Proceedings of the
International Conference on Mechanical Engineering 2003
(ICME2003) 26-28 December 2003, Dhaka, Bangladesh

ICME03-AM-29

CALIBRATION OF A MECHANISTIC BALL-END MILLING FORCE MODEL FROM NOISY CUTTING FORCE DATA

Abdullahil Azeem[1] and Hsi-Yung (Steve) Feng[2]

[1]Graduate Student
[2]Associate Professor
Department of Mechanical and Materials Engineering
The University of Western Ontario
London, Ontario
Canada N6A 5B9

ABSTRACT
Machine vibration due to structural rigidity, tool-part material and cutting parameter selection often results in noisy cutting force signals for most milling processes that are captured by dynamometer during cutting force measurements. This paper presents a mathematical approach to calculate the empirical cutting force coefficients from measured instantaneous noisy force signals in ball-end milling. The captured noisy force signals are processed by numerical fitting technique to extract the correct force values. Two different solution methods, namely, Forward and Backward solution methods, are proposed and implemented to solve the lumped discrete values of cutting mechanics parameters and the constant values of size effect parameters. An iterative two-stage procedure is employed to solve these parameters using both solution techniques. The effectiveness and comparison of the two different approaches in solving cutting force parameters has been demonstrated experimentally with a series of verification cuts.

Keywords: Model calibration, Instantaneous cutting force, Noisy force signal.

1. INTRODUCTION
In modern manufacturing, products having 3D sculptured surfaces are being designed and produced to meet the functional specifications. Ball-end milling is one of the most efficient and widely used processes to machine these complex surfaces. Majority of the milling operations are carried out with experience-based approaches. The optimum cutting conditions are determined after extensive shop floor tests. Overly conservative cutting conditions are often selected to ensure high quality of the machined product, which limits the process efficiency and leads to higher production costs. It is very difficult to select appropriate process parameters to achieve high productivity while maintaining part quality.

Cutting forces working on the cutter is one of the important variables that give significant cutting information. Excessive cutting forces cause low product quality, while small forces often indicate low machining efficiency. Accurate prediction of cutting forces is therefore critical for process planning in order to optimize the process parameters. The cutting forces in the milling process are directly related to the empirically determined cutting force coefficients in the mechanistic modeling approach. Accurate determination of these coefficients is very important in predicting cutting forces. Measured instantaneous cutting force data from the calibration cut is used to calculate the force coefficients. In most cases, noisy force data is captured by the dynamometer that is resulted from machine vibration. Noisy data has greater impact on solving the cutting force coefficients that affect largely in predicting cutting forces. The proposed solution procedures calculate the cutting force coefficient values upon processing the noisy force data.

A mechanistic cutting force model was first developed by Kline et al. [1]. The force coefficients were solved for each measured force signal and correlated with different cutting conditions. A polynomial expression was used to express the force coefficients within the specific range of cutting conditions. This model was later extended to consider cutter runout and cutting system flexibility [2,3]. Yang and Park [4] used orthogonal cutting data from turning tests to estimate the force coefficients as a function of cutting variables. The model was then extended for flexible cutting system [5]. Feng and Menq [6,7] developed a force model by approximating the force coefficients as a third order polynomial function and were obtained by an iterative procedure including the size effect parameters and the cutter runout parameters. The model was later improved by incorporating the flexible cutting system [8]. Budak et al. [9] used orthogonal cutting database to estimate the force coefficients in unified mechanics approach. Shin and Waters [10] solved the force coefficients for each cutting segment from instantaneous cutting forces. Feng and Su [11] showed that the coefficient values were different for non-horizontal cutter movements. The non-horizontal force coefficients were proposed as a function of the feed angle and could directly be solved from instantaneous measured cutting forces. Zhu et al. [12] used the average cutting forces and average process conditions to estimate the force coefficients from the generated database.

