2
Literature Review

2.1 INTRODUCTION

End milling is a commonly employed manufacturing process in aerospace, automobile, and die/mold making industries as it can produce complex shapes in a variety of materials with higher accuracy. However, the performance of end milling is restricted due to process disturbances such as geometric/kinematic errors of the machine tool, static and dynamic deflections of cutting tool and workpiece, tool wear and breakage, vibrations, cutter runout, fixturing errors, thermal errors, etc. Figure 2.1 depicts various sources of error during the end milling operation. The geometric error accounts for the inaccuracies in the basic design and assembly of the machine tool components. It causes irregularities in the relative motion among the mating parts. The thermal error is caused by the the increase in the temperature of the machine tool parts due to insufficient lubrication, long running hours, frictional resistance, etc. and results in the expansion of components such as screw, nuts, column, bed, etc. The errors due to the static and dynamic deflections of tool as well as workpiece are the result of cutting forces generated due to the shearing of work material engaged in the cutting action. The other set of errors are due to inappropriate clamping or selection of wrong fixtures.

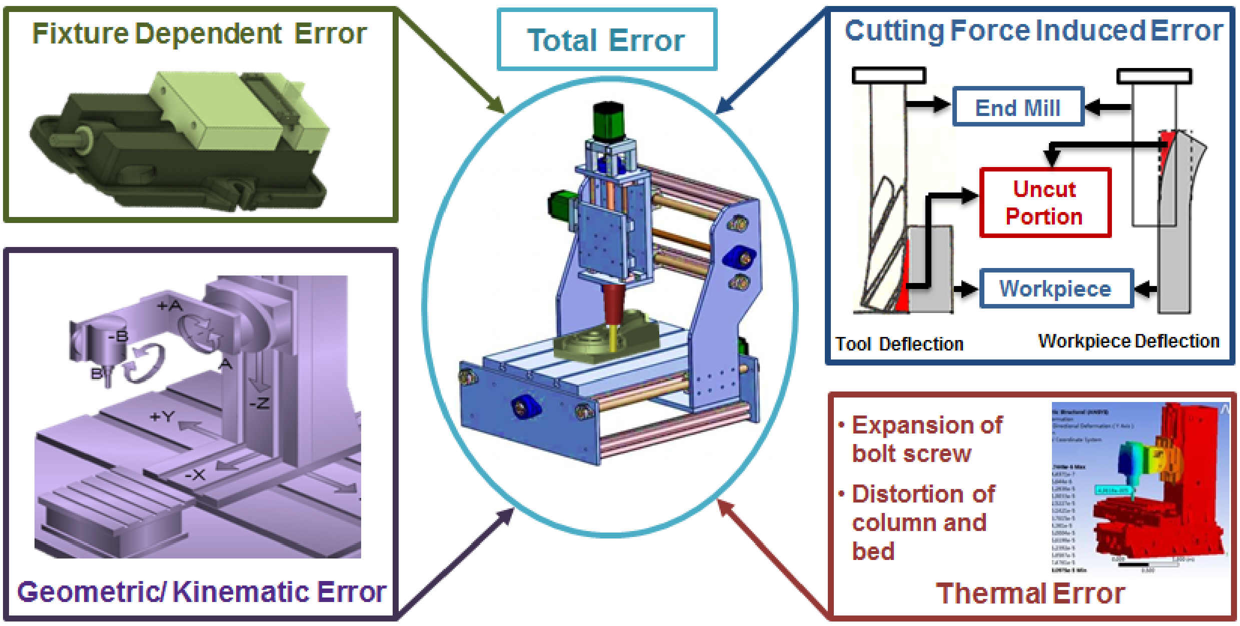

Figure 2.1 : Sources of Error in Milling

The presence of these errors during the operation result in a poor part quality and violation of manufacturing tolerances. The designer specifies dimensional and geometric tolerances on the components to account for these process disturbances collectively. It is highlighted that the cutting force induced process faults contribute majorly to the total error budget of end milling operation [Ramesh et al., 2000]. The cutting force induced errors are resulting due to change of relative position between the cutter path and workpiece thereby and resulting in the changed dimensions of the machined component. As cutting forces are inevitable during milling operation, dimensional errors cannot be eliminated completely and need to be controlled or compensated.

The present thesis aims to develop computational models for the estimation and control of cutting force induced geometric tolerances namely, flatness and cylindricity during end milling of straight and circular thin-walled components. The estimation of geometric tolerances necessitates the development of reliable models predicting distorted coordinates/point cloud representing the machined surface. It includes computational models to estimate cutting forces and associated process faults viz. static deflections of tool and workpiece in the present work. The development of predictive models for end milling of thin-walled components has been an active area of research for several years, and multiple attempts are reported in the literature. The literature survey presented in this chapter reviews past attempts related to the prediction of cutting force, modeling of tool-workpiece deflections and a mechanism to transform point cloud into geometric tolerance parameters. The chapter subsequently summarizes various compensation or control strategies for these process faults and discusses their effectiveness in controlling errors within the limits specified by the designer.

2.2 CUTTING FORCE

Cutting force is one of the major contributors for the majority of process faults during the end milling operation. The manufacturing industries are experiencing major transformations in the recent times due to the evolution of Industry 4.0. The newer set of technological solutions necessitate real-time monitoring of manufacturing processes using sensors followed by data analytics to evaluate the status and adjustment of parameters. It is necessary to have appropriate process knowledge embedded into the decision making system for the appropriate adjustment of process settings. Therefore, reliable predictive models for cutting force are essential while developing physics-based simulations and monitoring systems for different process faults. The development of predictive force models attracted the attention of both machine tool users and builders during the last few years. A predictive force model assists machine tool users in the selection of optimum cutting conditions for improved part quality, making real-time decisions related to process faults and thereby reducing cost and lead time. The cutting force models for end milling operation reported in the literature can be broadly divided into four groups;

- Experimental models
- Mechanics-based analytical models
- Mechanistic models
- Artificial Intelligence (AI) based data-driven models

The subsequent subsections discusses each of the above variant in a greater detail.

2.2.1 Experimental and Mechanics-based Analytical Models

The experimental models correlate cutting parameters (*RDOC*, *ADOC*, Feed rate, etc.), tool geometry, material properties, etc. with forces using empirical relationships. Law et al. [1999] employed regression analysis for correlating cutting conditions with forces. The model was able to estimate cutting forces in the tangential direction. Another model variant for estimating the dynamic component of the cutting force was proposed by deriving closed form expressions as an explicit function of the process and geometry attributes in various milling processes [Wang et al., 1994]. A multi-sensor system was developed for monitoring of end milling process [Chung and Geddam, 2003]. The system was proposed to obtain signals from various sensors that were further analyzed to determine cutting force and torque values under different cutting conditions. These models are not popular due to the requirement of conducting a large number of experiments and inability to predict an intermittent cutting nature of the milling operation.

Mechanics-based analytical models predicts cutting forces based on shear angle determination using minimum energy principle [Merchant, 1945]. The mechanics-based models aim to correlate chip area and cutting force components through parameters such as shear angle, mean friction angle, chip flow angle, cutting velocity, material properties, etc. using oblique cutting theory. Armarego and Deshpande [1989] proposed a simple mechanics-based model for cutting forces considering process issues such as cutter eccentricity and tool deflections. The proposed model estimated both average and instantaneous force values along with torque acting on the cutter. Li et al. [1999] proposed a theoretical model for milling forces based on the predictive machining theory and mechanics of milling operation. The end milling is a complex machining operation that restricts the realistic estimation of process parameters thereby limiting the applicability and reliability of these models in the computational domain.

2.2.2 Mechanistic Force Model

The mechanistic model predicts cutting forces in the discrete increments; angle by angle, flute by flute, and by dividing an end mill into axial segments slice by slice as depicted in Figure 2.2. It is necessary to determine the uncut chip area for each discrete element geometrically and the model correlates it with cutting force components using mechanistic constants. The constants assimilate the effect of material properties of the workpiece, cutting tool material and geometry, etc. into an empirical relationship that can be determined by performing a single or few experiments. Mechanistic force models are commonly employed to predict cutting forces for milling operations in the literature due to the ease of implementation and integration with the process fault modules.

