GEOMETRIC 3D MODELING AND DYNAMIC SYSTEM IDENTIFICATION IN PREDICTION OF ENTRY / EXIT METAL CUTTING FORCES

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I. INTRODUCTION

In interrupted cuts the insert enters/leaves the workpiece in fast changing geometry scenarios. The sudden change in engagement conditions leads, for reasons not completely understood yet, to more likely tool and workpiece failure. One obvious factor to consider for such a failure is the regimen of forces at tool entry / exit. Prediction of forces for fully developed (so called *static*) cuts have been developed extensively in the literature [1-5]. For this endeavor, a 2D approximation of the geometry (insert and material) engaged in the cut has been sufficient. Also, a low incidence of machining set-up dynamic modes is registered in the experimental data (forces, accelerations, etc). In contrast, in interrupted cuts, a very complex geometry is present, which can be analyzed neither as a 2D case, nor using the analytic forms of the surfaces involved. Also, sudden changes of engagement conditions excite the dynamics of the machining set-up, therefore modifying the signals of forces, accelerations, etc. To address the geometric complexity, specific types of geometric modeling has been used to characterize cut geometry [8]. This investigation uses several 3D geometric models (B-Rep, Exhaustive Enumeration, Primitive Instancing, etc.) of the insert and workpiece. They.allow an integrated treatment of insert, tool and workpiece geometries, and adequate calculation of contact areas and vector forces. The modification that the experimental data suffers because the dynamic excitation of the set-up is filtered out by using transfer functions that relate the real forces applied in the cutting process with the forces measured by a dynamometer holding the workpiece. The values of static cutting forces predicted using the 3D geometric information along with mechanistic [2] models are validated against experiments and then passed through the transfer functions to find the predicted dynamic forces. The agreement of the experimental and predicted dynamic forces validates the procedure implemented. In what follows, section II discusses the methodology used, section III focuses on aspects of the 3D modeling, section IV describes the results of the dynamic system identification procedure. Section V discusses the results of the static and dynamic force modeling and states the general conclusions of the investigations, suggesting promising research directions.

II. METHODOLOGY

Modeling of interrupted cut forces presents two obstacles: (i) complex geometric conditions, because the special design of many inserts, positioning of the tool holder, and geometry of the workpiece. (ii) distorted dynamometer force readings because the dynamic reaction of the machining set-up. Figure 1 shows the procedure followed to address the modeling: *cut parameters* (feed, depth of cut, tool, etc) are fed to the

