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Milling machining of CFRPs: a model to simulate and forecast the cutting forces intime domain

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Abstract—The machining of fibre reinforced composites is an important activity for optimal application of these advanced materials into engineering fields. During machining, any excessive cutting force has to be avoided in order to prevent any product reject in the last stages of production cycle. Therefore, the ability to predict the cutting forces is essential to select the process parameters necessary for an optimal machining. The aim of this paper is to analyse the cutting forces in CFRPmilling; in particular, this work highlights the reliability and potential of a numerical model as a forecasting tool for the real signal of the cutting force componentsof a multi-insert tool, obtained starting from the experimental signal of a tool with a single cutting insert. The signal components of the cutting force, as a function of the number of inserts, has been numerically analysed and then it has been validated by experimental tests.

Keyword- CRFP, milling, cutting force, tool insert, time domain.

I. INTRODUCTION

Composite materials milling is a rather complex task owing to material heterogeneity and to some problems, such as surface delamination appearing during the machining process, associated with material characteristics and cutting parameters. Milling is the machining operation most frequently used in manufacturing of fibre-reinforced plastics parts as a corrective operation to produce well defined and high quality surfaces that require the removal of excess material to control tolerances [1]. The machinability of fibre-reinforced plastics is strongly influenced by the type of fibre embedded in the composite and by its properties. Mechanical and thermal properties have an extremely importance on fibre reinforced plastic (FRP) machining. The kind of fibre used in the composites has a great influence in the selection of cutting tools (cutting edge, material and geometry) and machining parameters. It is fundamental to ensure that the tool selected is suitable for the material. The knowledge of cutting mechanisms is necessary to optimize the cutting mechanics and machinability in milling [1,2]. Composite materials, such as carbon fibre reinforced plastic (CFRP), made of carbon fibres used for reinforcing resin matrices, such as epoxy, are characterised by excellent properties as lightweight, high strength and high stiffness. These properties make them especially attractive for aerospace applications [2]. Surface roughness is a parameter that has a great influence on dimensional precision, on mechanical performance and on production costs. For these reasons, research developments have been carried out on purpose of optimising the cutting conditions to reach a specific surface roughness [3,4]. The required quality of the machined surface depends on the mechanisms of material removal and on the kinetics of machining processes affecting the performance of the cutting tools [5]. The works of a number of authors [6–12], reporting on milling of FRP, show that the type and orientation of the fibres, the cutting parameters and the tool geometry have an essential influence on the machinability. Everstine and Rogers [6] presented the first theoretical work on the machining of FRPs in 1971, since then the research carried out in this area has been based on experimental investigations. Koplev et al. [7], Kaneeda [8] and Puw and Hocheng [9] established that the principal cutting mechanisms are strongly correlated to fibre arrangement and tool geometry. Santhanakrishman et al. [10] and Ramulu et al. [11] carried out a study on machining of polymeric composites and they concluded that an increasing of the cutting speed leads to a better surface finish. Hocheng et al. [12] studied the effect of the fibre orientation on the cut quality, cutting forces and tool wear on the machinability. W. Hintze [13] investigated the case of delamination of the top layers during CFRP tape milling and he showed that delamination depends highly on fibre orientation and tool sharpness.D. Liu et al. [14] summarized an up-to-date progress in mechanical drilling of composite laminates reported in the literature; they covered drilling operations (including conventional drilling, grinding drilling, vibration-assisted twist drilling, and high speed drilling), drill bit geometry and materials, drilling-induced delamination and its suppressing approaches, thrust force and tool wear.

Enemuoh et al. [15] realized that with the application of the Taguchi technique and a multi-objective optimization criterion, it is possible to achieve cutting parameters that allow the absence of damage in FRP drilling. Paulo Davim et al. [16] studied the cutting parameters (cutting velocity and feed rate) under specific cutting pressure, thrust force, damage and surface roughness in drilling Glass Fibre Reinforced Plastics (GFRPs). A plan of experiments, based on the Taguchi technique, was established considering drilling with prefixed cutting parameters in a hand lay-up GFRP material. Sheikh-Ahmad et al. [17] studied the comprehensive model for orthogonal milling of unidirectional composites at various fibre orientations. Devi Kalla [18] studied the mechanistic modelling techniques for simulating CFRP cutting with a helical end mill. A methodology was developed to predict the cutting forces by transforming specific cutting energies from orthogonal cutting to oblique cutting. T. Yashiro et al. [19] confirmed that the measurement of the cutting temperature is important when dealing with CFRP: temperatures higher than the glass-transition temperature of the matrix resin are not favourable as they damage the laminate. In J. Liu et al. [20] a heat transfer model is developed to investigate the temperature distribution of CFRP workpiece in helical milling process. The relationship between cutting speed and temperature of processing is pointed out. In summary, it can be noticed that the works carried out on the machinability of FRP are basically related on the wear of cutting tools and on the quality of the surfaces, as a function of the cutting conditions, of the fibres distribution and of theinclination angle of fibres in the polymeric matrix.The purpose of this work has been to analyse the cutting forces of multi-insert tools in milling of CFRPs through the use of a simple numerical model. In particular, the aim has been to highlight the reliability and potential of a numerical model as a forecasting tool forthe real signal of the cutting force componentsof a multi-insert tool, obtained starting from the experimental signal of a tool with a single insert, using the superposition principle.In particular, the signal acquired in the case of a milling with a single insert wasanalysed experimentally and the signal relating to a multi-insert milling (with 2, 4, 6, 8 inserts)wasnumerically reconstructed from it. The simulated signals werecompared with those experimentally obtained to evaluate the reliability of the numericalmodel.A conclusion of the work, the force signals werederivedas a function of different process parameters varying the number of inserts,by means of the numerical model.