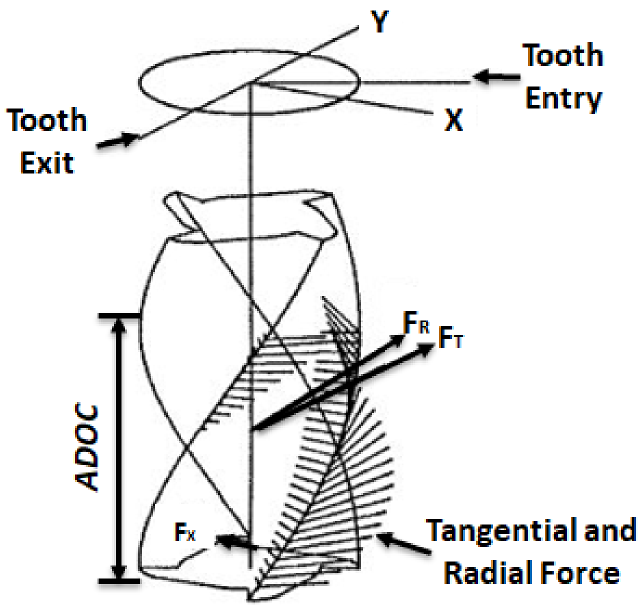

Figure 2.2 : Schematic of Mechanistic Force Model [Kline and DeVor, 1983]

Sabberwal and Koenigsberger [1961] introduced mechanistic models by establishing an empirical relationship between average chip thickness and cutting force components. The computational accuracy of the developed model was not good owing to the significant difference between the actual and average value of the chip thickness at peak and valley positions. Kline et al. [1982a] improved the model subsequently to predict the instantaneous variation of cutting forces with the angular rotation of a cutter. The cutter was discretized into numerous disks elements and angular divisions in the axial and radial directions respectively. Kline and DeVor [1983] studied the effect of cutter axis runout on the cutting geometry and incorporated the phenomenon in the model for better prediction accuracy. An accurate estimation of the chip thickness is an important parameter influencing prediction accuracy of the model. In this context, Sutherland and DeVor [1986] extended the mechanistic model for the prediction of cutting forces in a flexible end milling system. The developed model considers the effect of tool and workpiece deflections on the chip thickness and thereby cutting forces. The developed model showed better prediction ability than the previously developed rigid force model. Smith and Tlusty [1991] categorised force models considering different aspects of the cutting operation such as averaging of the chip thickness, static and dynamic deflections of tool and workpiece, etc. The study also indicated the major shortcomings and probable applications of these models. Yucesan et al. [1993] examined the effect of process parameters such as feed rate, cutting speed and tool rotation angle on the prediction accuracy of a model and concluded that the application of average cutting coefficients might lead to inaccurate prediction of forces. The studies approximated an instantaneous chip thickness into a single average value while estimation of cutting coefficients as it is not possible to measure forces acting on each disc element experimentally [Wan et al., 2007a].

Zhang et al. [2002] extended the application of mechanistic force model to predict cutting forces in the end milling of curved profiles with constant curvature by introducing workpiece radius in the mathematical formulations determining process geometry parameters i.e. uncut chip thickness and engagement angle. The developed model was further applied to predict cutting forces during milling of circular corner profiles having variable *RDOC* along the tool-path. It was accomplished by approximating the profile in numerous circular geometries having constant *RDOC* [Zhang and Zheng, 2004]. The model was further extended to estimate cutting forces during milling of the variable curvature surfaces by realizing the revised formulations for feed rate, engagement angles and uncut chip thickness [Rao and Rao, 2005]. It was demonstrated that process geometry attributes change continuously along the tool-path with considerable dependence on the convex and concave curvature of the workpiece. Wan and Zhang [2006a] proposed an iterative algorithm to estimate the variation of *RDOC* due to deflections of low rigidity thin-walled components. The variation of the *RDOC* was used to calculate revised chip thickness and cutting force. Desai et al. [2009] introduced the effects of cutter run-out by revising mathematical formulations of process geometry parameters during milling of curved geometries. The study showed that the nature of workpiece geometry has considerable influence on interactions among trajectories of cutting teeth. Liu et al. [2012] extended the model for estimating cutting forces during helical milling applied to hole making operation and analyzed the effect of side and end cutting edges. Hao et al. [2015] introduced an iterative procedure to estimate the linear and angular position of the cutting tool and coordinate transformations for the assessment of chip thickness during milling of curved geometries in the presence of cutter run-out.

The above literature discusses augmentation of various attributes in the mechanistic force models such as, process geometry, workpiece geometry, workpiece curvature, process parameters, cutter run-out, etc. The mechanistic force model associates cutting force components with the uncut chip area using empirical constants. The determination of empirical constants is an essential task while developing the force model as it has a substantial effect on the prediction accuracy. It is required to conduct a set of experiments to establish an analytical relationships that assimilates the effect of tool and workpiece material properties, cutter geometry, etc. using non-linear curve fitting. The prediction accuracy of the mechanistic model largely depends on the goodness of the relationship. Melkote and Endres [1998] highlighted the importance of "*size effect*" at lower *ADOC* values and showed that the cutting constants are drastically different under these conditions.The estimation of instantaneous cutting force components using an approximate empirical relationship yields lower accuracy at specific cutting conditions. It was demonstrated that the model with an average chip thickness relationship could not predict forces accurately at crest and trough positions due to the considerable difference between actual and average chip thickness. Yun and Cho [2000] replaced average chip thickness with instantaneous uncut chip thickness in the model by introducing instantaneous constants determined from the measured force data. The estimated cutting constant relationships were independent of cutting conditions such as feed rate, *RDOC*, *ADOC* and dependent on the combination of tool and workpiece material only. It was shown that the introduction of instantaneous cutting constants improved the prediction accuracy of the cutting force model significantly. Ko et al. [2002] reported that the lower prediction accuracy at small cutting widths is attributed to the marked influence of the bottom cutting edge and proposed to estimate cutting forces due to flank cutting edge independently. This was accomplished by subtracting cutting forces at a smaller *ADOC* from those at a larger *ADOC*. The newer approach effectively captured the dominance of "*size effect*" at lower chip thickness values using Boltzman function. The subsequent study by Wan et al. [2007b] proposed correlation of the cutting constants with average chip thickness using an exponential function to incorporate "*size effect*" at lower uncut chip thickness values. The cutting constants are linked with the uncut chip thickness using empirical relationships, and a summary of relevant models is presented in the literature [Wan et al., 2008a]. Dang et al. [2010] highlighted the importance of incorporating the bottom edge and proposed a methodology to consider separate cutting force components for the flank and bottom edges of the cutter. The study shows that it is essential to include the bottom edge in a model as it is always engaged in the cut and contributes significantly to the total cutting force. Thereafter, Wan et al. [2012] considered the rubbing effect of flank edge and developed a ternary model which includes forces due to flank and bottom cutting edges, and rubbing of the flank cutting edge. In subsequent studies, Kao et al. [2015] presented the importance of stable cutting conditions and cutter helix angle while estimating instantaneous cutting constants. The application of the least square method was also proposed to calibrate instantaneous cutting constants and runout parameters [Zhang et al., 2016]. A genetic algorithm-based model using Particle Swarm Optimization (PSO) is also devised to calibrate cutting constant and cutter run-out parameters simultaneously [Zhang et al., 2017]. A generalized approach estimating cutter runout parameters and cutting constants for the bottom and flank edges were presented during the flat-end milling operation [Zhang et al., 2018]. The significance of the bottom edge was examined during subsequent studies for a 5-axis milling operation [Li and Zhu, 2016] and micro-milling [Zhang et al., 2019].