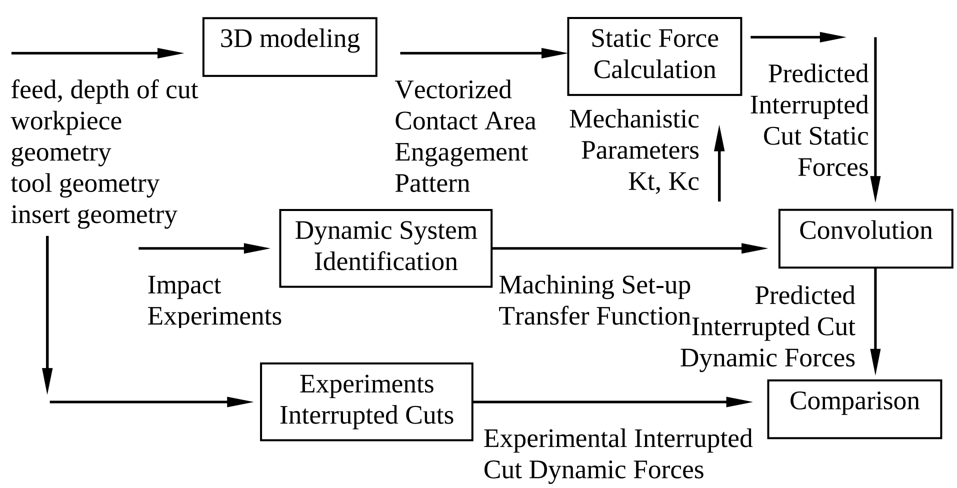

FIG 1. METHODOLOGY OF THE FORCE PREDICTION EXPERIMENTS AND ANALYSIS

3D Modeling module. It calculates the geometric characteristics of the cut, such as the *vectorized contact area, and the patterns of engagement*. These data are then used along with mechanistic parameters of the cutting process to produce the *predicted static forces* (with no vibrations included) that the tool and insert would generate in cutting an interrupted slab of the material chosen for the experiment. Another line of experiments aims to determine the transfer function that relates the dynamometer readings of cutting forces to the actual cutting forces. They differ if the dynamics of the machining set-up (workpiece, dynamometer, fixture) is excited by a sudden entry or exit of the insert. *Impact* (hammer) tests were conducted where the dynamometer reading (output) was correlated to the impact hammer signal (input) to obtain the *machining set-up transfer function*. The *predicted (interruped cut) static forces* were used as input to the machining set-up transfer function, producing the *predicted (interruped cut) dynamic forces*. They are compared with the experimental value, showing a substantial agreement.

III. 3D MODELING

This section discusses the integration of several standard 3D modeling schemes to represent the geometrical aspects of the cut. These aspects, relevant to force prediction are: (i) insert geometry, (ii) tool geometry, (iii) workpiece geometry, (iv) machining parameters. In this investigation several representation schemes (B-Rep, Primitive Instancing and Exhaustive Enumeration) were used and maintained simultaneously. The rational behind this diversity is to allow the expression of machining parameters in the natural jargon, while representing them internally in more efficient forms for the sake of calculation speed.

Insert Representation

Figure 2 shows a detail of an insert shape. Notice that insert characteristics are suitable to be represented using Primitive Instancing techniques. An insert primitive has the form: *insert(shape,length,width,thickness, nose_rad).* An example of such case is an *spgt(rectangular,7,7,3,1.5)*[1] rectangular insert with nose radius of 1.5 mm, and a flat, negative land. These primitives are internally represented building a Boundary Representation (B-Rep) of the insert. The B-Rep presents advantages when repositioning and sweeping of the insert is used to determine the volume of material removed during its pass over the workpiece. In addition to these representations, an Exhaustive Enumeration of the insert regions involved in the cut is used. This representation scheme is an approximation of the insert shape by a collection of small cells. Each cell presents coordinates, volume, and area, that are used to calculate the areas and volumes engaged in the cut and quantitatively identify each elementary area on the insert face. It should be noticed that the usual problem in 3D modeling of translation between schemes is avoided because only the translations Primitive Instancing-to-B-Rep and Primitive Instancing-to-Exhaustive Enumeration are needed.

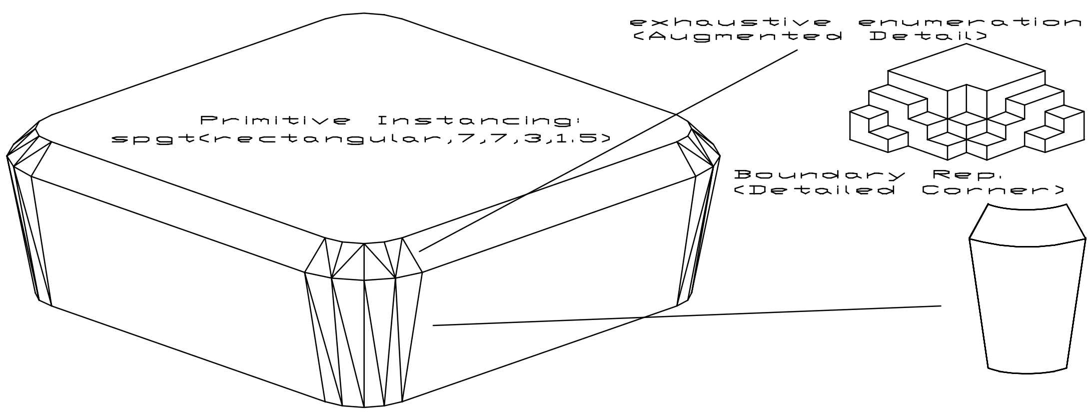

FIGURE 2. PRIMITIVE INSTANCING, B-REP AND EXHAUSTIVE ENUMERATION REPRESENTATIONS OF INSERT INFORMATION.