II. MATERIAL AND METHODS

A CNC milling machine was used to carry out the experiments, see Fig. 1, whose characteristics are a 15 kW spindle power and a maximum spindle speed of 15000 rpm. An end mill suitablefor CFRP machining wasmounted on the machine spindle. This mill had a diameter of40 mm and itpresented the possibility of mounting up to 8 inserts (the single insert was an APMT1135PDER-H1 UTi20T of MITSUBISHI), see Fig. 2. Autoclave process was considered to produce the composite material used for the experimental tests carried out in this work. The material was made of epoxy matrix reinforced with 50% of carbon fibre and presented a cross-plyfibre orientation. The laminate had a thickness of 13 mm, that was reached laying down 40 alternating plies of prepreg, and thetests were performed withoutcooling fluid.Themachined surfacecan be noticedin Fig. 3: the first machiningpass "a" wasexecutedin order to allow the correct tool access for subsequentmachining pass “b,c andd”.A single parameter set, representative of general experimental condition, withan axial cutting depth of 1 mm, a feed for tooth of 0.022mm and acutting speed of 100 m/min, was used to validate the numerical model.

To reproduce the range of process parameter commonly used in industrial field,two cutting speed levels,five mill typologies (with 1, 2, 4, 6 and 8 inserts) and four axial cutting depth values were considered, as visible inFig.4. As reported in the plan of experiments shown in Tab. 1, 120 experiment runs were carried out, sinceeach parameter setwasconducted for three times. To lowerthe consequence of any systematic error, a random sequence was implemented to carry out the experimental runs.A Kistler piezoelectric platform dynamometer (Type 9257 BA), visible in Fig. 5, was used to value the cutting force F_x,$F_y$and F_z.For choosing the acquisition parameters leading to the whole force signal data with the minimum time waste,several time intervals and frequencies were considered to sample the signals through the dynamometer. The X, Y and Z signalswere periodic and 16384 acquisition points were considered adequate to collect the whole signal data. Since the output of the dynamometer was collectedby an A/D converter and sampled at 10 kHz by a PC,each acquisitioncontaineda time signal ofabout1.6384s [21-24].

TABLE I. Experimental plan

Factors	Levels [#]	Value
p_a, Axial cutting depth[mm]	4	1.0 – 1.5 – 2.0 – 3.0
p_r, Radial cutting depth [mm]	1	25
V_t, Cutting speed [m/min]	2	100–300
f_t, Feed per tooth [mm]	1	0.022
Mill inserts [#]	5	1 – 2 – 4 – 6 – 8