In this paper, a new solution procedure to estimate the cutting force coefficients from an existing force model is demonstrated. To reduce the time and effort needed to calibrate the force coefficients, a single half-slot calibration cut was proposed by Azeem et al. [13]. This half-slot cut generates a lower triangular force matrix from which the force coefficients need to be solved using measured instantaneous cutting force signals. The noisy force signals from machine vibration need to be processed to capture accurate force values as instantaneous cutting forces are used to calibrate the force coefficients. After processing the noisy force data, two different solution methods are proposed and implemented to solve the force coefficients from the generated force matrix. The coefficient values obtained from both solution methods are used to predict the force signals and these predicted force signals are then compared with the measured force signals to validate the two different solution approaches.

2. MATHEMATICAL FORMULATION

The empirical chip-force relationships of a developed mechanistic cutting force model for ball-end milling are formulated [6] as follows:

$$dF_T(\theta, z) = K_T(z)\ dz\ [t(\theta)]^{m_T} \tag{1}$$

$$dF_R(\theta, z) = K_R(z)\ dz\ [t(\theta)]^{m_R} \tag{2}$$

where $dF_T(\theta,z)$ and $dF_R(\theta,z)$ are the differential tangential and radial cutting force components of a cutting edge element at a distance z from the cutter free end and at an angular position θ. The undeformed chip area for the cutting edge element is represented by the chip width dz and the undeformed chip thickness $t(\theta)$. $K_T(z)$ and $K_R(z)$ specify the variation of cutting mechanics parameters for cutting elements along the cutting edge and m_T and m_R explicitly characterize the size effect in metal cutting.

2.1 Model Calibration

From Eqs. (1) and (2), the empirical cutting force coefficients need to be determined to predict the cutting forces in ball-end milling. A single half-slot horizontal cut with an axial depth of cut of the nominal cutter radius R was proposed by Azeem et al. [13] to calibrate the force coefficients. Cutting mechanics parameters $K_T(z)$ and $K_R(z)$ were considered as lumped discrete values whereas size effect parameters m_T and m_R were assumed to be constant for a particular cutter-part combination.

For the single half-slot calibration cut with a two-fluted cutter, the tangential and radial cutting force coefficients cannot be decoupled. Nevertheless, at most one cutting edge is engaged in cutting at any particular cutter orientation during the half-slot cut. One of the cutting edges starts engaging the work material from the cutter free end and as the cutter rotates, the upper portion of the cutting edge is gradually engaged till it reaches the cylindrical part, i.e., the axial depth of cut. Once the full depth is engaged with the cutting edge, the full engagement continues till the cutting edge starts gradually disengaging from the work-piece. Similar to the gradual engagement phase, the disengagement phase also starts from the cutter free end. The specific cutter orientations for the engagement and disengagement phases depend on the cutter helix angle and the associated lag angles. 10 cutting discs of the same thickness are chosen to divide the cutting edge on the ball part. Each disc is again divided into 10 small cutting elements of width Δz along the cutter axis. The tangential and radial force components for the cutting elements can be expressed as:

$$\Delta F_{T_{1,1}} = K_{T_1} \Delta z\ [t_{1,1}(\theta)]^{m_T} \tag{3}$$

$$\Delta F_{R_{1,1}} = K_{R_1} \Delta z\ [t_{1,1}(\theta)]^{m_R} \tag{4}$$

where K_{T_1} and K_{R_1} are the lumped discrete values of $K_T(z)$ and $K_R(z)$ for the first cutting edge disc. $K_T(z)$ and $K_R(z)$ are considered as constant parameter values for each cutting edge disc, but vary from disc to disc.