Machining Parameters and Tool Representation

Regardless of the cutting process used (turning, milling, boring, etc), the insert position is given by angles with respect to the *instantaneous cutting velocity*, $\boldsymbol{v_c}$ (the velocity of the insert relative to the material). Figure 3 shows these angles, called side rake (α_s), back rake (α_b) and lead (α_l) for face milling, where $\boldsymbol{v_c}$ coincides with the tangential velocity of the insert. Besides that, the trajectory of the insert with respect to the workpiece is determined by three additional parameters: depth of cut (**doc**), feed (**f**) and the radius of the trajectory (**Rc** = cutter radius) if the insert is mounted on a rotatory frame (for example a face mill). If the process is turning, the trajectory may be considered as a straight line.

[1]Insert information from Kennametal Co. catalogs.

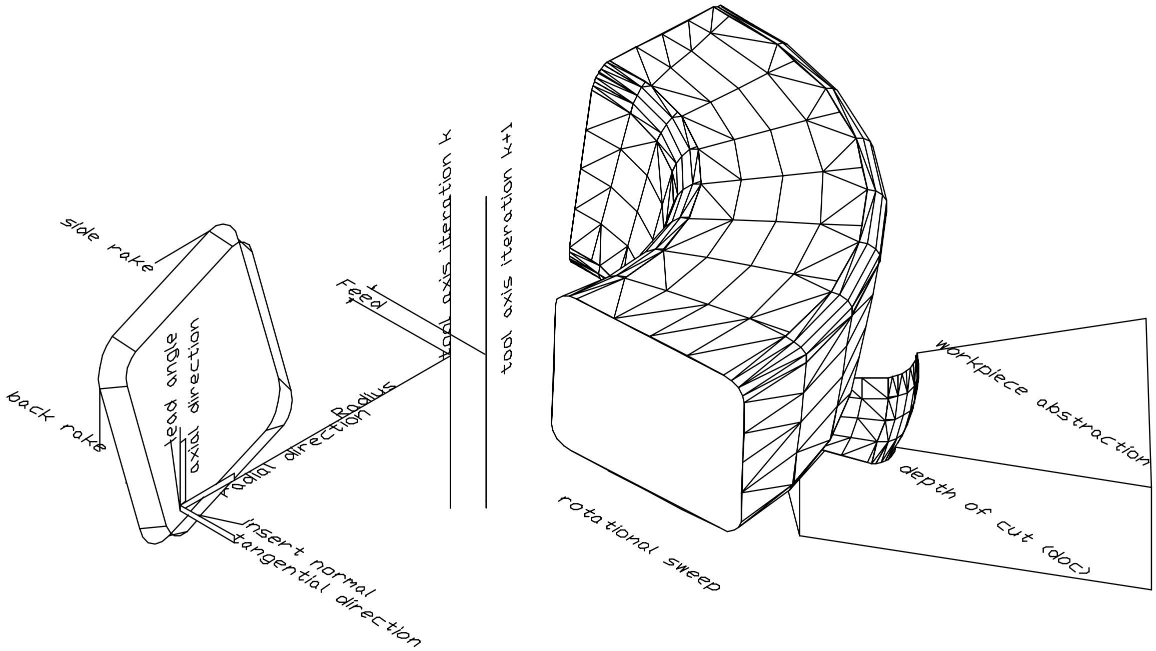

FIGURE 3. EFFECTS OF TOOL AND MACHINING PARAMETERS IN POSITIONING OF THE 3D MODEL OF THE INSERT.

The angles α_s, , α_b and α_l . are used to position the (3D model of the) insert in the desired cutting posture, while the parameters **doc**, **f** and **Rc** are used to transport it along its cutting path, during the cutting process simulation. The revolution of the insert about the toop axis produces the volume that is extracted in each pass of the insert across the workpiece (see Figure 3).