Replications	3
Total cuts	120

Figure 1. CNC milling machine

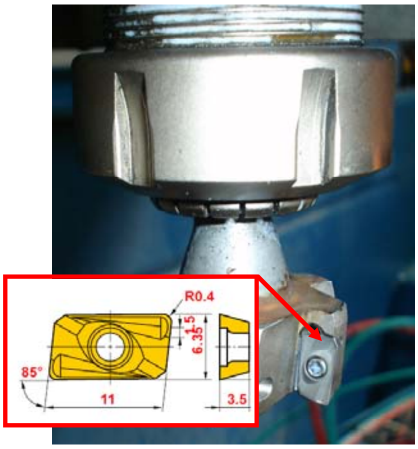

Figure 2. Milling Tool with one insert

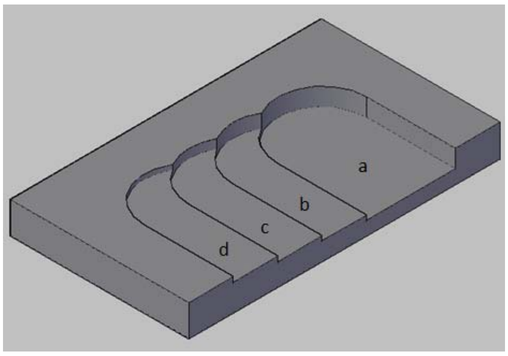

Figure 3. Sample after milling machining

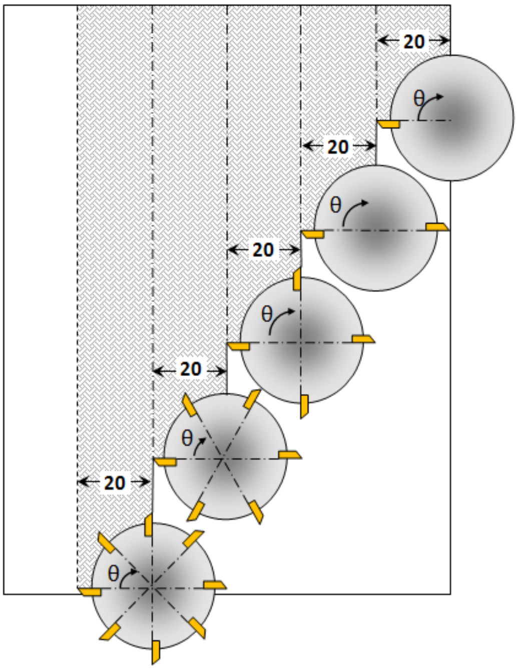

Figure 4. Typologies of millswith 1,2,4,6 and 8 inserts

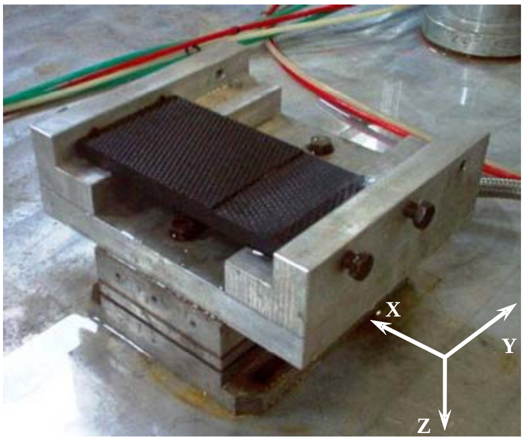

Figure 5. Gripping system/dynamometer/sample

III. Results and discussion: analysis of forces in time domain

The components F_x, F_y and F_z of force signal related to a mill with one insert were acquired by the dynamometer. Subsequently the portions corresponding to a contact angle of 0° to 90° were considered for 4 tool round and the average value was calculated. In Fig. 6 the acquired signal for one revolution of the tool is shown while in Fig. 7 there is the acquired signal for 4 revolutions of the tool.The signal relative to a mill with two insertwas simulatedby the experimental signal. This signal, using the superposition principle, was obtained by summing the contribution of each single insert and dephasing it of 180°, as shown in Fig. 8-10.The same methodology

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was used to simulate the signal relative to a tool with 4,6 and 8 inserts dephasing the signals of 90°, 60° and 45°respectively; the obtained simulated signalsare shown in Fig. 11-19. In these two last cases, unlike those with 2 and 4 inserts, during the process there are more inserts simultaneously in contact with consequent overlapping of the signals; therefore, it can be noted an increase of both the maximum and the minimum value of the three components of the cutting force.For the numerical models validation an experimental activity was carried out and the results regarding F_x, F_y and F_z components of cutting force were compared with simulated trends, and all the results are reported in Fig. 8-19.

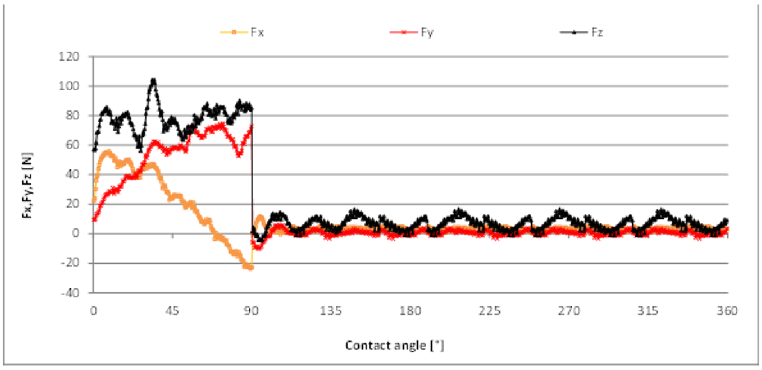

Figure 6. Time domain signal monitored in X, Y and Z direction for one tool revolution

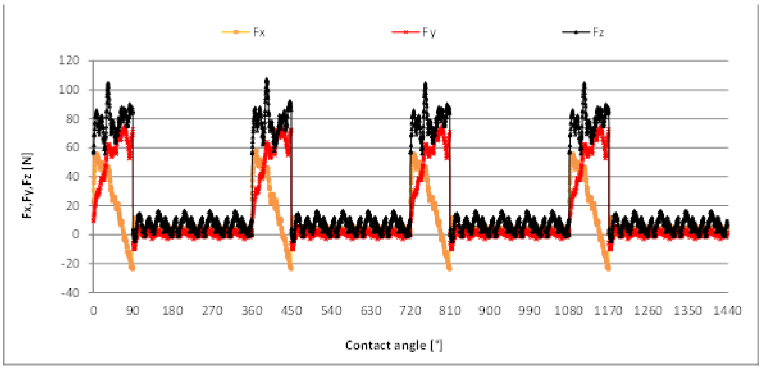

Figure 7. Time domain signal monitored in X, Y and Z direction for four tool revolutions

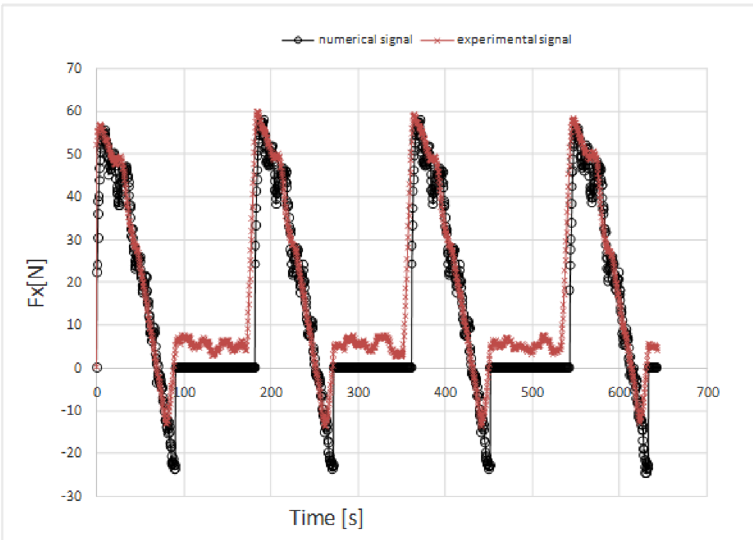

Figure 8. Example of time domain signal monitored in X direction for a mill with two inserts