2.2 Lag Angle Determination

Accurate representation of the helical cutting edge profile is essential when dealing with the instantaneous forces. Cutting edge profile on the cylindrical part of a ball-end mill is most often geometrically similar to that on a flat-end mill. Nonetheless, the design of cutting edge profile on the ball part of a ball-end mill can be arbitrary and thus, varies from cutter to cutter. For an arbitrary cutting edge profile, a measuring instrument is used to trace the cutting edges. The numerical expressions of the cutting edge profile on the ball part of the cutter used in this experiment was found [13] to be:

$$\delta(z) = -0.0068 + 0.2432\left(\frac{z}{R}\right) - 0.0775\left(\frac{z}{R}\right)^2 + 0.1617\left(\frac{z}{R}\right)^3 \tag{5}$$

3. EXPERIMENTAL WORK

The single half-slot calibration cut was performed on a Wahli-51 five-axis CNC horizontal machining center. An Ingersoll 12-mm TiAlN-coated carbide ball-end mill with two right-handed flutes was used for the half-slot cut. This ball-end mill had a constant helix angle of 30° for cutting edges on its cylindrical part. The workpiece material was SAE 1018 cold rolled steel that was securely fastened to the machine table. The cutting tool was fitted to the tool holder which was an integral part of the rotating cutting force dynamometer. This integrated unit was inserted into the machine spindle to carry out the ball-end milling experiment. The machining test was performed without coolant, as suggested by the cutting tool manufacturer, at a spindle speed of 948 rpm. A table feed rate of 101.6 mm/min (0.054 mm/tooth) was employed to reduce the machine vibration due to the relatively non-rigid rotary axis structure.

The instantaneous cutting forces in the x and y directions were measured with a Kistler 9124A rotating cutting force dynamometer. A Kistler 5221A stator was mounted on the spindle housing for transmitting the measured signals. These signals were then passed through a Kistler 5223A signal conditioner and into a National Instruments data acquisition board AT-MIO-16-E2 in a PC. The cutting force signals were digitized at a sampling rate of 23.7 KHz to achieve 1500 data points per cycle for a minimum of 15 complete cutter rotation cycles of cutting force data. The LabVIEW software was used to collect the sampled data and store them in the computer. The captured force data was in the form of analog signals with an output voltage range from –10V to +10V. The output voltage data (mV) was converted into force data (N) according to the below conversion factors provided by the manufacturer:

$$F_x\,(\mathrm{N}) = \frac{1}{0.455}\,\mathrm{mV}\,;\;\; F_y\,(\mathrm{N}) = \frac{1}{0.460}\,\mathrm{mV} \qquad (6)$$

4. DATA PROCESSING

Extraction of the correct force values at any specific orientation angle is quite difficult from the noisy force signals resulted from machine vibration. With numerical fitting technique, these noisy signals can be smoothed out to get the exact force values that are required for accurate estimation of force coefficients. The force signals were approximated by a five order polynomial expression with respect to cutter lag angle as follows:

$$F = a_1[\delta(z)] + a_2[\delta(z)]^2 + \cdots + a_5[\delta(z)]^5 \qquad (7)$$

where a_i, (i = 1 to 5) is a constant, and $\delta(z)$ is the local lag angle at a distance z from the cutter free end.

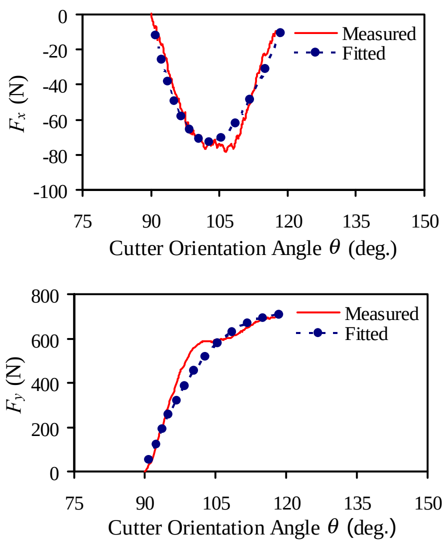


Fig 1. Measured and fitted cutting forces

Once the force signals are fitted, it is easy to extract the accurate force values at any specific cutter orientation angle. The required force values at different cutter orientation angles can be calculated using the polynomial expression in Eq. (7), which is shown against the measured noisy cutting force signals in Fig 1.