Workpiece Representation

Part of the geometrical complexity of the insert - workpiece interaction lies on arbitrarily shaped workpiece bondaries, and in the form the insert enters / leaves them. In addition, the workpiece to consider for cut simulation purposes is neither the nominal design, nor the original block of raw material. The large amount of computation resources needed to address such a task obligues a simplification in which only the local neighborhood of the workpiece interacting with the insert in each pass of the tool is considered. It is considered sufficient to approach the local workpiece surface by a tangent plane [6], given the very small ratio from characteristic dimensions of the cut (for example feed) to characteristic dimensions of the workpiece features (diameters, wides, lengths, etc). The workpiece, therefore, was approximated as a flat surface wedge, as shown in Figure 3.

Static Forces. Simulation and Experiments

Experiments in face milling where carried out in two series: (i) stable cuts for model calibration, and (ii) interrupted cuts with workpieces designed to maximize abrupt transition at entry or exit. The machining set-up shown in Figure 4 was used in the two series, only differing in the geometry of the workpiece used. For each one of the series 3 different cutters, and 5 different inserts were used, loading the cutter with only one insert at a time (fly cutting tests). It also shows the L-shaped interrupted cut workpiece, designed to produce a maximal transition with tool entry at the surface A. For the sake of brevity, only the data for the test corresponding to the double negative cutter, with regular insert, doc=0.05in, feed=0.01 in, and n=1500rpm are presented in Figures 4 and 5.

The model used to predict the cut and thrust forces is:

$\boldsymbol{F_{cut}} = \boldsymbol{K_c} \,.\, \boldsymbol{A_c} \,.\, \boldsymbol{u_c}$ $\qquad$ $\boldsymbol{F_{thrust}} = \boldsymbol{K_t} \,.\, \boldsymbol{A_c} \,.\, \boldsymbol{u_t}$

with the following meanings:

F_{cut}	Force in the cutting speed direction
F_{thrust}	Force in the chip flow direction
u_c	unit vector in the cut direction
u_t	unit vector in the chip flow direction
A_c	engaged area projected on u_c
$K_c(v_c,t_c)$	force per area coefficient for F_{cut}
$K_t(v_c,t_c)$	force per area coefficient for F_{thrust}
v_c	cutting speed
t_c	average chip thickness

For additional information on this model, the reader may consult [2]. It must be noticed that the application of the mechanistic model assumes calculation of u_c, t_c and A_c,. The F_{cut} and F_{thrust} forces are meaningful in the Insert Coordinate System. Frame transformation is applied to express them in the Cutter Coordinate System (tangential, radial and axial directions) or Dynamometer Coordinate System (feed, tranversal and axial directions, Figure 4). These calculations are provided by the 3D geometry module in an effortless way, since they represent *3D model properties* and frame transformation operations.

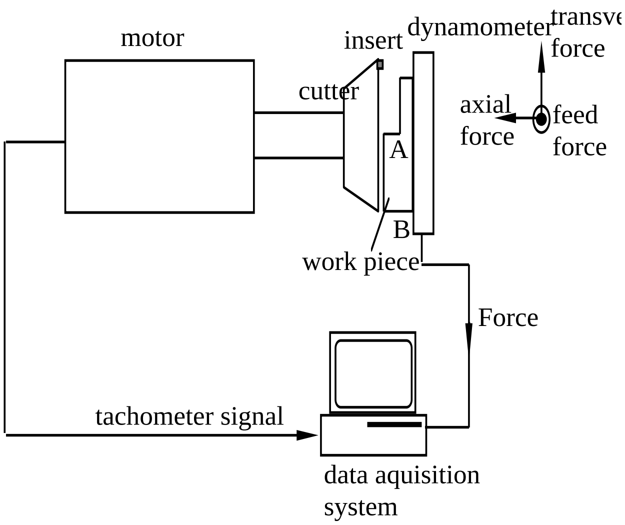

FIGURE 3. EXPERIMENTAL SET UP AND FORCE TERMINOLOGY.

