END MILLING FORCES BEHAVIOR STUDY BY SIMULATION AND FINITE ELEMENTS DINAMIC ANALISYS

Cristian Mangoni
Departamento de Engenharia Mecânica, Campus Universitário – Trindade, Florianópolis/SC Brasil, Caixa Postal 476 EMC – 88.010-970
e-mail: cristianmangoni@yahoo.com.br

Rolf Bertrand Schroeter
Departamento de Engenharia Mecânica, Campus Universitário – Trindade, Florianópolis/SC Brasil, Caixa Postal 476 EMC – 88.010-970
e-mail: rolf@lmp.ufsc.br

Paulo de Tarso Rocha de Mendonça
Departamento de Engenharia Mecânica, Campus Universitário – Trindade, Florianópolis/SC Brasil, Caixa Postal 476 EMC – 88.010-970
e-mail:mendonca@grante.ufsc.br

Abstract. *The milling is one of most universal machining process. However, the possibility of simultaneous action of several inserts upon the workpiece, the continuous chip thickness variation and the discontinuous cut make it difficult to develop a generic theoretical description of the variables that influence the process. The number of variables involved in this machining process made it impracticable, until recently, the attempt to extract trustworthy results by numerical simulation. However, the simulation is becoming more viable due to the improvement of proper numerical methods and the development of software and hardware. Nowadays, the cutting forces present on turning and milling process can be predicted by several models. In this work, theoretical and experimental procedures are developed to determinate end milling forces. These forces are used as input data for a finite element dynamic analysis for low stiffness parts submitted to the end milling fluctuating forces. A model to predict the end milling forces is proposed. This model is utilized for a dynamic finite element analysis on parts being machined with the objective of determining machining parameters to reduce extreme vibrations. The parameters varied at the dynamic analysis are the feed rate, the cutting depth and the cutting speed. The use of this computer assisted model permits the optimization of the cutting parameters before the process is started, therefore reducing the need of empirical experiments.*

Keywords: *End milling, forces, simulation, finite elements.*

1. Introduction

The machining research have been developed, historically, in two lines: one, the experimental research, usually models individually each specific engineering necessity; it supplies data banks for a wide range of situations, however with some lack in the capacity of predicting different situations; the other line of research deals with the problem through theoretical models that are frequently not easily applied in industrial environment (Ehmann, 1997; Luttervelt, 1998).

Machining is one of the most important manufacturing processes in the mechanical industry (Drosda, 1982). Even though its apparent simplicity, it is a complex process, in which the interactions between the cutting tool and machine-tool are critical. Besides technological aspects, the increase in legislation rigor about ecological aspects motivates the necessity of coordinate both lines, with focus in the development of general theories compatible with the industry necessities. In this way, the empirical line develops efficient methods to the data extraction that can be used in a theoretical model, which can be validated to a specific case. This procedure has been improved with the development of computational capabilities, which increases the reliability of predictions in the process behavior, with an impact on quality and productivity (König, 1997).

The necessity of reliable information of machining forces have been emphasized in several published researches. The milling forces study is important in the design of machine-tool elements like bearings, bases, drive, guides, fixation systems of tool and piece, in the determination of the cutting parameters, explanation of wear mechanisms, in prediction of vibrations amplitude and for estimating the machining precision obtainable (Altintas, 1994; Drosda, 1982; König, 1997).

The machining force components in the turning and milling processes, can be reproduced by models proposed by Kienzle and Altintas, among others (Altintas, 1994; König, 1997). These can feed numerical models, as finite elements method (FEM) to estimate tool overload or unfavorable machining situations, permitting, finally, that the cutting conditions can be reviewed before the process begins.

Considering an instant of time when the chip section in the turning and milling have the same width and thickness, it can be questioned about the forces in the two processes considering that both happen with the same tool and the same material. If the forces are similar in both processes, it can be postulated that the Kienzle model for turning can be valid for milling as well. So, an already existent data bank of turning constants can be used without necessity of new milling tests to be made.