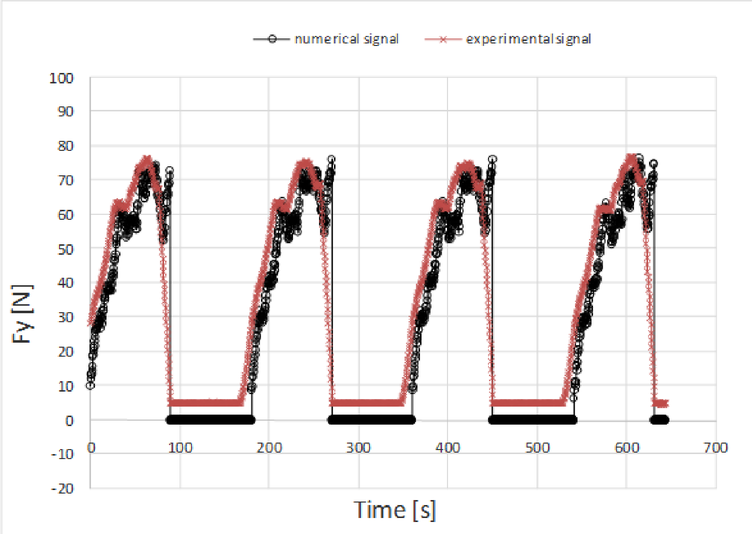

Figure 9. Example of time domain signal monitored in Y direction for a mill with two inserts

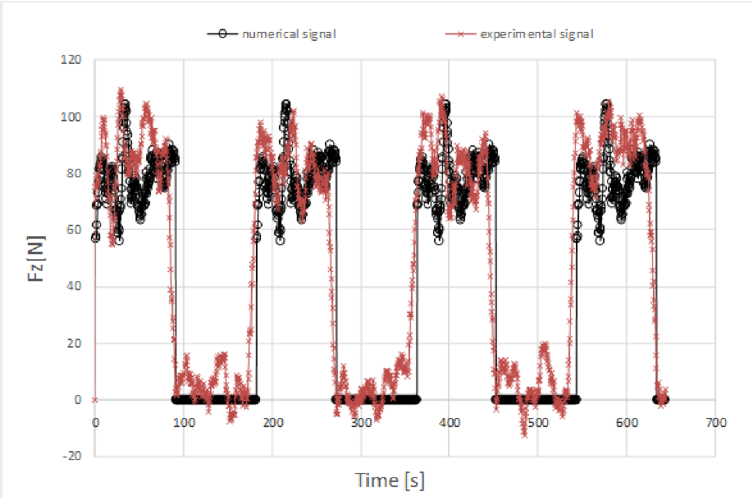

Figure 10. Example of time domain signal monitored in Z direction for a mill with two inserts

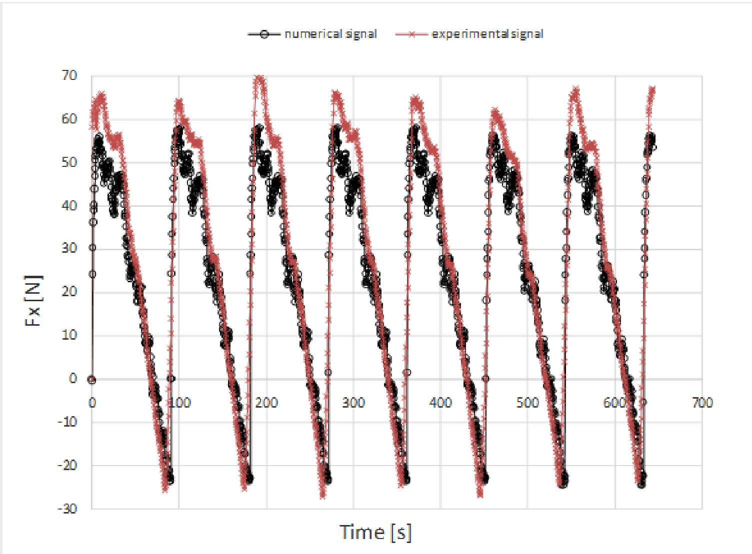

Figure 11. Example of time domain signal monitored in X direction for a mill with four inserts

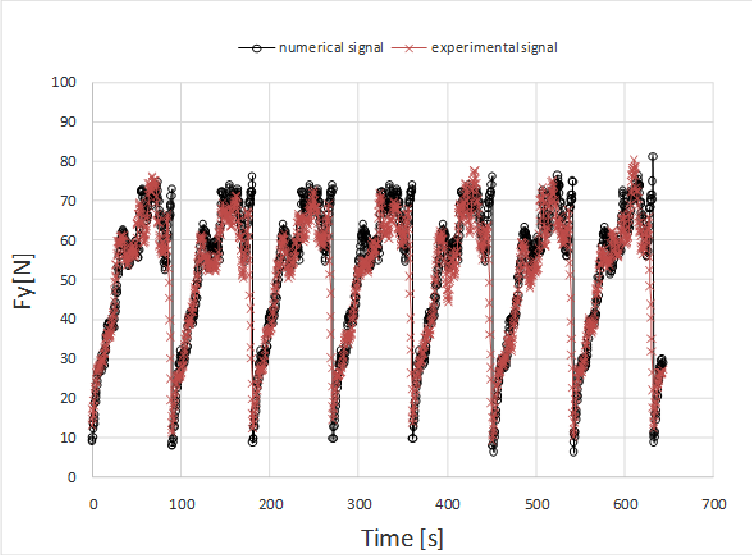

Figure 12. Example of time domain signal monitored in Y direction for a mill with four inserts