IV. DYNAMICS IDENTIFICATION

Identifying the dynamic characteristics of the machining set-up (workpiece, dynamometer, fixture) allows to quantify the contribution of vibrations to the measured force data. This is specially important in interrupted cuts, which excite high frequency vibrational modes. To identify the transfer function of measured to applied force (for the given set-up used), an impact hammer was used to hit the workpiece in the place in which the tool does when entering an abrupt cut (surface A, Figure 4). The reading of the hammer is considered as the applied force (input), while the dynamomter reading is seen as the read force (output). An ARX() model was fit to these signals in to determine the vibrational modes in the direction (transversal in this case) of the hit. The ARX() model has the form:

$$A(q^{-1}).Fr(t)=B(q^{-1}).Fa(t-n_k) + e(t)$$

with the following meanings:

Fr	reading of Transversal force
Fa	actual Transversal force
q^{-1}	delay operator
$A(q^{-1}),B(q^{-1})$	polynomials in q^{-1}
$e(t)$	white noise
n_k	pure delay between ***Fr*** and ***Fa***

the adequate model was estimated to be ARX(4,3,1) with 4 the degree of ***A()***, 3 the degree of ***B()*** and n_k =1.The model ARX(4,3,1) was applied assuming the ***Fa*** signal as calculated from the mechanistic model applied to interruped geometry; ***Fa*** was calculated by the modeling

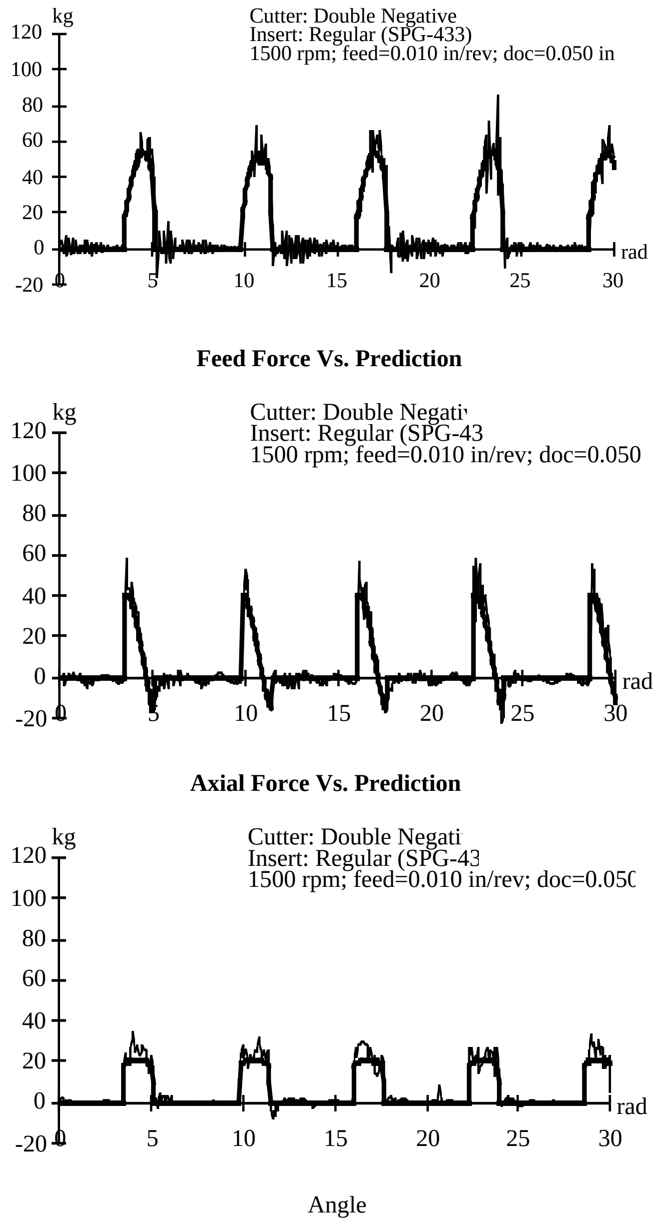

FIGURE 4. STATIC FORCES. EXPERIMENTS AND PREDICTIONS.

whose results for a brick-shaped workpiece appear in Figure 4 but applied to the L-shaped workpiece By using the ARX() model, ***Fr*** (dynamometer reading) was predicted, and compared with the experimental readings.