In this work end milling forces are theoretical-experimentally determined, which are subsequently used as input data in dynamic analysis by finites elements for low stiffness parts submitted to the alternating end milling forces. In this case, parameters that lead to smaller amplitude of vibrations can be numerically searched.

The finite elements method, at first consecrated in structural analysis applications, has been applied successfully in several areas (Mackerle, 1996). With the evolution of computers and programs, this tool, when calibrated with experimental data, can be applied successfully in the machining, especially in milling, which is always accompanied by mechanical vibrations.

Once the milling force behavior is validated, these results can be used as input data for a finite element model using dynamic analysis of the process. In this case can be simulated parameters that result in less vibration amplitude.

2. Theory Revision

2.1. End milling technological characteristics

Milling is a machining process in which the removal of workpiece material happens intermittently, with one or more cutting edges machining at the same time due to the relative movement between workpiece and cutting tool. Due to the intermittent cut, the types of contact between tools and workpiece have influence over forces behavior and the tool life

The motion in the process is a result of a rotation movement n given by the cutting tool, and the feed f_z by the workpiece or the tool. If the surface is generated by the top of the milling, by the secondary edge, the process is designated end milling. In the same way, a milling process in which the surface is generated by the edges in the circumference of the mill is known as peripheral milling. In the end milling the width of engagement a_e is considerably larger than the cutting depth a_p, Fig1.

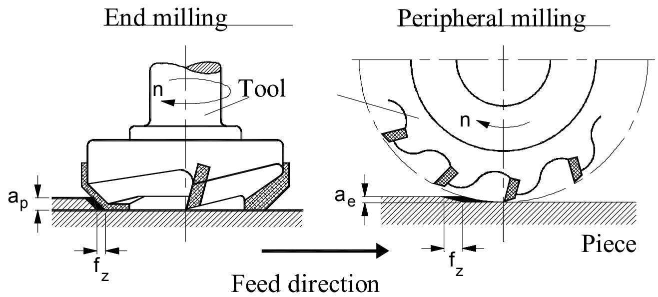


Figure 1. End milling and peripheral milling, (König, 1997).

2.2. End milling forces

A great advance of researches in metal cutting has been done from the 1920 decade, in United States and Europe. The use of mathematic models to describe the behavior of machining forces, cutting conditions, the tool life etc, became a prominent instrument to search for the best results in cost-benefits in the industrial production.

By definition, machining force is total force F that acts on a cutting edge. This force is decomposed in three other components: passive force F_p, feed force F_f and cutting force F_c.

During the milling each tooth or cutting insert is under an impact load when enter in the cutting region. The magnitude of this load depends mainly on workpiece material, cutting tool position, machining parameters and cutting tool geometry. The forces in milling are cyclic and strongly proportional to the cutting thickness in each position.

According to researchers like König (1997), and Altintas (1994), among others, methods and models were created to simulate the cutting forces, fact that is motivated by the relative complexity of the phenomena. The models, in their majority, consider the tool geometry, characteristics of the material machined, cutting conditions and sometimes also the cutting tool deformations and the vibration level present in the process. Generally the models are simplified, such that not always they consider simultaneously all the variable acting in the process.

2.3. Simulation in machining

The number of variables involved in a machining process, made impracticable, until recently, the extraction of trustworthy data through a numerical analysis. However, in the last years this strategy are becoming increasingly more viable due to several factors like: improvement of methods like finites elements and the development of more sophisticated programs and computers, which enables the solution of larger problems in adequate processing times.

One of the simulation advantages of the simulation is the possibility of reduction of cost involved in design by reducing the number of experiments, which are considered fundamentals (Luttervelt, 1998). Other the advantages of simulation worth noting are:

- There is no interference in the machining process and with a simple change of a numerical parameter, the awanser of the system in analysis can be simulated;
- Hypotheses can be tested;
- The simulation generally is easier to apply than analytical methods;
- The new situations, even with few knowledge level can be treated;
- The time can be controlled, it can be compressed or expanded;
- It can be better understood which variables are more important in relation to the performance, and how they interact between themselves and with other system elements;
- There are cases in which the process is not susceptible of experimentation, leaving the simulation as the only option of analysis;.