2.2.3 Artificial Intelligence based Data-driven Models

Artificial Intelligence (AI) based approaches were also applied to estimate cutting forces during various machining operations [Al-Zubaidi et al., 2011]. The AI-based approaches include fuzzy logic [Tandon et al., 2002], Genetic Algorithm [Cus and Balic, 2003], Artificial Neural Networks (ANN) [Suneel et al., 2002], etc. Among these, ANN-based approaches are well-researched due to the ease of learning implicit relationships between a set of input and output parameters from the dataset. Additionally, ANN can capture non-linear relationships effectively, which is essential for predicting cutting forces for the milling operation. Tandon and El-Mounayri [2001] explored the utility of a feed-forward neural network along with the backpropagation algorithm to predict cutting forces during the orthogonal turning operation. Tandon et al. [2002] extended the same algorithm for the prediction of cutting forces during the milling operation. An alternate variant of the similar algorithm employing the Levenberg–Marquardt algorithm was developed by Chien and Chou [2001]. The ANN model needs large training datasets during the development stage to learn the milling process mechanics. It was highlighted that the integration of the design of experiments based approach with ANN could reduce the number of tests significantly with the improved prediction abilities [Briceno et al., 2002], [Dave and Raval, 2010]. The accuracy and reliability of datasets used during the learning stage are critical in deciding the robustness of the ANN model. Radhakrishnan and Nandan [2005] developed a regression model to eliminate abnormal datasets from the experimental results and suggested to use filtered data in the training of the ANN model. It has been reported that the application of a regression-based approach can improve prediction accuracy of the ANN model significantly. Zuperl and Cus [2004] developed a multi-level perceptron based ANN models for the prediction of cutting forces during the ball-end milling operation. The study compared the prediction capabilities of different ANN architectures in the context of processing speed, memory usage, robustness, etc. Wang et al. [2019] used the ANN model to estimate instantaneous cutting constants of the mechanistic force model during machining of Carbon fiber-reinforced polymer eliminating the need to incorporate complex process mechanics through the mathematical equations. Vaishnav et al. [2020] proposed a hybrid model that generates the dataset required for training of the ANN model through the mechanistic force model instead of conducting numerous experiments. The prediction accuracy of the ANN model was improved due to the absence of outliers in the training datasets.

Based on the review of literature, it was realized that the complexity of experimental model increases with the number of variables in the system and numerous tests are required to condition the model. The experimental models provide qualitative information about cutting forces and intermittent variation of cutting forces is not captured. The mechanics-based model considers tool/workpiece geometries, material properties, cutting conditions and types of milling as an input to estimate cutting forces. The model suffers with an issue of higher computational intricacy due to involvement of several input parameters. Mechanistic model correlate cutting force components with chip area using cutting force constants. The model combines effect of material properties of cutting tool and workpiece into these cutting constants without depending on the chip removal behaviour of the cutting edge. The model evolved over several years to incorporate the effect of other important process characteristics such as *size effect*, cutting edges, cutter runout, tool-workpiece deflection, etc. It has been assimilated that mechanistic model can predict cutting forces with reasonable accuracy over a wide range of cutting conditions and requires fewer experiments for conditioning.

The ANN-based models have good potential to generalize over an extensive range of work materials and geometries, cutting tool materials, cutting conditions, computational efficiency, etc. However, it requires a large number of datasets for the development of a model. The accuracy of the ANN model is mainly dependent on the quality of datasets applied for the training. The majority of previous research work presented in the literature generates training datasets by conducting machining experiments over the entire range of input parameters and measuring cutting force. These experiments are costly and consume a considerable amount of time in the model development. Also, the accuracy of model is dependent on the quality of datasets used in the process of learning or training. The datasets generated using machining experiments contain a considerable amount of outliers due to process disturbances such as vibrations, tool-workpiece deflections, cutting temperature, etc. affecting the overall prediction accuracy of ANN model. The requirement of large datasets and noise in the experimental results lower the direct applicability of ANN models in the milling operation. However, the blending of ANN models with a physics-based model can overcome limitations of data driven models and thereby the developed hybrid model may lead to a better realization of the scientific knowledge.

2.3 STATIC DEFLECTION MODELS FOR CUTTING TOOL AND THIN-WALLED COMPONENTS

The end milling of thin-walled components involves considerably flexible cutting tool and workpiece which are prone to significant deflections under the action of periodically varying cutting forces. It results into the deviation of both elements from their assumed positions leaving uncut material on the machined surface. Additionally, the rigidity of thin-walled component reduces considerably with the progress of machining that results in increased static deflections of the component. Such issues associated with the material removal mechanism translate in the form of dimensional errors and violation of geometric tolerance specifications envisaged by the designer. The designer introduces a combination of straight and curved sections in many components to meet functional as well as aesthetic requirements. The variation of workpiece geometry has considerable influence on the nature and magnitude of the deflections. The curved sections exhibit significantly different structural characteristics compared to planar or straight sections of the components. For example, curved components can be machined from a concave or convex side, referred to as synclastic and anticlastic machining, respectively [Bera et al., 2010]. The models to estimate static deflections of cutting tool and thin-walled components have been an active area of research for some time and multiple attempts can be found from the literature. The section discusses various research efforts to estimate static deflection of cutting tool and thin-walled components.

The static deflections of cutting tool are quite common and more prominent when the slenderness ratio of the cutting tool is considerably higher. Whereas, the deflections of the workpiece are dominant while machining low rigidity structures such as thin-walled components. Kline et al. [1982b] developed a computer-based program to compute the deviation of cutter-workpiece immersion boundaries for thin-walled components. The static deflections of tool and workpiece were computed by employing cantilever beam formulation and FE-based methodology respectively. The concentrated cutting force was applied at the "*force centre*" with the point application decided by considering the weighted average of force values along the *ADOC*. Iwabe and Fujii [1988] modeled the relative displacement of a cutting tool and workpiece to predict instantaneous deflections. The springs were attached to the cutter and plates during the experimentation. The study considered the end mill as a cylindrical body while estimating deflections computationally through the cantilever beam methodology and experimentally with strain gauges. However, the shape of end mill is quite complex due to the presence of helical flutes and such approximation leads to inaccurate estimation of tool deflections. Kops and Vo [1990] introduced the concept of an "*Equivalent Diameter*" of the end mill. It provides the actual value of the moment of inertia and thereby improves prediction accuracy of the tool deflection model.

Budak and Altintas [1995] estimated workpiece deflections using FE-based methodology, followed by a systematic procedure to predict error at surface generation points. The thin-walled plate was modeled with 3-dimensional eight node iso-parametric elements. The tool generates curvature at the transient area with the workpiece which was approximated using a straight line as shown in Figure 2.3a. The cutting force acting on each axial disc element was computed and distributed at all the four nodes associated with each disc. Tsai and Liao [1999] extended the FE model by employing 12-node iso-parametric elements for discretization of the workpiece. The newer element has a mid-node at the center of four of the six edges, which are oriented in the direction of feed as shown in Figure 2.3b. The forces computed at each axial disc element are applied at the center node along line B-B. The immersion area has been meshed systematically to approximate actual cutter-workpiece interactions. The subsequent study presented a sophisticated FE model that inputs cutting forces directly from the mechanistic model to estimate tool deflections during steady [Yun et al., 2002a] and transient cutting situations e.g., machining corners of a rectangular pocket [Yun et al., 2002b]. The study correlated the profile of cutting force with resultant error and concluded that normal component of the force is a major contributor to the dimensional error. Ning et al. [2003] developed FE model to predict the deflections of thin-walled box shaped components. The effect of rigidity diminution of a workpiece with the progress of machining was neglected in the study which underestimated the dimensional error on finished components.