5. MATHEMATICAL SOLUTION

Upon obtaining the required lag angles and the corresponding force values, the force equations need to be solved to calibrate the force coefficients. From Eqs. (3) and (4), the elemental tangential and radial forces for all the 10 discs are resolved into x and y directions as:

$$\begin{bmatrix} A_{1,1} & & & B_{1,1} & & \\ \vdots & \ddots & & \vdots & \ddots & \\ A_{10,1} & \cdots & A_{10,10} & B_{1,1} & \cdots & B_{10,10} \\ C_{1,1} & & & D_{1,1} & & \\ \vdots & \ddots & & \vdots & \ddots & \\ C_{10,1} & \cdots & C_{10,10} & D_{10,1} & \cdots & D_{10,10} \end{bmatrix} \begin{bmatrix} K_{T_1} \\ \vdots \\ K_{T_{10}} \\ K_{R_1} \\ \vdots \\ K_{R_{10}} \end{bmatrix} = \begin{bmatrix} F_{xm_1} \\ \vdots \\ F_{xm_{10}} \\ F_{ym_1} \\ \vdots \\ F_{ym_{10}} \end{bmatrix} \qquad (8)$$

where F_{xm_i} and F_{ym_i} (i=1 to 10) are measured instantaneous cutting forces in x and y directions at 10 specific cutter orientation angles for successive engagements of the cutting discs. For kth orientation angle and jth cutting element of the ith cutting disc,

$$A_{k,i} = \sum_{j=1}^{10} \Delta z.\left[t_{k,i,j}(\theta)\right]^{m_T}\left[-\cos\theta_{k,i,j}(\theta)\right] \qquad (9a)$$

$$B_{k,i} = \sum_{j=1}^{10} \Delta z.\left[t_{k,i,j}(\theta)\right]^{m_R}\left[-\sin\theta_{k,i,j}(\theta)\right] \qquad (9b)$$

$$C_{k,i} = \sum_{j=1}^{10} \Delta z.\left[t_{k,i,j}(\theta)\right]^{m_T}\left[\sin\theta_{k,i,j}(\theta)\right] \qquad (9c)$$

$$D_{k,i} = \sum_{j=1}^{10} \Delta z.\left[t_{k,i,j}(\theta)\right]^{m_R}\left[-\cos\theta_{k,i,j}(\theta)\right] \qquad (9d)$$

The empirical cutting force coefficients were determined by a two-stage numerical fitting procedure. The procedure started with the conditions of constant m_T and m_R values of 1.0 and no cutter runout. The lumped discrete values of $K_T(z)$ and $K_R(z)$ were then solved from Eq. (8) with two different solution methods: (1) Forward Solution method, and (2) Backward Solution method. In order to identify the values of m_T and m_R and account for the inevitable presence of cutter runout, the solved values of $K_T(z)$ and $K_R(z)$ were used to calculate the x and y cutting forces at five cutter orientation angles (110° to 150° with 10° interval). These orientation angles were chosen because all the cutting edge discs on the ball part were simultaneously engaged with the workpiece and the measured forces were of relatively significant magnitude. The calculated cutting forces were then evaluated against the measured cutting forces at these orientation angles for the two asymmetric cutting edges due to runout. A non-linear search routine was implemented to minimize the sum of squares of the deviations between the calculated and the measured cutting forces. This yielded the optimal set of m_T and m_R, and the runout parameters ρ and λ, which had been iteratively used in Eq. (8) to update the lumped discrete values of $K_T(z)$ and $K_R(z)$.

