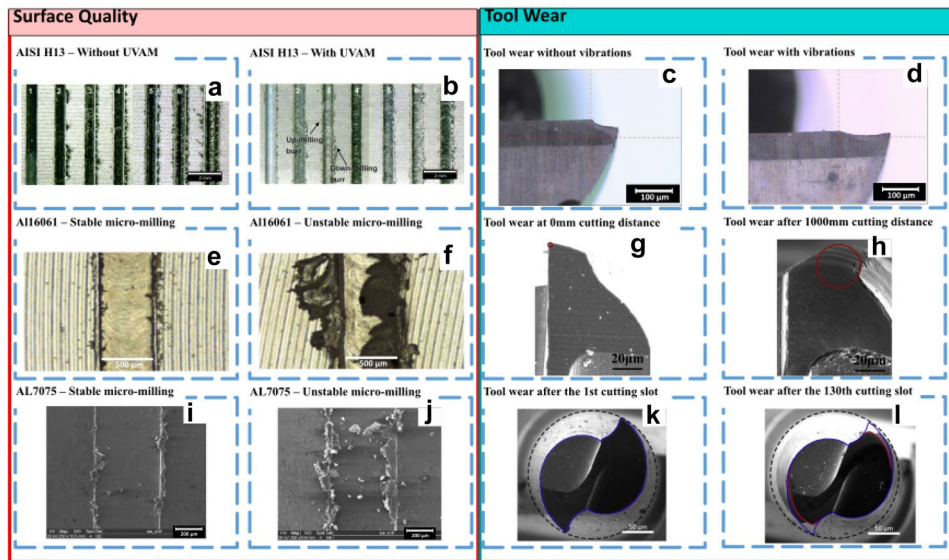


Fig. 18 Summary of the surface quality and tool wear in micro-milling regarding different conditions: **a, b** AISI H13 surface quality after micro-milling slots with and without UVAM respectively [130]; **c, d** photos of the tool wear with and without vibration respectively [160]; **e, f** Al16061 surface burrs images before and after chatter respectively [62]; **g, h** tool

wear shapes comparison at 0 mm and 1000 mm cutting distance respectively [161]; **i, j** SEM pictures of AL7075 workpiece material under stable and unstable cut respectively [95]; **k, l** tool wear progression under the authors respective parameters combination from the 1st to the 130th slot respectively [162]

the mechanics and dynamics of the tool; the kinematics itself is not sufficient for relevant prediction parameters; however, kinematics is useful for quick comparison and in order to obtain a rough idea of the phenomenon [159]. At the micro-scale, dynamic vibration is a challenging problem that affects the cutting tool life. The elastic recovery model has a significant effect on the intensity of the force at a low feed rate due to the main elastic-plastic regime [82]. The study shows the importance to choose the correct elastic recovery model according to the study region, which is correlated to the value of the feed rate. In micro-milling the lubrication as a result of improving the dynamic behavior and stability, it can significantly extend the tool life. Further research can be conducted on the lubrication aspects related to dynamic characteristics in the field of ultra-precision micro-milling operation. The summary of different micro-milling operations regarding the surface quality and the tool wear, the effect of the vibration, and chatter is shown in Fig. 18 where these corresponding effects can clearly be identified. Therefore, the need to avoid the chatter is proved and justified.

6 Conclusion

In this paper, research and knowledge of the dynamics of micro-milling operations have been clearly exposed, including its global definition and mathematical model. The experimental investigation related to dynamics, such

as the vibration occurrences and consequences, has been presented. Chatter reduction technique and the application results on the surface quality and tool life demonstrate the importance and benefits of dynamics studies. The main outcomes of this paper are stated as follows:

1. The dynamics theories in micro-milling have been clarified in Sect. 2. Researchers have greatly improved the cutting force model in the shearing area; when the chip is formed, the cutting force model can be precisely identified and calculated. However, the size effect is likely to appear in micro-milling and is likely to drive the cutting force model in the plowing area; the difficult part in the plowing regime is the determination of the uncut chip thickness considering the tool runout, process damping, and gyroscopic effect that can result in the inaccurate cutting model. We can note that most of the results obtained by the researchers considered the plowing forces as a linear function. The dynamic stiffness method is used for vibration characterization. Euler Bernoulli and the Timoshenko beam theories are often applied for the study of the tool deflection. The tool-tip dynamics can be obtained by the receptance coupling method, which has shown good results in milling and micro-milling operations.
2. The detection of the dynamic phenomenon has been presented in Sect. 3. The choice of MEMS highly impacts signal quality. Vibration monitoring sensors often used by researchers are summarized as well as their corre-

sponding setup in the experimental process. The signal treatment according to the FRF is detailed and its uses in chatter detection and stability.

3. The main chatter can successfully be reduced in micro-milling operation, and the common technique that has been presented here are the vibration-assisted methods, the damping and stiffness improvement of the system, and the optimization of the parameters such as the spindle speed, depth of cut, feed rate, and the tooth path.
4. By looking at all the results obtained by the researchers in the field of dynamics in micro-milling, better surface quality can be observed and an improvement in the tool life. Those benefits are strongly sought by tech field companies. Thus, micro-milling operations have good prospects for the future.

7 Further studies

The development of the neural network-based method has shown good results among the researchers; however, the use in micro-milling is limited, and more research can be conducted in this area as the prediction model involves a combination of multiple parameters. A real-time-based algorithm for a reactive signal treatment is very challenging and is moreover a future strong point to focus on. Chatter prediction and monitoring in micro-milling have shown good results; however, the dynamic model presented by the researchers can be improved in order to lower the differences between the analytical or numerical model and experimental results, and the enhancement of the size effect in the dynamics is one way to achieve a high prediction model. The use of active magnetic bearings in micro-milling is very limited; further studies can be conducted in order to confirm its utility in micro-milling operations. The clamping effect has shown its utility in macro-machining operations; however in micro-milling due to the small force amplitudes, the worthiness has not been clearly expressed and might also be a topic of research. The influence of the process damping on the surface generation can be investigated and work on the development of a novel micro-milling tool-holder for chatter suppression by the enhancement of the modal parameters such as the damping and the stiffness can have a great impact on the surface quality improvement. However, further studies should also be conducted on the lubrication impact on the chatter reduction and dynamic behavior in micro-machining operations.

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Data availability The authors confirm that the data and material supporting the findings of this work are available within the article. The raw data that support the findings of this study are available from the corresponding author, upon a reasonable request.

Code availability Not applicable.

Declarations

Ethics approval The authors declare compliance with ethical standards.

Consent to participate The authors consent to participate.

Consent for publication The authors consent to publish.

Conflict of interest The authors declare no competing interests.

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