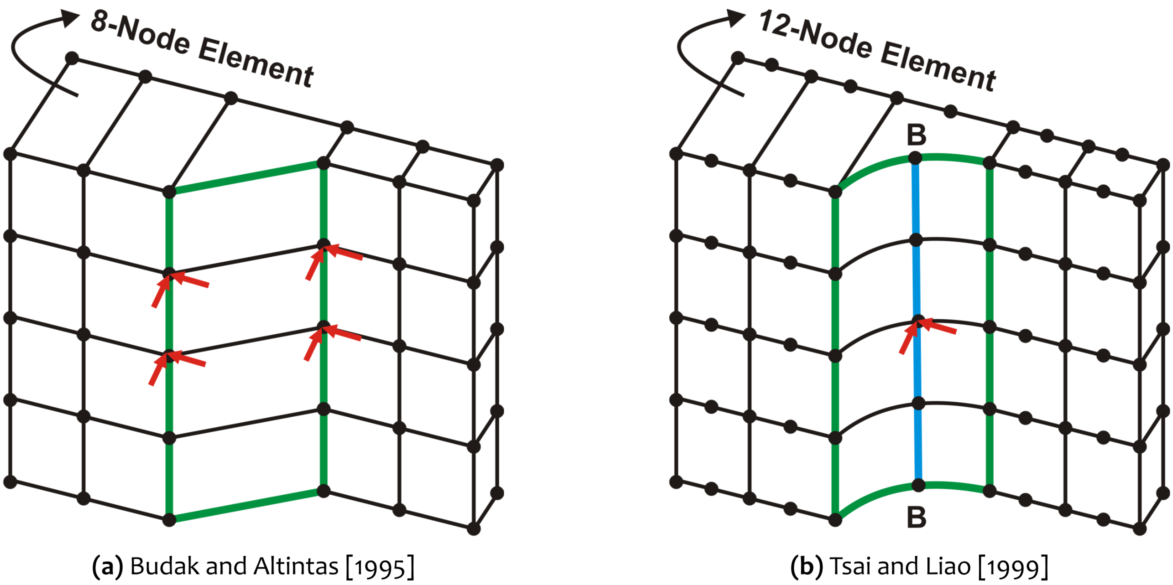

Figure 2.3 : Various FE Models of the Thin-walled Component

Ryu et al. [2003] proposed an alternate approach for the estimation of tool deflections in side-wall machining by combining cutting edge locus and time simulations. The model had a faster error prediction capability than other methods presented in the literature. Ratchev et al. [2002] developed a flexible force model for the prediction of cutting forces which were input to the FE model for estimating static deflections of the workpiece. The static deflections were also measured online using sensors and off-line subsequently using CMM. It was proposed that the application of mechanics-based theories is not feasible for estimating deflections of thin-walled components and use of FE model can be an effective solution [Ratchev et al., 2004b]. The methodology to estimate workpiece deflection induced dimensional error evolved further by developing a systematic approach that enables the direct transfer of cutting forces from the mechanistic model to FE model [Wan et al., 2005]. Subsequently, the FE-based tool and workpiece deflection model was combined for the estimation of static form errors in end milling [Wan and Zhang, 2006b]. The model includes tool and workpiece deflections during computation of revised immersion boundaries and includes variable workpiece rigidity during the machining. The model also incorporates change of the workpiece rigidity with the progress of machining while estimating dimensional error [Wan and Zhang, 2006a]. The study accomplished an iterative procedure by establishing the convergence criteria for *RDOC* and uncut chip thickness.

Guo et al. [2006] developed FE-based approach to predict deflection induced surface errors by including effects of pre-stressed workpiece condition, clamping forces and reduced rigidity of the thin-walled component during machining. Dépincé and Hascoet [2006] predicted dimensional errors considering tool deflections by employing the contact point technique instead of the contact curve. The contact location refers to an interaction point between the tool and a plane comprising the tool-axis. The error along the milled surface is defined as the trace of this contact point. Schmitz et al. [2007] analyzed the effect of cutter run-out and stability on the surface error during milling of curved geometries. Bera et al. [2010] estimated tool-workpiece deflections to analyze the variation of dimensional error during milling of thin-walled tubular geometries. The study also analyzed the effect of chip load on surface error during machining curved surface through the convex and concave side. It was observed that the deflections of tubular geometries are significantly lesser due to increased stiffness of the component and the contribution of the tool deflection is dominant. Desai and Rao [2012] presented the classification scheme to correlate the axial variation of tool deflection induced error profile with cutting widths. The study also proposed mathematical formulations for calculating the axial location of *"kink"* in the error profile. The classification scheme was further extended to link axial surface error profiles with cutting widths during end milling of thin-walled components using a FE-based methodology [Arora et al., 2019]. In recent studies, it is also shown that the axial position of *"kink"* is not identical along length of the component and it changes with the workpiece curvature during machining of curved geometries [Agarwal and Desai, 2020].

Kang and Wang [2013] developed two different iterative algorithms, a Flexible Iterative Algorithm (FIAL) for the prediction of surface errors in milling of low rigidity thin-walled components and a Double Iterative Algorithm (DIAL) to evaluate the position and magnitude of the maximum dimensional error. The developed algorithms were compared with the previous algorithms and it was realized that the errors predicted using the developed algorithm confirm with the experimental data, and less time is required for evaluation [Kang et al., 2014]. In subsequent studies by Dong et al. [2016], the FE-based methodology was proposed to analyze the combined effect of clamping and milling forces on the dimensional errors. The outcomes of the proposed methodology was validated for ten different fixturing layouts. The FE-based methodology was also extended to explore the effect of component thickness [Wang et al., 2015], cutting temperature [Bolar and Joshi, 2017], tool inclination angle [Liu et al., 2020a], and other process parameters on workpiece deflections during milling of thin-walled components. Li et al. [2018] presented a methodology to predict dimensional errors during 5-axis milling of thin-walled components. Wimmer et al. [2019] examined the influence of cutter diameter, number of flutes, and helix angle on the surface error profile during milling of thin-walled components. Recently, Yue et al. [2019] coupled cutting forces with the elastic deformation of the thin-walled parts to predict surface error by employing the theory of bending and torsion. It was concluded that the deflection of the workpiece varies the location of cutting point and thereby variable chip thickness. Wu et al. [2020] presented a methodology for enhanced prediction ability of the workpiece deflection model by including the effect of heat generated and flank wear during milling of poor machinability materials such as Titanium alloys.

The previous literature presents various approaches related to modeling of tool and workpiece deflections during end milling operation. The majority of research attempts involved the application of FE-based algorithms to estimate workpiece deflections. The models differ from one another based on the element type, methods of meshing, nature of cutting force application etc. On the contrary, tool deflection is modeled assuming the end mill as a cantilever beam by employing physics-based formulation or FE-based methodology. Further, the studies also estimated the dimensional error using deflections data for different geometries such as straight, circular and free form surfaces. The models estimating tool and workpiece deflection induced dimensional errors evolved over the years with the development of systematic approaches to enhance the prediction accuracy. Some of the important features include the direct transfer of cutting forces to deflection models, incorporating variation in the workpiece rigidity and curvature, fixture layouts, etc.

2.4 MODELING OF GEOMETRIC TOLERANCES

The manufacturer is required to perform stringent inspection of machined components to check the conformance with tolerance specifications laid by the designer. The inspection process reports deviations of manufactured component with reference to a standard or ideal feature. For example, evaluation of straightness/flatness is carried out with reference to a planar surface or circularity/cylindricity evaluation is to be performed with reference to a circular feature/cylindrical surface. The flatness of a planar component is defined as the normal distance between two parallel planes enclosing actual or manufactured coordinates representing the flat surface. Meanwhile, the cylindricity is defined as the difference in radii of two co-axial bounding cylinders enclosing point-cloud data representing the actual or manufactured surface. The designers specify geometric tolerances as per *GD&T* principles [ASME Y14.5-2009, 2009], [ISO 1101:2017, 2017] using size, form and orientation. The size corresponds to the dimension of a feature while form represents geometric tolerances and orientation is denoted as an inclination of the feature. In the past studies, researchers developed several techniques for the evaluation of geometric tolerances. The main aim of these methods is to define two surfaces such that all measured points are enclosed within these surfaces and the distance between surfaces should be minimum. In the case of straightness and flatness tolerance, the defined surfaces are two parallel lines and planes respectively. Whereas, in the case of circularity and cylindricity tolerance, the surfaces are two concentric circles and co-axial cylinders with different radii. The estimation of geometric tolerances has been well-researched with the majority of attempts focusing on the development of efficient and reliable algorithms. This section highlights methods developed by various researchers in the past for the evaluation of geometric tolerances. The research attempts have been categorized into two groups, Geometric techniques and Numerical techniques.