5.1 Forward Solution Method

In this solution approach, the x-y force equations for the first disc were taken into consideration as:

$$\begin{bmatrix} A_{1,1} & B_{1,1} \\ C_{1,1} & D_{1,1} \end{bmatrix} \begin{bmatrix} K_{T_1} \\ K_{R_1} \end{bmatrix} = \begin{bmatrix} F_{xm_1} \\ F_{ym_1} \end{bmatrix} \qquad (10)$$

K_{T_1} and K_{R_1} values were obtained by solving the above simultaneous linear set of equations. These coefficient values for the first disc were then used to solve the coefficients values for the second disc from another set of force equations with simultaneous engagement of both first and second discs. This continued until all the force coefficients were obtained with successive simultaneous engagement of all 10 cutting discs. In this solution technique, the coefficient values of the first cutting disc affected rest of the force coefficient values. The K_{T_1} and K_{R_1} values were solved from the measured instantaneous force data at cutter orientation angle 0.972°, where only the first disc was completely engaged with the work part.

5.2 Backward Solution Method

The solution starts by solving the force coefficients from the last disc engaged with the work part. For i number of cutting discs (10 in the present work), the equations to obtain the force coefficients for the ith disc were expressed as:

$$\begin{bmatrix} \sum_{j=1}^{i-1} A_{i-1,j} & \sum_{j=1}^{i-1} B_{i-1,j} \\ \sum_{j=1}^{i-1} C_{i-1,j} & \sum_{j=1}^{i-1} D_{i-1,j} \end{bmatrix} \begin{bmatrix} K_T \\ K_R \end{bmatrix} = \begin{bmatrix} F_{xm_{i-1}} \\ F_{ym_{i-1}} \end{bmatrix} \qquad (11)$$

where K_T and K_R are the assumed constant force coefficient values for the previous (i-1) discs. For ith disc, there were (10-i+1) number of coefficient values from (10-i+1) sets of equations, average values of which gave the respective force coefficient values. Let m = 10-i+1. For p = 1…m, the force equations for pth coefficient values of the ith disc could be expressed as:

$$\begin{bmatrix} A_{i+p-1,i} & B_{i+p-1,i} \\ C_{i+p-1,i} & D_{i+p-1,i} \end{bmatrix} \begin{bmatrix} K_{T_p} \\ K_{R_p} \end{bmatrix} = \begin{bmatrix} F_{xm_{i+p-1}} - \left(\sum_{j=1}^{i-1} A_{i+p-1,j} \right) K_T - \left(\sum_{j=1}^{i-1} A_{i+p-1,j} \right) K_R - a - b \\ F_{ym_{i+p-1}} - \left(\sum_{j=1}^{i-1} A_{i+p-1,j} \right) K_T - \left(\sum_{j=1}^{i-1} A_{i+p-1,j} \right) K_R - c - d \end{bmatrix} \qquad (12)$$

where

$$a = \sum_{q=1}^{p-1} A_{i+q,i+q} K_{T_{i+q}} \qquad (13a)$$

$$b = \sum_{q=1}^{p-1} B_{i+q,i+q} K_{R_{i+q}} \qquad (13b)$$

$$c = \sum_{q=1}^{p-1} C_{i+q,i+q} K_{T_{i+q}} \qquad (13c)$$

$$d = \sum_{q=1}^{p-1} A_{i+q,i+q} K_{R_{i+q}} \qquad (13d)$$

Total m sets of coefficient values were solved from Eq. (12). The average of these values resulted the desired force coefficient values for the respective cutting discs as:

$$K_{T_i} = \frac{\sum_{p=1}^{m} K_{T_p}}{m} \; ; \; K_{R_i} = \frac{\sum_{p=1}^{m} K_{R_p}}{m} \qquad (14)$$

In this technique, the coefficient values of the last (10th) cutting disc affected rest of the force coefficient values. The $K_{T_{10}}$ and $K_{R_{10}}$ values were solved from the measured instantaneous force data at cutter orientation angle 18.487°, where all the 10 cutting discs were simultaneously engaged with the work part.

6. RESULTS AND DISCUSSION

Fig 2-3 show the lumped discrete cutting mechanics parameter values $K_T(z)$ and $K_R(z)$ along the cutter axis from Forward and Backward solution methods.

