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# A MULTI-LINEAR CUTTING MODEL FOR DRILLING TOOLS

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***Abstract:*** *This study deals with the development of a new cutting model for drilling. This model is based on an experimental approach which links the drill geometric parameters to the mechanical actions of the cutting operation. Literature proposes many works about this subject in which analytical or numerical models answer the problem using behaviour laws, strain and stress shields, temperature. The presented method consists in correlating geometry and behaviour in an experimental way without modelling the real complexity of the phenomenon. Comprehension of the influence of geometric parameters on cutting efforts for any part of the cutting edge is the main purpose of this work. The use of an original single variable cutting edge drill prototype allows fully quantifying forces and torques exerted on any point of the cutting edge.*

***Key words:*** *cutting model, drilling, point geometry, experimental approach.*

## 1. INTRODUCTION

In this article, cutting phenomena are treated, especially forces and torques locally exerted on the cutting edge. Thus, geometrical characteristics (cutting face and cutting edge angles) are taken into account to determine cutting parameters (forces, torques) as shown in Fig. 1.

Usually studies are based on models, which implement hypothesis on behaviour laws, frontier conditions and geometrical data. Then, models are validated and even tuned thanks to experiments [1, 2, 3].

The presented method consists in establishing a multi-linear model from experiments. Entry variables of the model only depend on geometrical characteristics of the tool. Obviously, this approach cannot globally answer the whole mechanical issue (temperature field, heat flux, stress and press field). Yet, a direct relation can be put forward between geometric parameters and mechanical actions for both tool and matter.

For these reasons, the term “behaviour model” is used rather than “mechanical action model”. Thanks to results from the experimental model, forces and torques are determined for any point of the cutting edge. In the same way, the model allows to simulate the global behaviour of the drilling tool.

## 2. MEANS OF EXPERIMENT

### 2.1. Measurement of mechanical actions

The LMP and LGM²B laboratories of Bordeaux 1 University have six component dynamometers at their disposal [4]. These devices are able to measure all of the 3 forces and the 3 torques at any point of the workspace. Therefore, 6 data are available (forces and torques according to each direction) and using the well-known formula of torques transportation, these data can be expressed at any desired point [5].

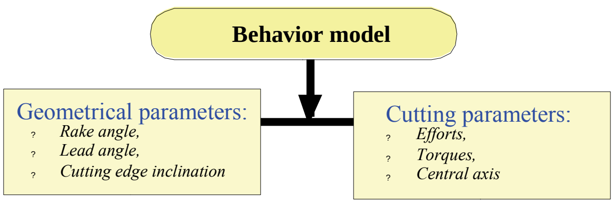



**Fig. 1.** Principle of behaviour model.

### 2.2. Drilling tool prototype

Commonly, a drill is composed of several edges. If the tool is supposed to be perfectly symmetric, mechanical actions are also symmetric; for radial components are annihilated one another. Since flutes work simultaneously, it is not possible to identify the contribution of a single flute (edge) to the global cutting efforts.

The behaviour analysis must be carried out using a single flute drill whose edge position, inclination and orientation are adjustable. The chosen solution is presented in Fig. 2. The cutting edge is made of a thin cobalt tungsten carbide tip clamped on a bowl joint. The orientation is trigged by shims (angles: κ and γ), then position is obtained by translating the whole system (dec). Finally, the assembling is flanged using a crosshead and a screw set.

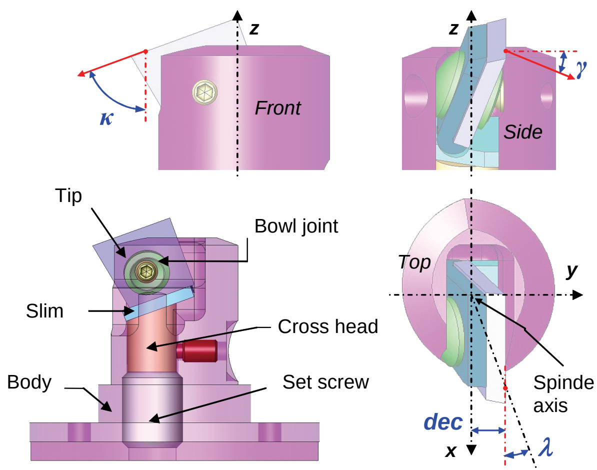



**Fig. 2.** Drilling tool prototype.

The geometrical parameters which vary the prototype geometry are: κ, γ dec, respectively, the lead angle, the rake angle and the translation shift. This shift allows to trig the edge inclination angle: λ. The mathematical relation between them is given by (1). An additional parameter: $r$ (corresponding to distance that separates the current point $M_i$ to the spindle axis) is necessary to divide the cutting edge into 8 segments. Practically, parameters κ, γ can take 5 fixed positions thanks to the shims. The parameter dec can be continuously trigged.

$$\lambda_{(r)} = \arcsin\left(\frac{\text{dec}}{r}\right). \tag{1}$$

### 2.3. Experimental protocol

Experimental method consists in drilling (using the drill prototype) a 20 mm diameter hole in a prepierced hole on a NC lathe (RAMO RTN30, NUM 1060).