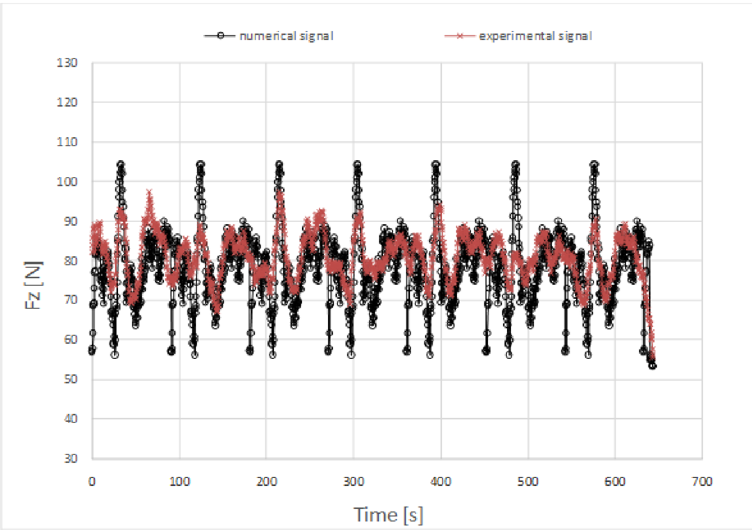

Figure 13. Example of time domain signal monitored in Z direction for a mill with four inserts

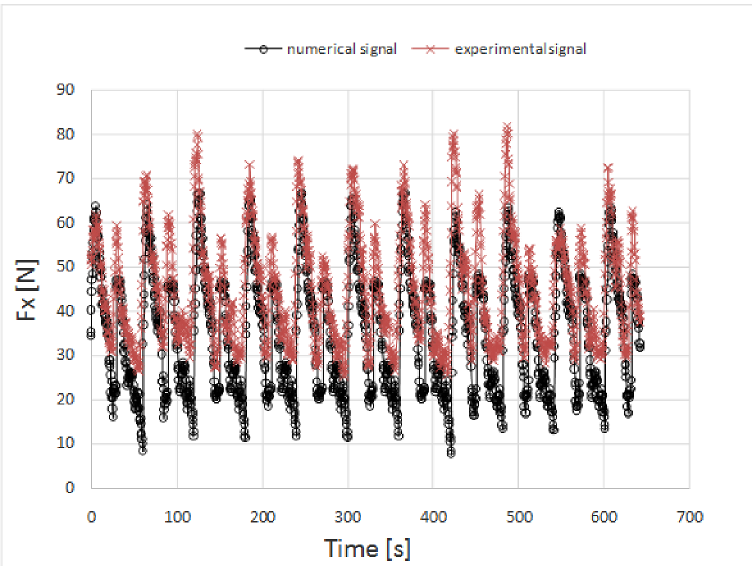

Figure 14. Example of time domain signal monitored in X direction for a mill with six inserts

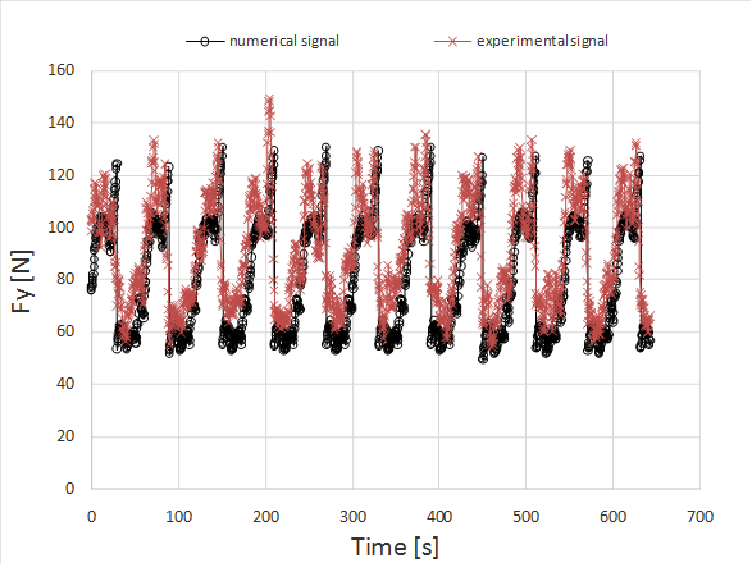

Figure 15. Example of time domain signal monitored in Y direction for a mill with six inserts

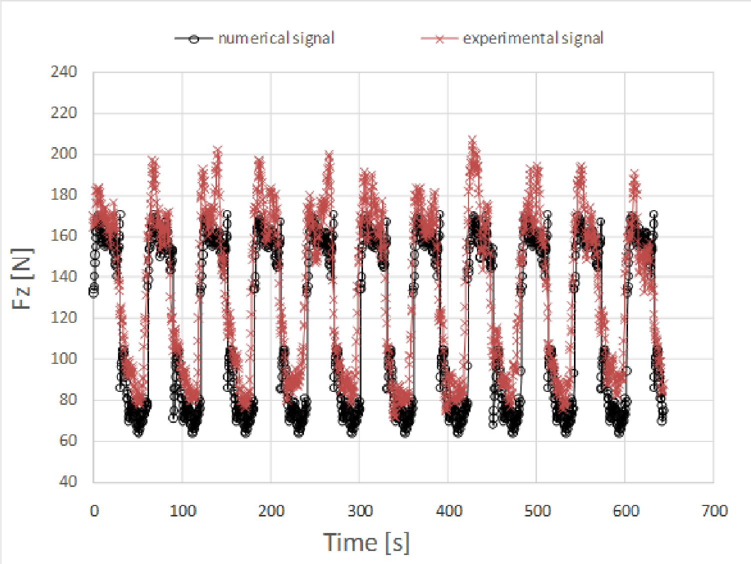

Figure 16. Example of time domain signal monitored in Z direction for a mill with six inserts