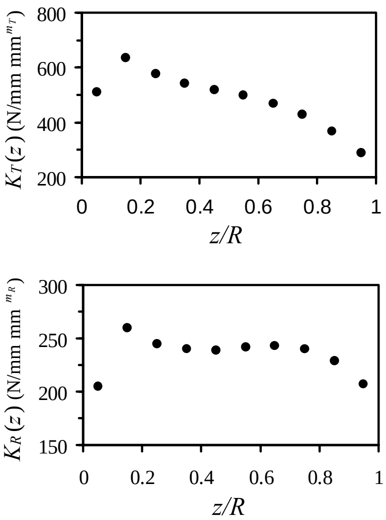


Fig 2. $K_T(z)$ and $K_R(z)$ values along the cutter axis (Forward solution method)

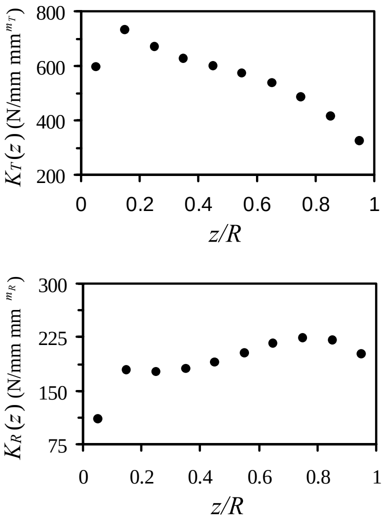


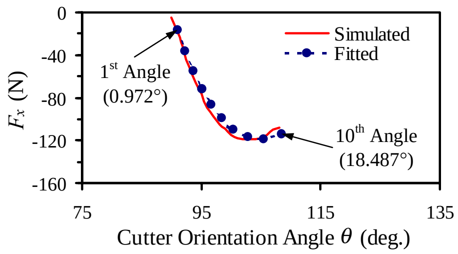
Fig 3. $K_T(z)$ and $K_R(z)$ values along the cutter axis (Backward solution method)

Optimized values of size effect parameters (m_T,m_R) and the cutter runout parameters (ρ,λ) for two different solution approaches are shown in Table 1.

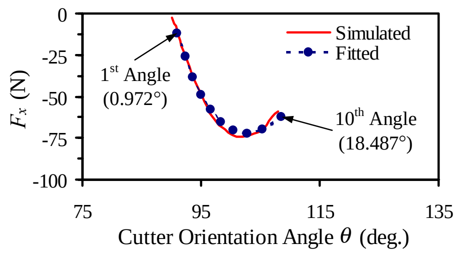
Table 1: Size effect and cutter runout parameters

Method	m_T	m_R	ρ (mm)	λ (deg.)
Forward	0.57	0.65	0.011	250
Backward	0.61	0.64	0.010	249

Force values in x and y directions at 10 different cutter orientation angles and the simulated x-y force signals from the solved coefficient values for the half-slot calibration cut are presented in Fig 4. The solid lines represent the simulated force signals and the dashed lines represent the fitted force values. The simulated force data at the very first orientation angle (0.0972°) is closer to the fitted force data in Forward solution method



(a)



(b)

Fig 4. Simulated and fitted cutting forces for (a) Forward, and (b) Backward solution method

compared to the same in the Backward solution method. In contrast, the simulated force data at the last (10th) orientation angle (18.487°) in Backward solution method is closer to the fitted force data compared to the same in Forward solution method. This supports the two solution approaches where the coefficient values of the first disc is responsible for rest of the force coefficient values in Forward solution method, whereas in the Backward solution method, the coefficient values of the last (10th) disc is responsible for rest of the force coefficient values.