Some disadvantages can be cited:

- Development of models require qualified people;
- Frequently, the results of the simulations are difficult to interpret. Since models try to capture the variability of the system, it may be difficulties to determine when a result is due to some significant relation in the system or to random process constructed and inlayed in the model;
- Simplifications applied to the model, aiming at economy of resources, usually lead to unsatisfactory results

Besides the diversity of input and output variables, intern variables also make the machining simulation difficult (Luttervelt, 1998). The workpiece material has significant effects in the results of the machining process, and frequently it is difficult to determine their properties. The interface of cutting tool/workpiece is also complex, and the phenomena therein depend on the pressure, temperature, speed, tool and piece properties, medium lubri-coolant, among others factors. As a result of this variety of properties, a large database is necessary, whose creation is expensive and time consuming.

3. Proposed model for end milling forces

The Kienzle model is usually used for the turning forces calculation because in this process the cut parameters are generally constant. Such fact makes the force analysis easier in the turning than in the milling process, where the chip thickness varies with the immersion angle. Considering one instant of time when the chip section in both processes have the same width and thickness, the forces in both processes are equivalent, if the same material is machined with the same tool parameters in both processes. So, the Kienzle model can be used for milling, which permits the use of previously existent databanks of turning, without the necessity of milling tests.

Once founded similarity between end milling and turning forces results, for the same cutting conditions, experiments can be realized with the objective of cutting constants determination. The force variation is related to the chip thickness variation, that is a function of the immersion angle ϕ. The basic strategy for the proposed model consists, therefore, in calculating the instantaneous values of the force throughout each cutting cycle. The forces obtained in experimental milling are compared with the results of the proposed model when it is fed with the constants of turning.

In the turning process the forces are normally decomposed in: cutting force, feed force and passive force. In the milling process, the tangential, radial and axial directions can be correlated with the turning forces components.

The principal modification applied to Kienzle equation is in the radial and tangential forces acting on the edge in the milling process is basically the consideration that in the milling, the chip thickness h varies periodically along the trajectory traveled by the edge in the workpiece. So, the tangential and radial forces are described by:

$$F_t(\phi) = k_{c1.1} \times b \times h^{(1-mc)} \operatorname{sen}(\phi) \quad (1)$$

$$F_r(\phi) = k_{f1.1} \times b \times h^{(1-mf)} \operatorname{sen}(\phi) \quad (2)$$

The forces that act in the x-y plan due to trignometical decomposition of tangential and radial forces results in:

$$F_x(\phi) = -F_t \cos(\phi) - F_r \operatorname{sen}(\phi) \quad (3)$$

$$F_y(\phi) = +F_t \operatorname{sen}(\phi) - F_r \cos(\phi) \quad (4)$$

4. Experimental Methodology

The turning experiments for this work were realized with the objective of obtain the Kienzle experimental curve. It is obtained through the bilogarithmic plot of the quotient between the cutting force and the machining width *(F_c/b)* with the machining thickness (h). These experiments make possible the attainment of the specific cutting force *($k_{c1.1}$)* and the exponent *(1-m_c)* of the Eq. (1), that are workpiece material characteristic, as well as material and geometry of the cutting tool. These constants are necessary for the comparison between the proposed model and the results of experimental end milling forces.

4.1. Machines and Equipment

The turning force experiments were realized on a lathe CNC COSMOS 20U, manufactured by ROMI and using a piezoelectric platform Kistler 9257A, signal amplifiers Kistler 5011, acquisition board National Instruments PCI-MIO-16E-1. The milling force experiments were realized in a CNC ROMI Polaris F400 milling machine. For the force acquisition it was used a piezoelectric platform Kistler 9265A with a range from 0 to 15 kN.