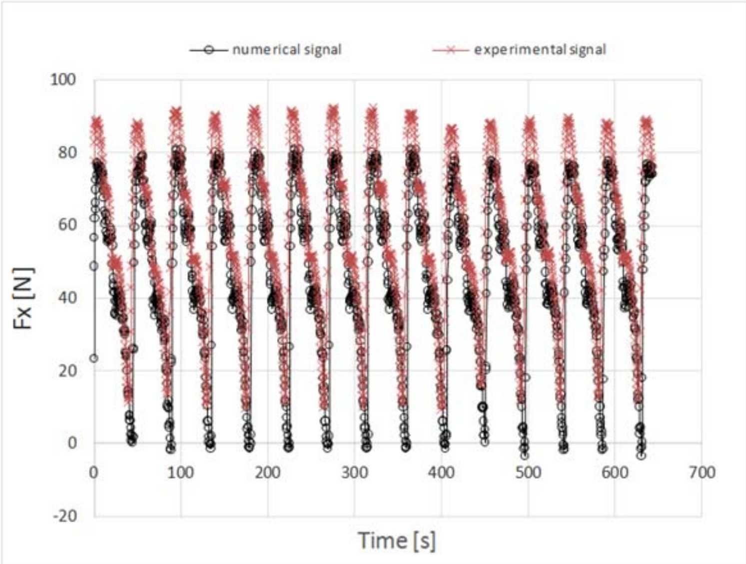

Figure 17. Example of time domain signal monitored in X direction for a mill with eight inserts

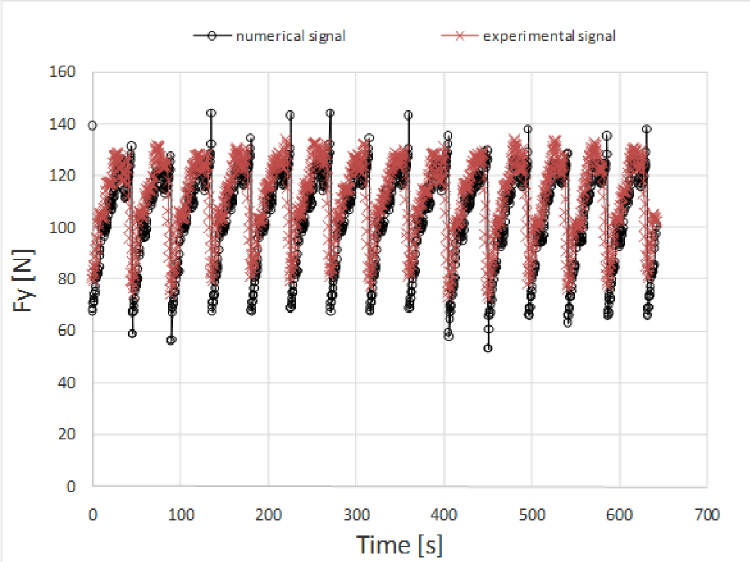

Figure 18. Example of time domain signal monitored in Y direction for a mill with eight inserts

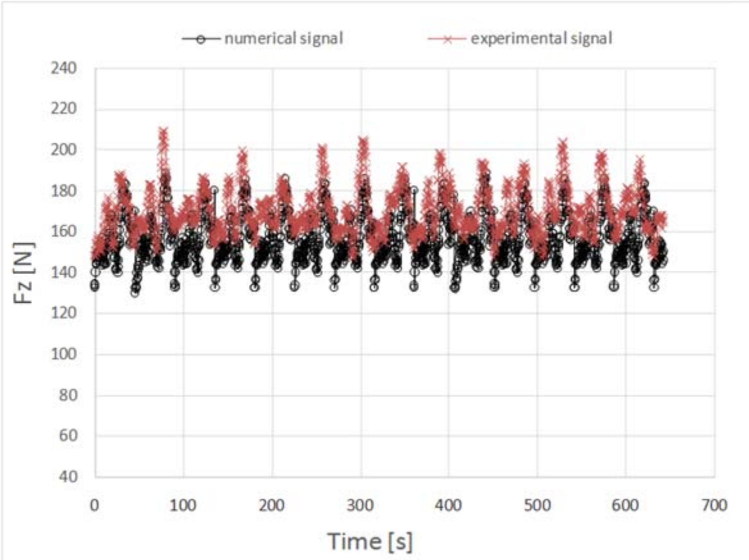

Figure 19. Example of time domain signal monitored in Z direction for a mill with eight inserts

For all graphs related to the tools with 2, 4, 6 and 8 inserts, a good match of both the signals wasobserved in correspondence of the minimum and maximum values. In particular, the simulated signals and the experimental data diverge more than 20% in sections where the tool is in contact with the material. The most evident differences can be noted in the sections where the inserts are not in contact, in which the experimental signal presents not null values due to background noise present in the acquisition phase.Once the numerical model had been validated, it was used to simulate the trend of the forces signal with the change of the number of cutting edges and of the process parameters shown in Table 1.As regards the influence of process parameters on the components of the cutting force, the average value and the maximum value were calculated, for each acquired signal, as a function of axial cutting depth Paand of the number of tool inserts, as reported in Fig. 20-27. Fig. 20 shows the average value of the F_x component of the cutting force as a function of the axial cutting depth and of the number of inserts for a cutting speed of 100 m/min. As it can be seen from the graph, the mean value of the F_x component of the cutting force increases with the axial cutting depth and with the number of inserts present on the tool.This is due to an increase of material amount removed by the tool per unit time. In particular, as it can be seen from the graph, the mean value of the F_x component of the cutting force changes from a minimum value of about 10N, obtained with an axial cutting depth of 1 mm and a tool with one insert, to a maximum value of about 60N,obtained with an axial depth of 3 mm and a tool with 8 inserts.Fig. 21 shows the maximum value of F_x component of the cutting force as a function of axial cutting depth and of the number of inserts for a cutting speed of 100 m/min.In this case, the graph shows that the maximum value of F_x component of the cutting force increases with axial cutting depth, while it does not change with a number of inserts up to 4, but increase sharply with 6 and 8inserts.This becauseover 4 inserts more teeth are simultaneously in contact with the material.In fact, as it can be seen from the figure, the maximum value of the F_x component of the cutting force changes from a minimum value of about 60 N, for an axial cutting depth of 1 mm and a tool with one insert, to a maximum value of about 90N,for an axial depth of 3 mm and a tool 8 with inserts.Similar considerations were obtained for the F_y and F_z components, see Fig. 22-25. These simulations were extended also to machining operations with a cutting speed of 300 m/min; from the obtained results, it was found that with such a speed all three components of the cutting force are reduced in comparison with the condition with a cutting speed of 100 m/min. This is due to an increase in cutting temperature, which facilitates the machining; this phenomenon occurs with increasing cutting speed and it causes a reduction of the cutting forces.As an example,in Fig. 26 and 27 there are the graphs of the F_z component as a function of axial cutting depth and of the number of inserts respectively, for a cutting speed of 300 m/min.