The half difference between the final diameter and the prepierced hole diameter give the depth of cut for the test ($a_p$). Varying the prepierced hole diameter changes the current depth of cut: $a_p$ (Fig. 3). As a consequence, the six components dynamometer displays forces and torques corresponding to the current depth of cut and the chosen geometrical parameters (dec, κ and γ).

Diameters of the prepierced holes can sweep a wide range: from 4 to 18 mm by 2 mm steps. This entails that depth of cut vary from 1 to 9 mm by 1 mm steps and radii move from 2.5 to 9.5 mm.

It makes possible to get local mechanical actions expressed by a screw ($T_{ri}$) applied at the current point $M_i$. The cutting edge is segmented by subtracting, for each test, values obtained by the drilling of the nearest upper prepierced diameter (2). Reconstruction of the local mechanical effort is obtained by the superposition principle applied to every segment of the cutting edge.

$$\forall i \in [0,8], \begin{cases} T_{ri} = T_{ap_i} - T_{ap_{i-1}} \\ T_{r0} = T_{ap_0} \\ a_{p_i} = i+1 \\ r_i = \dfrac{20 - a_{p_i}}{2} \end{cases} \tag{2}$$

Step by step, every point ($r_i$ parameter) has its mechanical screw (forces and torques) calculated.

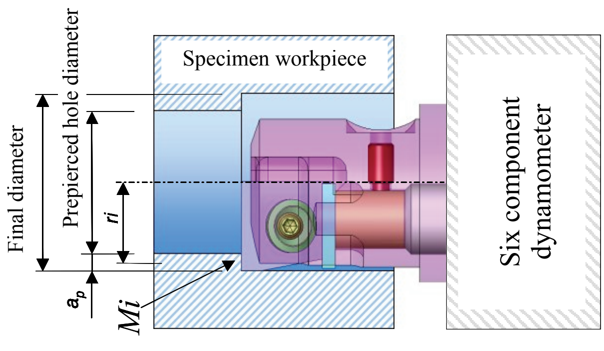



**Fig. 3.** Drill prototype in situ.

*Table 1*

**Census of the parameters and their values**

| States | $r$ (mm) | | States | dec (mm) | κ (°) | γ (°) |
|---|---|---|---|---|---|---|
| E1 | 2.5 | | E1 | 0 | 0 | 0 |
| E2 | 3.5 | | E2 | 0 | 0 | 20 |
| E3 | 4.5 | | E3 | 0 | 20 | 0 |
| E4 | 5.5 | X | E4 | 0 | 20 | 20 |
| E5 | 6.5 | | E5 | 3 | 0 | 0 |
| E6 | 7.5 | | E6 | 3 | 0 | 20 |
| E7 | 8.5 | | E7 | 3 | 20 | 0 |
| E8 | 9.5 | | E8 | 3 | 20 | 20 |
| | | | E9 | 1.5 | 10 | 10 |

### 2.4. Design of experiment

Cutting parameters ($N$, $f$) are fixed; values for the rotation speed and the feedrate are respectively: 1 100 rpm and 0.05 mm/rev. The test only deals with one material: 2024 aluminium.

A reasonable number of values has to be chosen for each parameter in order to limit the size of the design of experiment (DOE). Taking into account that all of the values for the $r$ parameter are kept (*i.e.* 8 values), limitation of the number of values occurs for the following parameters: dec, κ and γ. Literature [6, 7] proposes in a first approach only to consider the frontier values for all parameters, plus a central value; hence a total number of 9 experiments. This DOE is made of 3 parameters, thus the domain is a cube. Frontiers of the domain are the summits of the cube and the central value is the centre of the cube. As a consequence, the entire DOE leads to 72 experiments (Table 1).

## 3. BEHAVIOR MODEL

Using results from the experimental protocol, data are treated in order to set an experimental cutting model.

Treating process can be divided into several steps:

- extraction of the useful part of the signal,
- segmentation of the cutting edge (superposition principle),
- expression of the screw at current point ($M_i$).

Even if the experimental protocol is based on the DOE methodology, it does not completely respect this formalism. Numerous works on the DOE contributes to determine the number of states and their values. The main goal consists in establishing a multi-linear model.