4.2. Tool and Material

The workpiece material utilized in the tests of forces was gray cast iron GG25 (DIN Standard). The tool utilized in the turning was of type square SPMT 100408R-HQ, produced by ISCAR. The tool holder utilized was PQLNL 2525 M-09.

The inserts utilized in milling were the same of the turning tests. The tool holder used was a milling head F90SP-D63-22-FP10, produced by ISCAR, with diameter of 63 mm and 7 inserts.

4.3. Experimental Procedures

The machining parameters utilized were cutting speed of 140 m/min, and cutting depths of 2 mm. The feed were determined by series of normalized numbers R 20 according to the norm ISO 3685. The forces data were acquired with a 1000 Hz acquisition frequency. For each machining condition were realized 5 repetitions in different workpieces. The milling was performed with full engagement angle to allow the forces analysis against the immersion angle varying from 0 to 180^o. The model validation used just one insert in the end milling head, to make easy the analysis and comparison with the turning process.

5. Proposed model validation

Figure 2 compares experimental forces in the turning and milling processes, for each condition in both processes. As the milling force is variable, the milling data displayed corresponds to an engagement angle of 90°, where the chip cross-section has the same dimensions in both processes for the same machining parameters. The forces in both processes are similar, which allows the estimate of the milling forces trough the turning models, as the proposed model.

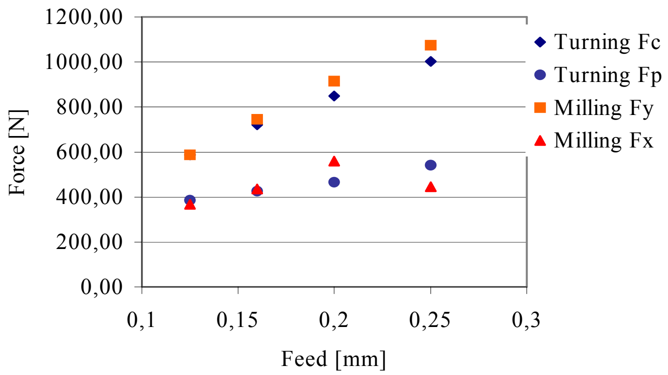
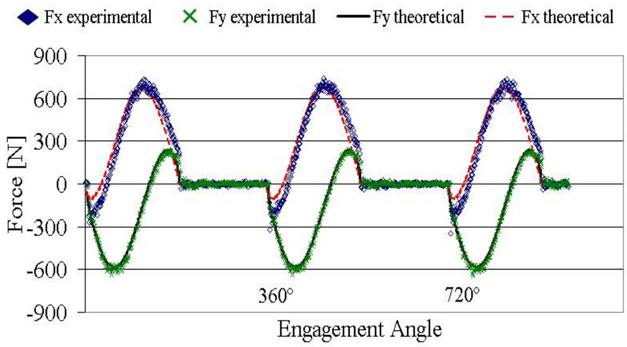


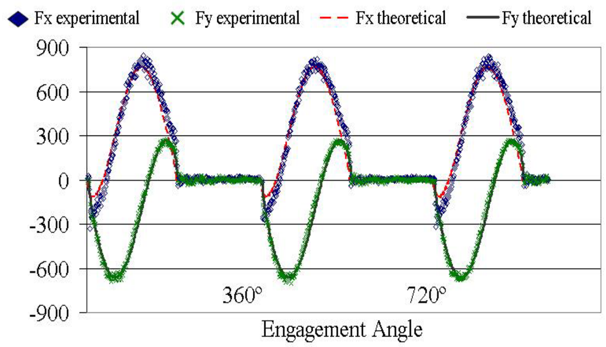
Figure 2. Comparison between turning and end milling forces.

Figure 3 shows the force results of the proposed model and experimental data of end milling using a cutting depth of 2 mm and speed of 140m/min. When the mill describes an engagement angle of 90°, the cutting force is equivalent to F_x and the feed force is equivalent to F_y.