2.4.1 Geometric Techniques

The objective of geometric techniques is to determine two parallel bounding features enclosing the point-cloud representing an actual feature with the minimum normal distance between considered features. The algorithms employing geometric technique initiate with a random solution, which is iteratively improved until optimal or near optimal solution is attained. Shunmugam [1986] introduced the concept of deriving a median plane as a reference from the point-cloud data to estimate crest and valley points. It was observed that the value of geometric tolerance determined using the median technique had been relatively lower compared to the conventional Least Square Technique. Lai [1988] presented another approach that gives the minimum solution for 2-D straightness problems based on the minimum zone criterion. The convex hull technique was applied to evaluate the minimum zone of the convex hull that encloses all the measured data points. The same approach was further extended to evaluate the minimum zone for flatness by Traband et al. [1989]. The subsequent studies proposed, a computational geometry-based technique to generate a pair of concentric cylinders for checking the cylindricity tolerance of a feature [Roy and Zhang, 1992]. The method divided, the cylindrical surface into several cross-sections normal to the *CMM's* local *Z*-axis. A 2-D convex hull and Voronoi diagrams were used to compute a pair of concentric circles. The circles are used to find a pair of concentric cylinders that formulates the minimum zone required for form tolerance analysis. The approach assumes that the orientation of the cylindrical features is around the *Z*-axis of measurement. Roy and Xu [1995] improved the model subsequently to determine the inclination of the center axis for the verification of orientation tolerances. Samuel and Shunmugam [1999] proposed an algorithm using Divide-Conquer and Merger technique originally developed by Preparata and Hong [1977] to construct 2-D and 3-D convex hulls for the evaluation of straightness and flatness. The algorithm was validated using representative cases involving uniform and non-uniform point-cloud data. The algorithm was extended to evaluate circularity [Samuel and Shunmugam, 2000]. In subsequent studies, an alternate computational geometric technique was developed to enclose the point-cloud using limacon cylinders and estimated the minimum separation distance for circularity [Venkaiah and Shunmugam, 2007a] and cylindricity [Venkaiah and Shunmugam, 2007b] tolerance evaluation. Limacon is an arc derived by moving a point outside a circle about a point on the circle itself. The Limacon obtained was extruded along a straight line to get Limacon cylinders for the evaluation of cylindricity.

2.4.2 Numerical Techniques

Numerical techniques compute deviations of given set of data points from an ideal geometry and seeks to minimize the same. The primary objective of numerical techniques is to develop an objective function that can be improved using generalized optimization methods. The approach is computationally efficient but leads to inferior results sometimes due to mathematical approximations. This section summarizes the research attempts to evaluate geometric tolerance using numerical techniques. The technique considers actual point-cloud data in the form of deviations from an ideal geometry and solicits to minimize the value of an objective function that defines the zone with the minimum deviation between reference features.

Murthy and Abdin [1980] summarized different numerical techniques such as least-square fitting, Monte-Carlo approach, Simplex search, Spiral search etc. in the determination of geometric tolerances. Among these techniques, least-square fitting is commonly employed to evaluate geometric tolerances due to lesser computational complexity. However, simplex search can be applied to the discontinuous nature of functional relationships for handling the n-dimensional problem by applying simple arithmetic computations. Monte Carlo technique is best suited to optimization problems with fewer variables. The spiral search technique can be applied when the number of variables is two or three and gives a better value since it searches for all possible solutions. It was observed that the least square fitting technique accords a unique solution for geometric tolerances but it does not confirm the minimum zone deviation and leads to an over-estimation of tolerances. Fukuda and Shimokohbe [1984] suggested an alternative approach for evaluating the minimum value using minimax approximation. The minimax approximation technique is reported to take more time than the least-squares method for straight/flatness, but less time for circularity/cylindricity. Shunmugam [1987] compared linear and normal deviation of form errors for the engineering surface using the least-square technique. The comparison showed that the difference between values obtained from linear and normal deviation is insignificant for the practical use. It was also found that the normal deviation approach requires larger computation time, which is not justifiable in view of the marginal difference in the values obtained. Dhanish and Shunmugam [1991] proposed an algorithm based on the Chebyshev approximation to estimate the minimum normal distance between two parallel or similar features. The subsequent studies proposed, an algorithm to simplify the non-linear nature of the problem by formulating a series of linear problems for simplified evaluation of flatness [Carr and Ferreira, 1995a] and cylindricity [Carr and Ferreira, 1995b]. The proposed algorithm converges effectively to the minimum zone solution without any loss of generality.

Suen and Chang [1997] proposed ANN-based algorithms for evaluation of straightness and flatness. Namboothiri and Shunmugam [1998a] presented a new approach for evaluation of form error using L1 – approximation. This approach was considered more effective when the data points contain considerable outlier information. A numerically stable Singular Value Decomposition (SVD) technique is used for the solution in case of degeneracy. One of the advantages of using L1 – approximation is the ability to identify and compensate errors in the solution approach due to outlier points [Namboothiri and Shunmugam, 1998b]. The generalized non-linear optimization procedure for circularity evaluation based on a minimum radial separation criterion was proposed by Wang et al. [1999]. It was shown that the developed methodology gives accurate results with less computation time. A unified linear approximation technique for evaluating the form errors was proposed by Weber et al. [2002] in the subsequent study. The non-linear equation for individual geometric form was linearized by implementing Taylor's expansion and the solutions was obtained using linear programming. The numerical techniques are considered ubiquitous methods to solve optimization problems and they are computationally efficient. However, it may result in inaccurate results due to mathematical approximations in a few cases.

Liu et al. [2001] developed a hybrid approach comprising a genetic algorithm and geometric characterization to evaluate straightness and flatness tolerances. Kovvur et al. [2008] and Cui et al. [2013] used the Genetic Algorithm-based methodology in the form of PSO to evaluate geometric tolerances. The PSO is an evolutionary method proposed by Eberhart and Kennedy [1995]. An unconstrained non-linear objective function of the form tolerances is used for the optimization without any conversion to the linear formulation. Wen et al. [2010] highlighted that the PSO algorithm could estimate geometric tolerances efficiently, offering the ease of computational implementation compared to other techniques presented in the literature. Pathak et al. [2017] presented a modified version of PSO to overcome inefficiencies, such as computation time and number of iterations required to obtain the optimum solution. It is concluded that the computation time depends on the efficient selection of parameters involved in the algorithm, such as number of particles in the swarm and the initial positions of particles in the space. Chiabert et al. [2017] proposed a probabilistic approach and compared its effectiveness with the Least Square Method in error estimation and uncertainty evaluation. Zheng et al. [2019] developed an algorithm based on kinematic geometry optimization to compute the minimum zone cylindricity error with enhanced computational efficiency.

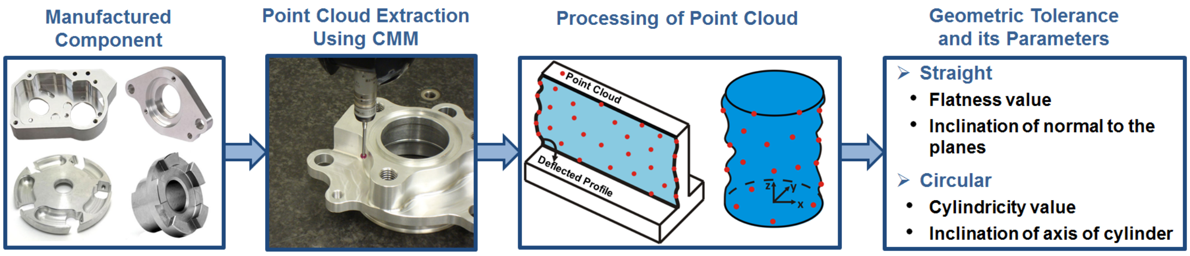

Figure 2.4 : Geometric tolerance estimation without process faults.

The majority of research attempt presented in the literature aims at the development of computational approaches that estimate the geometric tolerance parameters accurately and efficiently. Figure 2.4 shows an overall summary of the framework employed for estimation of geometric tolerance related parameters in the literature. The point-cloud data essential for the estimation of geometric tolerances is captured from the *CMM* without any linkages with the process faults. Recently, some studies have been done to examine the effect of machining attributes on geometric tolerances. Obeidat and Raman [2011] estimated workpiece deflections during the end milling of flat plates to determine the location of the maximum error, thereby optimizing the number of inspection points required to determine the flatness. Sheth and George [2016a] used statistical techniques to evaluate the significance of process parameters on surface roughness and flatness during the face milling operation. Mikó and Rácz [2018] studied the effect of surface roughness on flatness and angularity during the ball-end milling operation. The linkage of process parameters such as cutting speed and depth of cut with cylindricity is also studied during the drilling operation [Sheth and George, 2016b].

2.5 REDUCTION OF TOOL-WORKPIECE DEFLECTION INDUCED ERRORS

The cutting forces are inevitable during the end milling operation and the faults associated with it cannot be eliminated completely. The problems associated with static deflections of cutting tool and workpiece are quite severe while machining of thin-walled component with cutter having larger overhang. Such situations involving end milling of thin-walled components having low rigidity with large cutter overhang are inevitable due to functional requirements of the product. The static deflections of cutting tool and workpiece result into violation of dimensional and geometric tolerances specified by the designer. It is imperative for the manufacturer to not only estimate these tolerances but also control the same by devising appropriate strategies. The ideal control strategy will offer the ease of implementation on the shop floor without compromising machining productivity. A variety of approaches are suggested in the literature to aid process planner in achieving these objectives. The strategies can be broadly divided into two groups; Compensation of deflections and Control of deflections. The subsequent subsections discuss both these strategies considering major strengths and limitations.