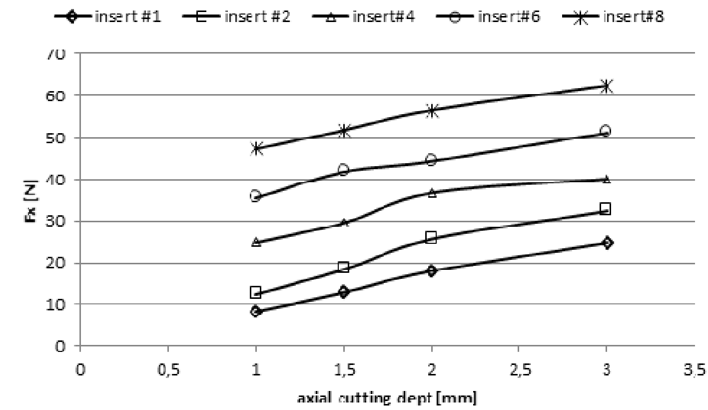

Figure 20. Average Fx vs. Pa with the change of the number of inserts: Feed per tooth “ft” 0.022 mm; Vt 100 m/min

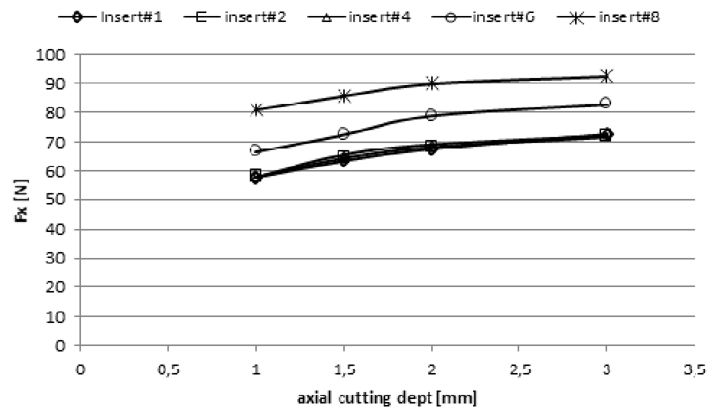

Figure 21. Max Fx vs. Pa with the change of the number of inserts: Feed per tooth “ft” 0.022 mm; Vt 100 m/min

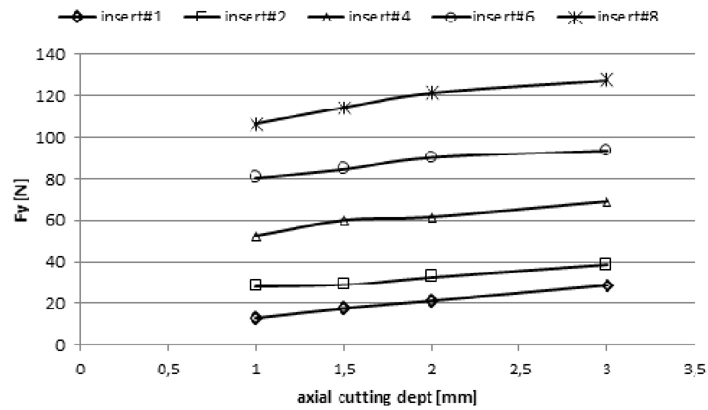

Figure 22. Average Fy vs. Pa with the change of the number of inserts: Feed per tooth “ft” 0.022 mm; Vt 100 m/min

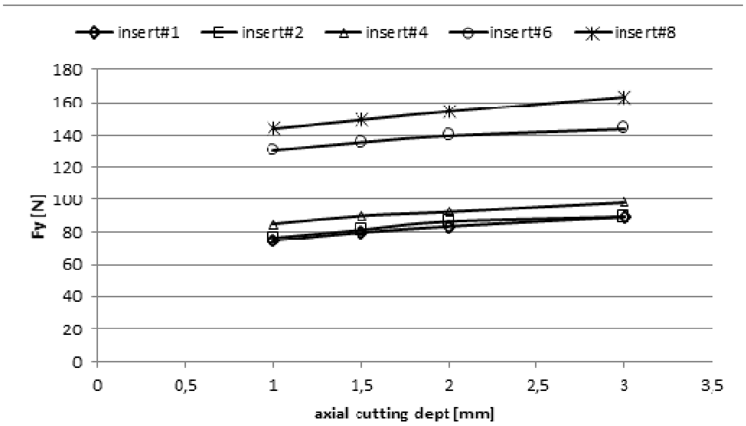

Figure 23. Max Fy vs. Pa with the change of the number of inserts: Feed per tooth "ft" 0.022 mm; Vt 100 m/min