The proposed model, when compared with the experimental results, presents satisfactory results, especially in the larger forces. In the beginning of the cut a small discrepancy is observed, due to the fact that the Kienzle model do not present good results for the feed forces with small chip thickness without compensating it. However, these forces have almost irrelevant magnitudes when compared with the forces during the rest of the cutting. The results show the viability of the proposed model, such that the Kienzle turning constants can be used for the prediction of the end milling forces. The use of these constants facilitates the simulation processes due to the data bank existent and the easiness of the turning tests for new workpiece materials or cutting tools. The Kienzle constants used are: $k_{c1.1}$ = 870,7 N/mm^2, (1-m_c) = 0,577, $k_{f1.1}$ = 515 N/ mm^2, (1-m_f) = 0,55.



(a)



(b)

Figure 3. Comparison between theoretical and experimental forces f_z = 0,16 mm in (a) and 0,20 mm in (b).

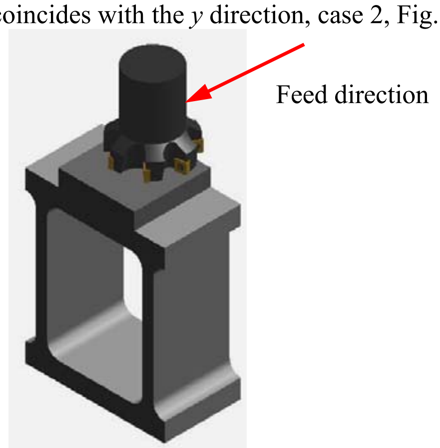
The proposed model, when compared with the experimental results, presents satisfactory results, especially in the larger forces. In the beginning of the cut a small discrepancy is observed, due to the fact that the Kienzle model do not present good results for the feed forces with small chip thickness without compensating it. However, these forces have almost irrelevant magnitudes when compared with the forces during the rest of the cutting. The results show the viability of the proposed model, such that the Kienzle turning constants can be used for the prediction of the end milling forces. The use of these constants facilitates the simulation processes due to the data bank existent and the easiness of the turning tests for new workpiece materials or cutting tools.

6. Dynamic analysis using finite elements

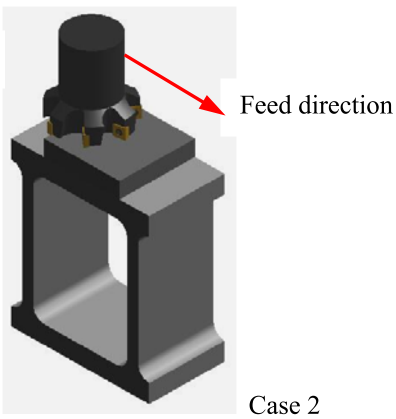
The use of numerical methods for the solution of engineering problems are widely used in several areas to assist in the understanding of physical phenomena, in order to get an approximation of results or to identify and evaluate the most influent parameters in the problem context (Cook, 1988). With the evolution of computers and programs, this tool, when calibrated with experimental data, can be applied successfully in the machining, especially in milling, which is always accompanied by mechanical vibrations.

In this work, it was made a dynamic analysis for low stiffness workpieces, compared to the tool stiffness, submitted to the end milling fluctuating forces. This restriction means that only the workpiece is modelated by finite elements, with the aim of simulate machining conditions with parameters that lead to smaller vibration amplitude for low stiffness workpiece.

For the end milling analysis in low stiffness parts a base was designed and constructed, with the first natural frequency relatively low in relation to the other vibration modes. This base is constituted by a monolithic aluminum block. Two cases were simulated, one in which the feed direction coincides with the *x* direction, case 1, and the other in which the feed direction coincides with the *y* direction, case 2, Fig. 4.