2.5.1 Deflection Compensation strategies

The error compensation strategies aim at limiting the machining tolerances within specific limits without compromising the productivity. The compensation approaches follows a two-step process,

- Step 1: Estimating static deflections using computational models or online/offline measurement system
- Step 2: Developing an online or offline strategy to compensate error estimated in Step 1.

One of the commonly employed strategy during machining of thin-walled components is the tool-path modification approach. The fundamental idea of this approach is to modify the programmed position of the cutting tool such that the error is controlled within specified tolerances. Lo and Hsiao [1998] devised tool-path modification strategy for components to be produced in a large quantity or mass production. The profile of deflection induced error was obtained by performing inspection of the machined component using *CMM*. The modified tool-path was generated by mirroring of coordinates obtained from the inspection of machined components. The subsequent parts were machined by inserting new coordinates to the Numerical Control (NC) program and significant improvement was observed in the part quality. Seo and Cho [1999] used cantilever beam formulation and FE analysis for the estimation of tool-workpiece deflections to generate the modified tool-path for several geometries. The application of computational models reduced the experimental efforts and the algorithm was generalized to several geometries. In later studies, the ANN-based model was developed by Cho and Seo [2002] to correlate cutting parameters directly with the surface error without need of computational models in determining the modified tool-path. Ramesh et al. [2000] reviewed various error compensation techniques and concluded that the tool-path modification strategy is ideal when errors are systematic, repeatable and measurable. The tool-path modification technique does not require any modification in the existing hardware of the machine tool and does not compromise machining productivity. Law and Geddam [2003] extended this approach to the end milling of pockets comprising of straight and circular concave sections. It was highlighted that different strategies are required for the linear and concave corner profiles.

Ratchev et al. [2005] developed a flexible force model for the prediction of workpiece deflections and used the same for developing a compensation strategy based on the tool-path modification approach. The developed approach was an iterative procedure that considers variation in the cutting parameters during machining due to compensation of tool-path [Ratchev et al., 2006]. The tool-path modification approach was extended subsequently to compensate tool deflection induced dimensional errors during milling of variable curved geometries [Rao and Rao, 2006]. The study examined the efficacy of tool-path compensation strategy for several variable curvature geometries such as logarithmic spiral, turbine blade and elliptical concave and convex surface. It was reported that the study depicts significant improvements in the dimensional error with the modified tool-path. Dépincé and Hascoët [2006] proposed an iterative procedure called a mirror method for compensating errors resulting due to tool deflections. The methodology aims to locate the position of the cutter such that deflection is compensated completely and error is eliminated. It was highlighted that the non-linearity in the deflection profile along the axis of the cutter necessitate appropriate selection of the reference for the compensation is critical in deciding the effectiveness of implementation.

Chen et al. [2009] predicted the deformation of thin-walled components during the multi-layer milling operation. The study developed a compensation strategy based on the tool-path optimization approach by employing a coupling relationship between cutting forces and machining deformation. Bera et al. [2011] applied the tool-path modification approach to compensate tool-workpiece induced surface error during machining of tubular geometries. Huang et al. [2014] proposed an adaptive tool-path modification approach during 5-axis milling of thin-walled components using an inspection probe installed on the machine tool. The proposed strategy was validated by considering the machining of an impeller blade. Desai and Rao [2016] presented the concept of constant engagement tool-path while machining of curved geometries. The study proposed generating the profile of a semi-finished geometry such that constant engagement is offered while machining the final geometry. Du et al. [2017] used the tool-path optimization approach and tilting of the end mill to compensate the error in the feed and axial directions. The study employed shearing as well as plowing mechanism-based cutting force model to predict the deflection of the low rigidity components. In recent studies, a novel method to compensate machining error during 5-axis milling was proposed by Li and Zhu [2019]. The computational approach based on distance function was developed to obtain the modified tool-path. Habibi et al. [2019] introduced a two-step algorithm to regulate tool orientation and its position to compensate surface form error during 5-axis ball milling operation.

2.5.2 Deflection Control Approaches

The control of deflection refers to the minimization of cutting force induced tool-workpiece deflections by optimizing process parameters such as *ADOC*, *RDOC*, feed rate, etc. or devising an appropriate cutting strategy of cutting sequence planning. The procedure for controlling deflections involves two-step process;

- Step 1: Establishing the relationship between process/cutting parameters and deflections,
- Step 2: Fine tuning of the process/cutting parameters to minimize deflections.

Budak and Altintas [1995] developed a model that identifies the variation of feed rate along the cut to maintain the dimensional errors within specified tolerances. The model assists process planners in reducing the static error by varying feed rate appropriately during the machining of plates. Shirase and Altintaş [1996] illustrated the utility of variable pitch helical end mills in controlling dimensional error by varying the chip load. In subsequent studies, Law et al. [1999] presented a methodology to minimize tool deflections by reducing cutting forces at corners of the pocket. This was accomplished by machining of corners using diagonal cutting mode which considerably reduced the variation of *RDOC*. Stori and Wright [2001] applied parameter space partitioning approach for the efficient selection of *ADOC* and *RDOC* during end milling operation. The results showed that depth of cuts are critical while planning machining operation from the perspective of material removal rate and error control. Ryu and Chu [2005] proposed an alternative methodology to reduce form errors in peripheral milling by employing successive down and up milling. The study also appreciated the effect of flute count, tool geometry and cutting conditions on tool deflection and dimensional error. Wan et al. [2008b] proposed an optimization method for simultaneous selection of feed rate and depth of cut to achieve higher material removal rate without compromising the tolerance specifications. The method was compared with the tool-path compensation technique and it was depicted that the parameter optimization method was more appropriate for obtaining tolerance within the required specifications. Desai and Rao

[2008] studied the effect of direction of parameterization and cutter diameter on process geometry parameters, cutting forces and surface error during milling of variable curvature geometries. The study concluded that the surface error at a given location on the curve varies with machining direction due to a change of the process geometry and cutting forces. Rauch et al. [2009] applied trochoidal strategies to avoid up-down combination of cutting and full immersion during milling with maximum *RDOC* value. The potential of torochoidal and plunge milling have also been investigated for pocket milling applications [Rauch and Hascoet, 2007]. The influence of tilt angle of the end mill on the deformation of the part and thereby surface error was also investigated [Lee et al., 2003]. The maximum value of the deflection at 0°, 15° and 45° was estimated, but smallest value was observed at 45°. Abbasi et al. [2016] studied the importance of cutter tilt angle in the case of ball-end milling and found that the lower deflection value was attained at 5°, which can be approximated as normal to the machined surface of the component.

During milling of thin-walled components, the stiffness of the workpiece reduces significantly with the progress of operation leading to larger deflections of the component. It poses a considerable challenge for the process planner to regulate or homogenize deflections of the component. Koike et al. [2012] investigated this aspect and proposed a material sequence optimization methodology to add material in the form of blocks to the machined workpiece for deriving the unmachined shape. The blocks were added considering the minimum workpiece displacement as an objective function. The actual sequence of removing material was inversely proportional to the sequence of adding the material. The algorithm was further improved by introducing the effect of tool orientation as a controlling parameter [Koike et al., 2013]. It affects the cutting efficiency due to the increase of non-cutting time and often generates cutter marks while changing the direction of the feed. Wang et al. [2017] proposed an enhanced version of the previous algorithm that overcomes limitations and generates a more realistic cutting sequence. In the algorithm, dimensions of blocks were variable which further reduces deflections of the workpiece in comparison to the previous algorithm. Also, the post-optimization process was performed to combine adjacent blocks in the direction of feed to improve the cutting efficiency. Ma et al. [2018] applied a similar algorithm considering rigidity at a cutting position as objective function to schedule instantaneous cutting amount while machining curved surface. Altintas et al. [2018] employed feed rate scheduling to control surface error during ball-end milling process. Recently, FE-based approach was proposed by Liu et al. [2020b] to optimize the shape of workpiece and minimize the machining induced stresses during the grinding operation.