V. RESULTS AND CONCLUSIONS

Figure 5 shows two signals for the dynamic interrupted cut forces; the experimental one, as collected by the dynamometer, and the other, predicted by the ARX() model application. In the figure, only the traversal force is shown (see Figure 4), presenting very good agreement. Notice that specially in the overshoot of the system reacting to the suddenly applied force.

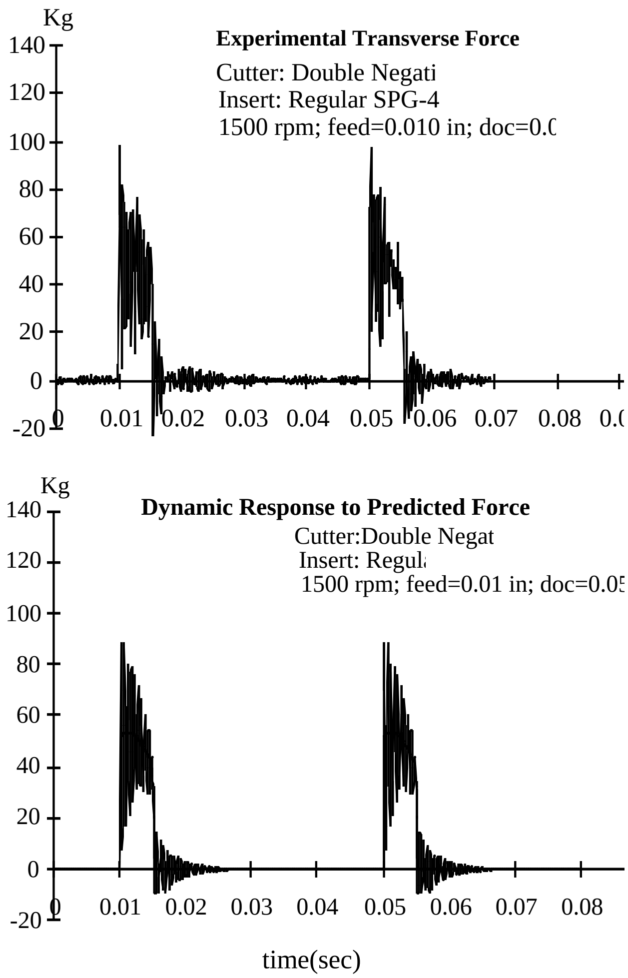

FIGURE 5. DYNAMIC FORCES. EXPERIMENTS AND PREDICTIONS

Mechanistic models created for stable cuts were used to predict cutting forces in interrupted cuts. A special module to implement 3D geometrical calculations was incorporated in order to include the effect of the complex geometry of the interrupted cut.in the part corresponding to area, volume engagement and chip flow direction. To apply the mechanistic models, the 3D geometry module was used also, with the static, continuous cut forces calculated showing a good agreement with the experimental ones. The dynamic measured forces, however, being affected by the dynamic response of the set up, could not be directly compared with the predictions of the mechanistic model. To address this difficulty, the dynamics of the machining set-up was estimated through impact tests, and expressed by an ARX() model fitted to the impact test data. The predicted static interrupted forces, passed through the ARX() model indeed generated the same response as recorded by the dynamometer used in the interrupted cut tests. This result suggests that the nominal static mechanistic model is good enough to predict the force levels at entry / exit. Insert / workpiece failure should be traced to stress distributions rather that simple force levels. In should be stressed that in the tests and simulations run, engaged area calculation for very involved geometries was performed. Such calculation was made possible by the inclusion of the 3D model(s) used, and it would have been unattainable by 2D approximations of the insert, cutter or workpieces. The same can be foreseen if finite element stress analysis is to be carried out in the future.

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