Case 1



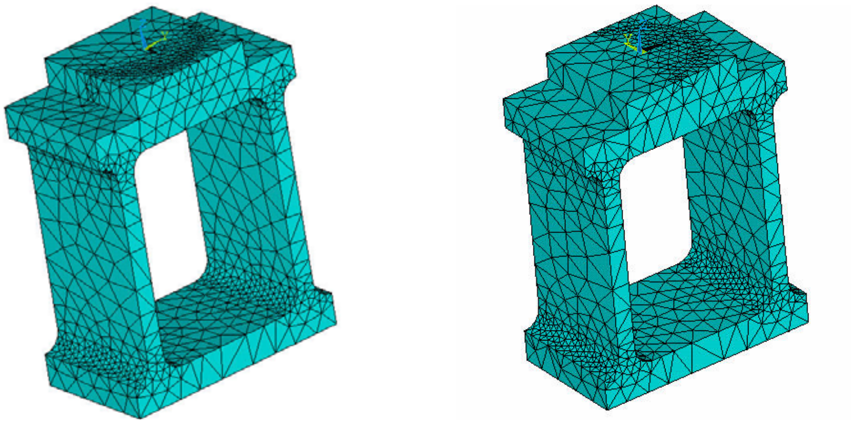
Case 2

Figure 4. Simulated cases.

The finite elements used were the tetrahedral of 4 nodes with linear interpolation functions and bubble function. As boundary conditions, all nodes in the inferior surface are fixed, simulating the setting on the base of the machine-tool.

The loading was applied along an arc, Fig. 5, where the load magnitude was varied with engagement angle. Additionally, several load histories were applied simultaneously in different nodes, simulating a mill with several teeth. These forces change position, direction and magnitude in each time increment. The program was parameterized, so it allows the change of variables without the necessity of a new programming. A parametric program was built, allowing automatic data generation. The simulation used 7 teeth, the same number of mill inserts used in the tests

The method used for the numerical simulation was the transient dynamic analysis, with the method of complete direct integration and the Newmark method, incorporated in the software ANSYS.



Case 1 Case 2

Figure 5. Workpiece modeled by finite elements.

6.1. Speed variation

One of the analyses performed, showed in this work, is the mill rotation variation with the objective of identify the piece deflection for each speed Fig. 6. The cutting parameters for these analyses were cutting depth (a_p) of 1 mm and feed per tooth (f_z) of 0.1 mm. This kind of analyses allows the identification of more suitable rotation bands to the reduction of vibrations amplitudes in the flexible parts end milling.

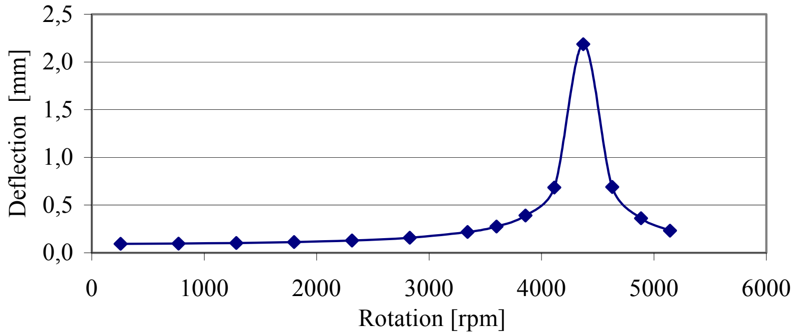


Figure 6. Piece deflection varying the mill rotation.

The workpiece deflection for the cutting conditions simulated is about 0.08 mm for rotations under 3000 rpm. The maximum amplitude of vibrations happens in 4370 rpm, with tooth passing frequency of 510 Hz, which coincides with the natural frequency of the workpiece.

Through the realization of experimental analysis, Polli et al (2003) confirms that the condition in which the tooth passing frequency approaches the natural system frequency is favorable to prevent the self-excited vibrations, although the forced vibrations are maximized. In this work it is considered that the cutting depth used do not exceed the stability limits for the self-excited vibrations appearance. Therefore, the analysis of forced vibrations in this work does not consider regenerative vibrations.