Based on the review of error compensation and control strategies as presented in this section, it can be inferred that the variety of strategies are reported in the literature. The tool-path modification approach is most prominent in case of compensation strategies as it does not require hardware modifications or any compromise in the machining productivity. The strategy aims to modify the relative position between tool and workpiece using a computational or on-machine measurement technique. The effective implementation of the tool-path modification approach during machining of thin-walled component is a major challenge for the process planners due to variation in magnitude and profile of the error along the direction of feed and *ADOC*. On the contrary, the strategies related to the control of tool-workpiece deflection by optimizing process/cutting parameters often compromises with the material removal rate due to machining at conservative values. It results in the under utilization of the machine tool and thereby reduces the cutting efficiency. Further, the research work considering material removal sequence optimization approach that discretizes material to be removed into a set of blocks regulates the deflection of the thin-walled component. However, such approach often leads to cutting sequences that involves infeasible movement of the tool, combination of up-down milling, change of feed direction and increased non-productive time.

2.6 SUMMARY

This chapter presented a review of the literature related to the modeling of several aspects related to the end milling operation. It is concluded that the predictive models are extremely important for process planners in the effective decision making. The predictive models for end milling operation aim to estimate cutting forces, predicting tool-workpiece deflections and reduction or control of deflection induced errors. The literature showed that the mechanistic model is one of the most preferred option to predict cutting forces among available variants. However, the prediction accuracy of different variants of mechanistic model is not identical over a range of cutting conditions viz. *RDOC*, *ADOC*, and feed rate. During end milling of thin-walled component the variation in the *RDOC* is observed due to deflections of the workpiece [Ratchev et al., 2004a]. Therefore, the "*flexible*" force prediction model is required which evaluates cutting forces over a range of *RDOC*. The strategies controlling deflection induced error also necessitates optimization of cutting widths and feed rate that requires better prediction ability of the model over the entire range [Stori and Wright, 2001].

The approximation of instantaneous uncut chip thickness as an average value is inevitable as it is not feasible to measure elemental forces acting on each disk element experimentally. The estimation of instantaneous cutting force components using an approximate empirical relationship yields lower prediction accuracy at specific cutting conditions. It is reported that the lower prediction accuracy at smaller cutting widths is attributed to the marked influence of the bottom cutting edge [Dang et al., 2010]. The total cutting force acting on an end mill at any instant can be obtained by the summation of flank and bottom edge force components. A set of previous studies neglected the bottom edge contribution while few research attempts highlighted the importance of bottom edge and emphasized the need of separate cutting constants in the model. Therefore, the thesis investigates the importance of incorporating the bottom cutting edge in the force model by conducting a performance assessment of three approaches presented in the literature over a wide range of cutting conditions as depicted in Figure 2.5. The first approach establishes the relationship between average chip thickness and cutting constants derived from the measured cutting forces [Wan et al., 2008a]. The second approach considers the extraction of flank forces from measured cutting force data to obtain separate flank constants [Ko et al., 2002]. The third approach considers the determination of flank constants and associated cutting forces similar to the second approach, but it considers an additional contribution of the bottom edge through separate constants to determine total cutting forces [Dang et al., 2010].

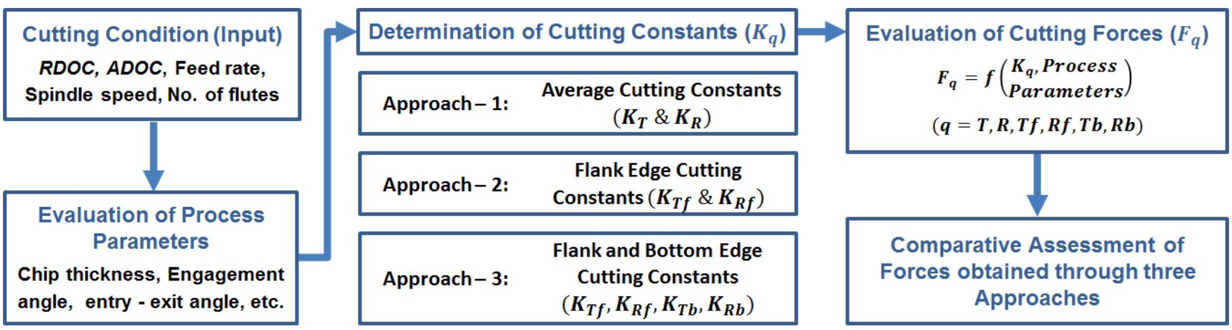

Figure 2.5 : Approaches for Assessment of Cutting Force Models

In addition to incorporation of the bottom and flank cutting edge effects in the mechanistic force model, another important issue to be addressed is the establishment of an efficient relationship between cutting constants and uncut chip thickness. The existing approaches employ curve fitting techniques to the experimental data for establishing cutting constant relationships. The experimental data contains significant noise and outliers due to the process dynamics and thereby yields poorly fitted cutting constant relationship and reduced prediction accuracy of the model. In recent times, the application of data-driven or machine learning models is becoming imperative to evolve the relationship similar to human perceptions among input and output datasets. It will be interesting to develop a hybrid cutting force model that can deal with uncertainties involved in determining constant relationships effectively by replacing the curve fitting with a machine learning-based approach as shown in the Figure 2.6.

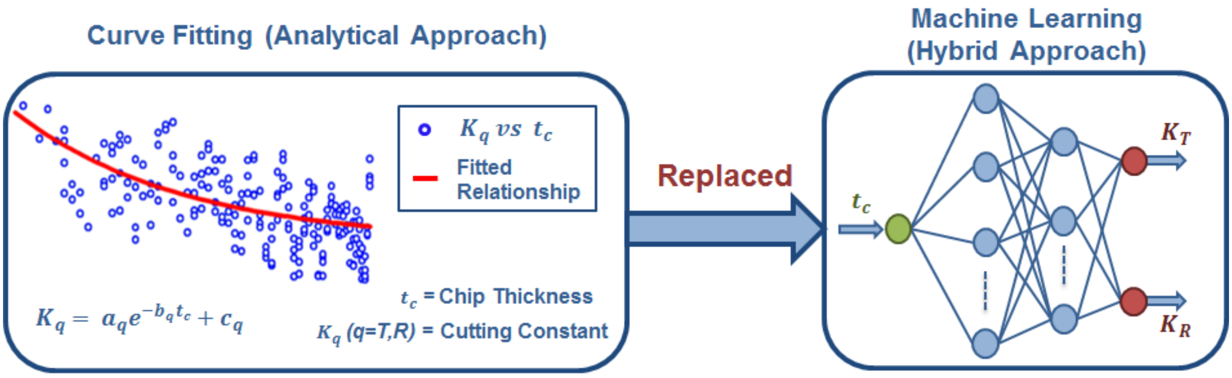

Figure 2.6 : Determination of Cutting Constant Relationship

Based on the review of literature, it is also realized that the estimation of dimensional error due to tool-workpiece deflections has been investigated thoroughly. The nature and magnitude of cutting tool [Desai and Rao, 2012] and workpiece [Arora et al., 2019] deflection induced surface error is highly nonlinear and non-identical under different cutting conditions and closely linked with the cutting widths (*RDOC* and *ADOC*). The widely employed methodology for the estimation of tool deflections is a cantilever beam formulation, whereas FE-based methodology is applied to estimate workpiece deflections. The determination of geometric tolerances during end milling of thin-walled components requires computation of deflected coordinates representing machined feature. The overall framework necessitates systematic computational procedure incorporating end milling process physics through cutting force model, tool-workpiece deflection model, and mechanism to transform deflections into distorted coordinates representing the machined surface. The present thesis also devices a cantilever beam formulation and FE-based methodology integrated with the mechanistic force model to estimate coordinates or point cloud representing the deformed machined surface as highlighted in Figure 2.7. It has been highlighted in the literature that the actual machining operation occurs at considerably lower *RDOC* due to the deflection of the thin-walled components which further reduce cutting forces. This aspect has been incorporated while estimating cutting forces, workpiece deflection and distorted coordinates in the thesis work.