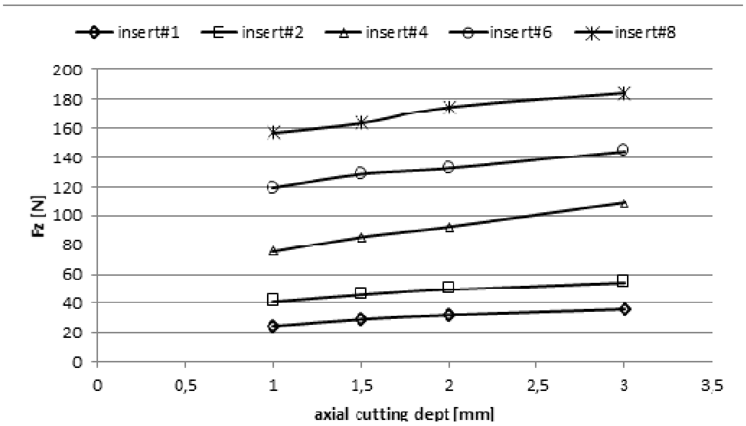

Figure 24. Average Fz vs. Pa with the change of the number of inserts: Feed per tooth "ft" 0.022 mm; Vt 100 m/min

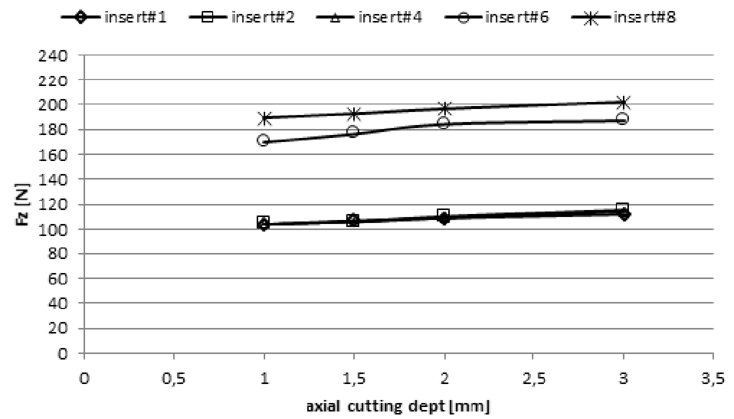

Figure 25. Max Fz vs. Pa with the change of the number of inserts: Feed per tooth "ft" 0.022 mm; Vt 100 m/min

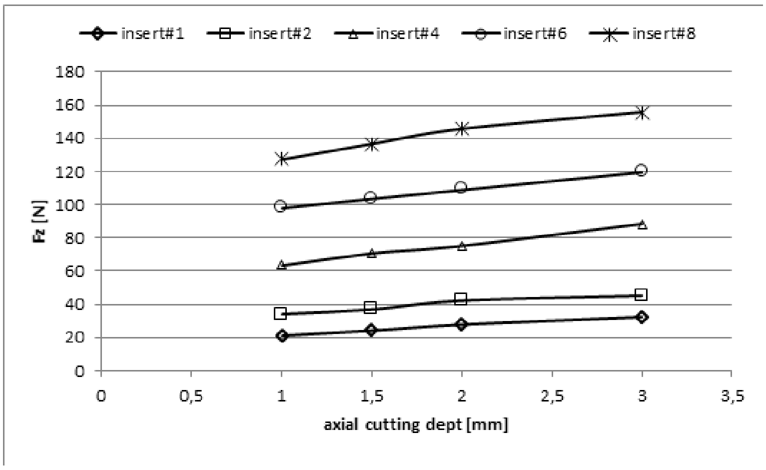

Figure 26. Average Fz vs. Pa with the change of the number of inserts: Feed per tooth “ft” 0.022 mm; Vt 300 m/min

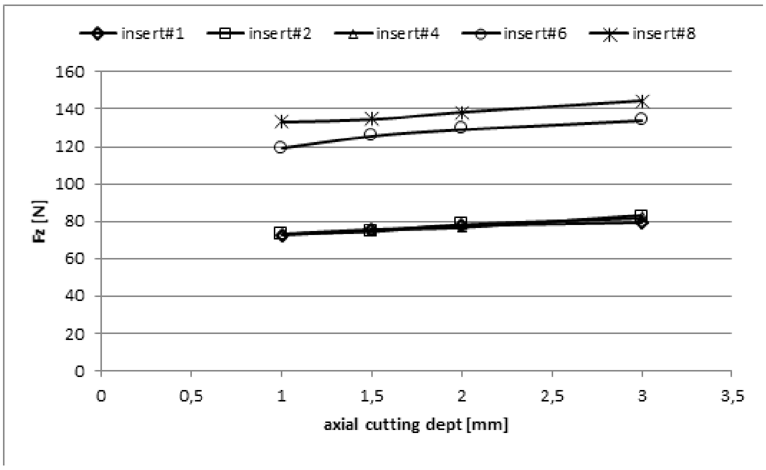

Figure 27. Max Fz vs. Pa with the change of the number of inserts: Feed per tooth “ft” 0.022 mm; Vt 300 m/min

IV. CONCLUSION

This work highlights the reliability and potential of the numerical model as a forecasting tool for the real signal of the cutting force components, obtained starting from the experimental signal of a single cutting insert tool, using the superposition principle.Such information may be taken into account in advance for processing optimization and/or as a function of the design constraints, such as processing time, MRR, machining power, tool wear, surface finish, etc. In particular,in the present work the signal analysis pointed out that a tool with 8cutting insert allows to carry out the processing with greater stability and improved surface finish, moreover there is an increase in MRR of four times compared with the tool with 2 cutting insert.

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