Table 2: Parameters for verification test cuts

Test No.	**Feed** (mm/tooth)	**Axial Depth** (mm)	**Radial Depth** (mm)
1	0.054	6.0	3.0
2	0.054	6.0	1.5
3	0.043	6.0	1.5

Three test cuts with different cutting conditions as listed in Table 2 were performed to compare and validate two proposed solution methods. The associated instantaneous cutting forces were calculated using the

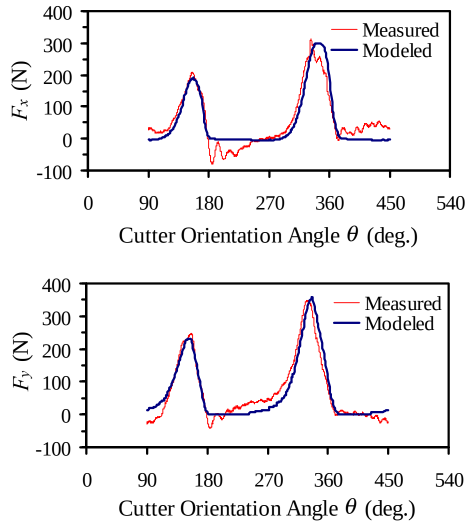


Fig 5. Measured and modeled x-y force signals (Forward solution method)

calibrated cutting force coefficients. Fig 5-6 show the graphical comparison of the modeled and measured x and y cutting forces for test cut No. 2. In these figures, the heavier lines represent the calculated cutting forces from

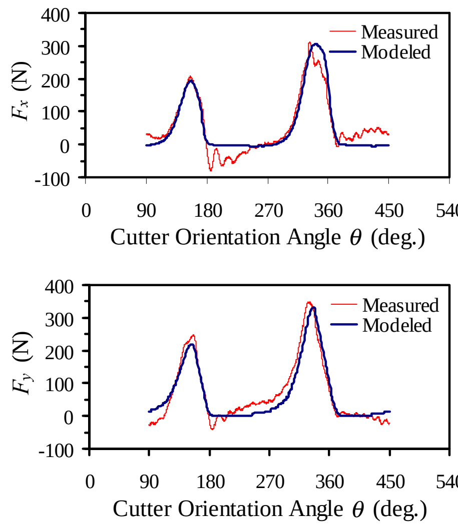


Fig 6. Measured and modeled x-y force signals (Backward solution method)

the mechanistic model whereas the thinner lines represent the measured cutting forces. Good agreement between the modeled and the measured cutting forces clearly demonstrates the validity of both approaches.

In Forward solution method, the solution starts from the very first cutting disc. The x and y forces, at the orientation angle where the first disc is completely engaged with the work part, are used to solve the force coefficient values that are ultimately used to solve rest of the force coefficient values. So the force coefficients for the first disc directly affect the force coefficients for rest of the discs. The orientation angle for the first disc to be completely engaged with the work part was found to be 0.972°, which is right after the cutter start engaging the work part. The cutting system might not be stable at that very first instance. Also the cutting force at this angle is very small and little deviation from this force due to system instability significantly affects all the force coefficients that results inaccurate prediction of cutting forces. On the other hand, the solution in the Backward approach starts from the very last disc. The forces, at the orientation angle where all 10 cutting discs are simultaneously engaged with the cutter part, are used to solve the coefficient values for the last disc, and the solved values are used to calculate the coefficient values for rest of the cutting discs. The cutter orientation angle for all the discs to be completely engaged was 18.487°, which is quite a large angle compared to the one in the previous (Forward) method. The cutting system is more stable at this position and forces at this angle are also quite large. Little deviation of these larger force values doesn't significantly affect the coefficient values of the last disc and hence rest of the discs.

7. CONCLUSIONS

Accurate estimation of cutting force coefficients is critical to cutting force prediction in milling process. The cutting force coefficients are calibrated from the measured force data in mechanistic modeling approach. For most milling processes, the machine vibration causes the dynamometer to capture noisy instantaneous force signals. It is very difficult to obtain the exact force values at a certain orientation angle from the noisy force signals, especially at the very starting angles where the cutter edge just starts engaging with the work part.