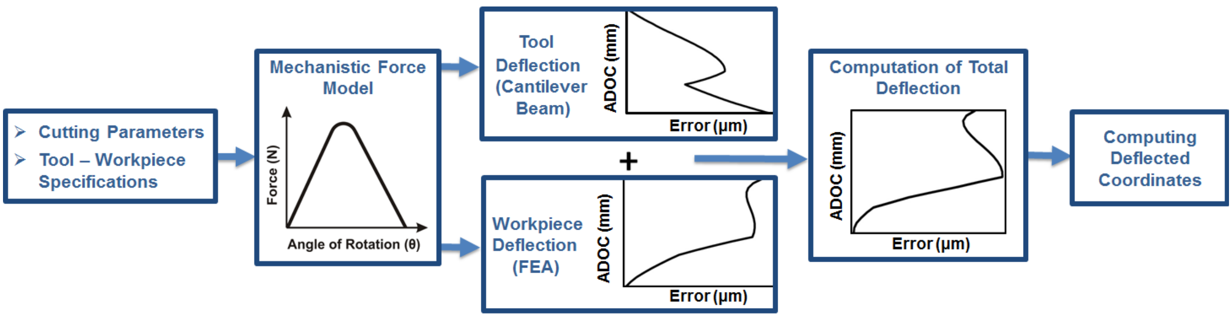

Figure 2.7 : Estimation of Distorted Machined Surface

It was also realized that the inherently lower rigidity of a thin-walled component results in static deflections, and it is a primary source for the distortion of machined surface. The quality of the machined surface is not only expressed using surface error or roughness parameters but also dictated using dimensional and geometric tolerances such as flatness and cylindricity in the case of straight and circular components. The geometric tolerances deal at the macroscopic level, and its evaluation is significantly different in comparison to surface error. However, the research attempts considering the assessment of geometric tolerances are limited to algorithm development based on the point-cloud data acquired using *CMM* with no relation to process faults such as workpiece deflections in the case of thin-walled geometries. The estimation of geometric tolerances is crucial for process planners in selecting appropriate cutting conditions to limit it within an acceptable range such that the component meets functional requirements in an assembly. There has been no attempt reported in the literature that correlates process faults, for example, static tool-workpiece deflections with geometric tolerances. The present thesis associates static deflection of cutting tool and workpiece with geometric tolerances during the end milling of thin-walled straight and circular components. It is attempted by adopting computational models to estimate static deflections of the tool and thin-walled components, estimating distorted machined surface, and transforming the same to geometric tolerances using the PSO algorithm. The overall framework for estimating the geometric tolerances proposed in the present thesis is depicted in Figure 2.8.

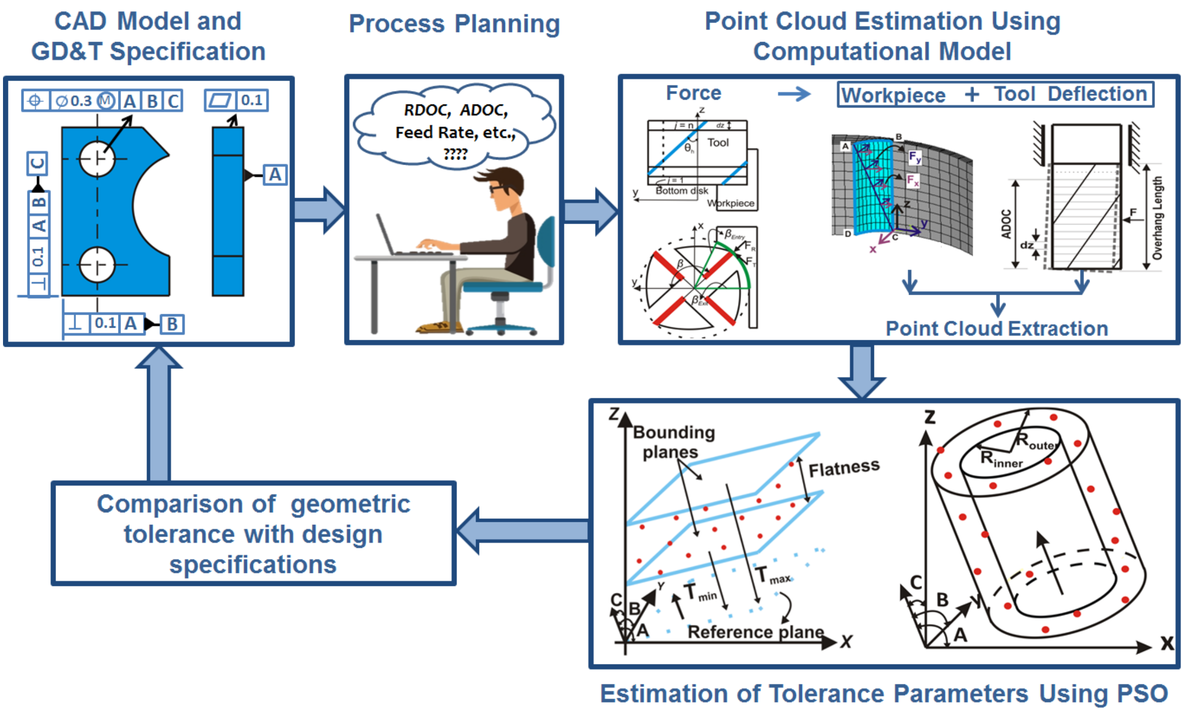

Figure 2.8 : Physics-based framework for geometric tolerance estimation

The literature also presented different strategies to compensate and control cutting force induced dimensional errors. The compensation strategies consider minimum error location as a reference point and compensates the dimensional error. However, the tolerance value i.e., the difference between the minimum and maximum error remains unaltered, therefore, these approaches are ineffective while compensating geometric tolerances as shown in Figure 2.9. Alternatively, the control strategies aim to minimize the spread of the deflection profile by optimizing process/cutting parameters, cutting sequences, etc. and control the dimensional error. It is assimilated that strategies controlling deflections offer better suitability in comparison to the compensation for geometric tolerances. However, these control strategies may lead to the decrease in machining productivity due to the application of conservative cutting parameters. The thesis presents a novel strategy that alter the semi-finished workpiece geometry such that the geometric tolerances are controlled while performing the final machining sequence without compromising machining productivity as depicted in Figure 2.9.

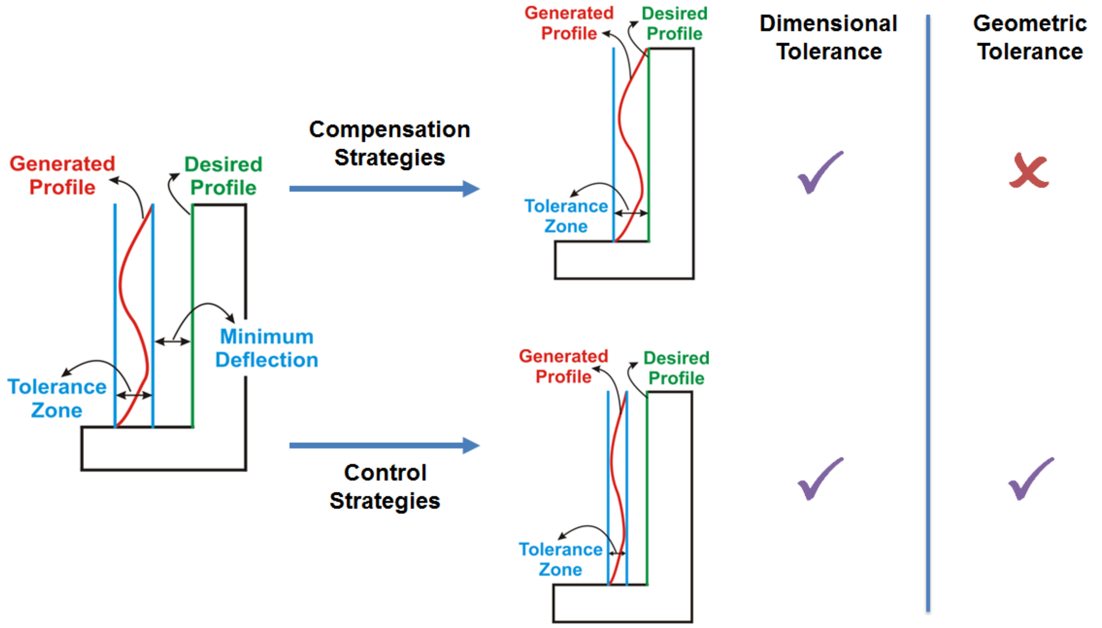

Figure 2.9 : Comparison of Compensation and Control Strategies

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