6.2. Cutting depth and feed variation

In the workpiece deflection analysis, the variation of parameters as cutting depth (a_p) and feed per tooth (f_z) permit to evaluate the influence of these parameters in the vibration amplitude of low stiffness workpieces. The results of the simulations for the cases 1 and 2 are shown in the figure 7, varying the feed per tooth and keeping the cutting speed constant at 140 m/min, with the cutting depth constant at 1mm. As expected, the piece deflection increases with the cutting depth increase. In case 1, where the rigidity is lower in the maximum cutting force direction, the piece deflection is higher than in case 2, where the rigidity is lower in the maximum feed force direction.

Another analysis made was the cutting depth varying, keeping the cutting speed constant at 140 m/min and the feed per tooth at 0,1mm. The maximum deflection increased with the cutting depth increase, and this is more significant than when the feed is increased. These results in milling show clearly that the cutting depth is the most important parameter in amplitude vibration for low stiffness workpieces. Consequently, the increase of this parameter can lead to high vibrations values.

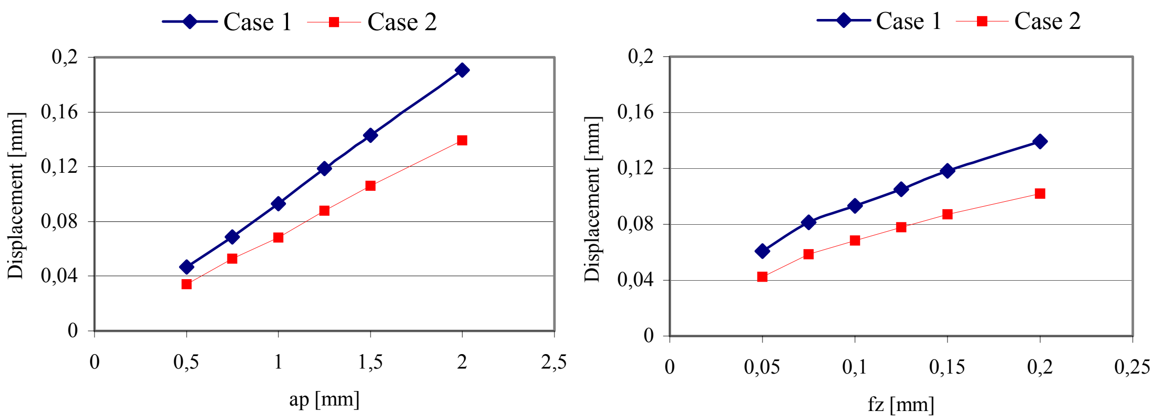
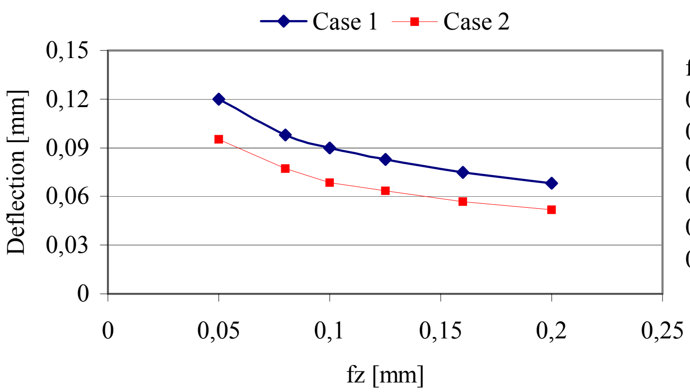


Figure 7. Deflection variation keeping a_p and f_z constant.