The accuracy of the measured forces at each orientation angle is of much concern in the current study as instantaneous cutting forces are used to calibrate the force coefficients. In this paper, the details of the force measurement procedures in ball-end milling process are described. After capturing the noisy force data due to machine vibration, a numerical fitting technique is implemented to process the captured data. The force coefficients need to be solved from this processed force data. Two different solution approaches, namely Forward and Backward solution methods, are described to obtain the force coefficient values. The force parameters obtained from two different approaches are used to predict the cutting forces with varying cutting parameters to validate the solution techniques. Although the predicted signals show good match with the measured force signals for both the approaches, the Backward solution method is believed to be more acceptable compared to the Forward solution method based on cutting stability and process reliability.

8. ACKNOWLEDGEMENTS

This research has been in part supported by Natural Sciences and Engineering Research Council of Canada (NSERC) and Materials and Manufacturing Ontario (MMO). The authors wish to thank Dr. L. Wang, Dr. P. Orban, Mr. D. Kingston and Mr. S. Kowala of Integrated Manufacturing Technologies Institute, National Research Council of Canada (IMTI-NRC) for their technical support in conducting the experiments. Ingersoll Cutting Tool Company is also gratefully acknowledged for providing the ball-end mills for this research work.

9. REFERENCES

1. Kline, W. A, DeVor, R. E. and Lindberg, J. R., 1982, "The prediction of cutting forces in end milling with application of cornering cuts", International Journal of Machine Tool Design and Research, 22:7-22.
2. Kline, W. A., and DeVor R. E., 1983, "The effect of runout on cutting geometry and forces in end milling", International Journal of Machine Tool Design and Research 23:123-140.
3. Sutherland, J. W. and DeVor, R. E., 1986, "An improved method for cutting force and surface error prediction in flexible end milling systems", ASME Journal of Engineering for Industry 108:269-279.
4. Yang, M. and Park, H., 1991, "The prediction of the cutting force in ball-end milling", International Journal of Machine Tools and Manufacture, 31:45-54.
5. Sim, C. and Yang, M., 1993, "The prediction of the cutting force in ball-end milling with a flexible cutter", International Journal of Machine Tools and Manufacture 33:267-284.
6. Feng, H. Y. and Menq, C. H., 1994, "The prediction of cutting forces in the ball-end milling process – I", International Journal of Machine Tools and Manufacture 34:697-710.
7. Feng, H. Y. and Menq, C. H., 1994, "The prediction of cutting forces in the ball-end milling process – II", International Journal of Machine Tools and Manufacture 34: 11-719.
8. Feng, H. Y. and Menq, C. H., 1996, "A flexible ball-end milling system model for cutting force and machining error prediction", ASME Journal of Manufacturing Science and Engineering 118:461-469.
9. Budak, E., Altintas, Y. and Armarego, E. J. A., 1996, "Prediction of milling force coefficients from orthogonal cutting data", ASME Journal of Manufacturing Science and Engineering 118:216-224.
10. Shin, Y. C. and Waters, A. J., 1997, "A new procedure to determine instantaneous cutting force coefficients for machining force prediction", International Journal of Machine Tools and Manufacture 37:1337-1351.
11. Feng, H. Y. and Su, N., 2001, "A mechanistic cutting force model for 3D ball-end milling", ASME Journal of Manufacturing Science and Engineering 123:461-469.
12. Zhu, R., Kapoor, S. G.. and DeVor, R. E., 2001, "Mechanistic modeling of the ball-end milling process for multi-axis machining of free-form surfaces", ASME Journal of Manufacturing Science and Engineering 123:369-379.
13. Azeem, A., Feng, H. Y., and Wang, L., 2003, "A simplified approach for determining empirical cutting force coefficients for ball-end milling", *Transactions of NAMRI/SME*, pp. XXXI:121-128.