The results of this simulation are satisfactory, once that the forces increase linearly with the cutting depth a_p increment, while the feed increment causes a slower increase of the forces (König, 1997). It can be explained by the Kienzle equation, where the theoretical thickness chip exponent (1-*mc*) is always lower than 1 and the force is directly proportional to the theoretical chip width. The increase of the theoretical chip thickness h results in the decrease of the chip upsetting degree, consequently, in less specific energy necessary to remove it, what explains the simulated results behavior

6.3. Variation of de a_p e f_z with constant machining rate

Anothers simulations were realized varying the machining parameter a_p e keeping constant the chip removal rate with the objective to identify the combinations of parameters that take the lesser vibrations amplitude without compromising the productivity. Figure 8 shows the results of this simulation, where were obtained the lesser vibration amplitude for higher feed values



Parameters

fz (mm)	ap(mm)
0,05	2,0
0,08	1,25
0,10	1,0
0,125	0,8
0,16	0,625
0,20	0,5

Figure 8. Deflection variation with constant machining rate.

The maximum vibration amplitude tolerable in a machining process depends on the application. In roughing operations, what determines this level is mainly the vibration effect on the tool life. As a result of the simulations, a cutting strategy to reduce the vibration amplitude is machining with the maximum feed possible, since the secondary times of this strategy and the tool life are in acceptable levels.

7. Conclusions

Experimental results comparing the forces in the turning and milling processes for the same machining conditions show that the forces are similar in both processes, which lead to a more detailed investigation of the models for the forces in the processes.

The results of the proposed model for the forces estimation is compared with experimentally measured forces in different cutting conditions. It is observed that the proposed model could successfully reproduce the cutting forces in the end milling process, allowing a trustworthy estimate of the milling forces using the Kienzle constants. This, in turn, allows the use of databases available for turning constants, without the need of performing exhaustive milling tests.

When the tooth passing frequency approaches the natural system frequency the vibrations level increase. In addition as a result of the simulations it was possible to identify which speed and feed direction result in lower vibrations levels. This information allows using paths tool that present better results without modifying the productivity of the process.

In roughing operations the most important parameter defining the forces, and consequently amplitude of vibrations, is the cutting depth. This can is verified in finite element simulations as well as in experimental works. A manner to decrease the vibrations levels is through the feed maximization and reduction of the cutting depth.

The use of finite element method showed satisfactory results in the simulation of the milling process, substituting in part the experimental procedure. The finite elements analysis does not require interference in the productive process and, with a simple parameter change, the system response can be estimated without the necessity of physical construction of test pieces. In addition, this model can be applied to any low stiffness workpiece that shows the potential for future studies and applications.

8. References

Altintas Y.; Spence A. “A Solid Modeller Based Milling Process Simulation and Planning System”, Journal of Engineering for Industry, [S.l.], v. 116, n. 61, 1994.

Cook, R. D. ; Malkus D. S.; Plesha, M. E. “Concepts and applications of Finite Elements Analysis”. Wiscosin: University of Wisconsin, 1988.

Drozda, T. J.; Wick, C. “Tool and Manufacturing Engineers Handbook: Machining.” 4. ed. Deaborn, Michigan: Society of Manufacturing Engireers, 1982.

Ehmann, K. F.; Devor, R. E. “Machinning Process Modeling: a Review. Journal of Manufacture Science and Engineering”, [S.l.], v. 119, p. 655-663, 1997.

König, W.; Klocke, F. “Fertigungsverfahren: Drehen, Fräsen, Böhren”. 4. ed. Düsseldorf: VDI-Verlag, 1997.

Luttervelt, C. A. et al. Present situation and future trends in modelling of machining operations, Annals of the CIRP, [S.l.], v. 47, n. 2, 1998.

Mackerle, J. “Finite-element analysis and simulation of machining: a bibliography (1976-1996)”, Journal of Material Processing Technology, Linköping, Suécia, v. 86, p. 17-44,1999.

Polli, M. L.; Weingaertner, W. L.; Schroeter, R.B., Gomes, J. O. “Machining Parameters Selection to Avoid Charter in High Speed Milling”. Annals of 17th International Congress of Mechanical Engineering. São Paulo, 2003.

9. Responsibility notice

The authors are the only responsible for the printed material included in this paper.