Computer tools make calculation of multi-polynomial models easy. These models reduce the mean-square error, yet they do not match with the type of DOE.

Indeed, number of interpolation points is not sufficient to build an above two degree polynomial.

In addition, angle values in the DOE are always positive (Table 1). At the opposite, rake angle can take negative values (close to the web for real drills). As a consequence, the model has to be extrapolated. Thus, high degree polynomials, quickly diverge when getting out of the domain.

For these reasons, the model uses linear equations (κ, λ, γ):

$$T = \left\{ \begin{array}{c} \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \alpha_{1\lambda} & \alpha_{2\lambda} & \alpha_{3\lambda} \\ \alpha_{1\kappa} & \alpha_{2\kappa} & \alpha_{3\kappa} \\ \alpha_{1\gamma} & \alpha_{2\gamma} & \alpha_{3\gamma} \\ \alpha_{1r} & \alpha_{2r} & \alpha_{3r} \\ \alpha_{1\lambda\kappa} & \alpha_{2\lambda\kappa} & \alpha_{3\lambda\kappa} \\ \alpha_{1\lambda\gamma} & \alpha_{2\lambda\gamma} & \alpha_{3\lambda\gamma} \\ \alpha_{1\lambda r} & \alpha_{2\lambda r} & \alpha_{3\lambda r} \\ \alpha_{1\kappa\gamma} & \alpha_{2\kappa\gamma} & \alpha_{3\kappa\gamma} \\ \alpha_{1\kappa r} & \alpha_{2\kappa r} & \alpha_{3\kappa r} \\ \alpha_{1\gamma r} & \alpha_{2\gamma r} & \alpha_{3\gamma r} \end{bmatrix}^T \cdot \begin{bmatrix} 1 \\ \lambda \\ \kappa \\ \gamma \\ r \\ \lambda\,\kappa \\ \lambda\,\gamma \\ \lambda\,r \\ \kappa\,\gamma \\ \kappa\,r \\ \gamma\,r \end{bmatrix} \\ \hline \begin{bmatrix} \alpha_4 & \alpha_5 & \alpha_6 \\ \alpha_{4\lambda} & \alpha_{5\lambda} & \alpha_{6\lambda} \\ \alpha_{4\kappa} & \alpha_{5\kappa} & \alpha_{6\kappa} \\ \alpha_{4\gamma} & \alpha_{5\gamma} & \alpha_{6\gamma} \\ \alpha_{4r} & \alpha_{5r} & \alpha_{6r} \\ \alpha_{4\lambda\kappa} & \alpha_{5\lambda\kappa} & \alpha_{6\lambda\kappa} \\ \alpha_{4\lambda\gamma} & \alpha_{5\lambda\gamma} & \alpha_{6\lambda\gamma} \\ \alpha_{4\lambda r} & \alpha_{5\lambda r} & \alpha_{6\lambda r} \\ \alpha_{4\kappa\gamma} & \alpha_{5\kappa\gamma} & \alpha_{6\kappa\gamma} \\ \alpha_{4\kappa r} & \alpha_{5\kappa r} & \alpha_{6\kappa r} \\ \alpha_{4\gamma r} & \alpha_{5\gamma r} & \alpha_{6\gamma r} \end{bmatrix}^T \cdot \begin{bmatrix} 1 \\ \lambda \\ \kappa \\ \gamma \\ r \\ \lambda\,\kappa \\ \lambda\,\gamma \\ \lambda\,r \\ \kappa\,\gamma \\ \kappa\,r \\ \gamma\,r \end{bmatrix} \end{array} \right\}_{M\,(M,er,e\theta,z)} \tag{3}$$

## 3. RESULTS AND DISCUSSION

The study is based on a former geometrical model developed at the LMP laboratory [8] plus equations of the behaviour model here defined. The cutting edge and the screw are segmented in several elements.

For any element of the edge, values from the geometrical model are injected in the matrix of the multi-linear behaviour model and leads to the calculation of forces and torques. Each micro screw is expressed at the current point $M$ in the local frame $(M\boldsymbol{e}_r\,\boldsymbol{e}_\theta)$ as shown in Fig. 4. The geometrical model allows swapping from the local coordinate system $(M\boldsymbol{e}_r\,\boldsymbol{e}_\theta)$ to the global coordinate system $(O,\boldsymbol{x},\boldsymbol{y})$ according to the parameter $\theta$, which depends on the distance $(r)$ between the current point $M_i$ and spindle axis. The axis $(O,\boldsymbol{x})$ is chosen passing by the contact point between the cutting edge and the web diameter.

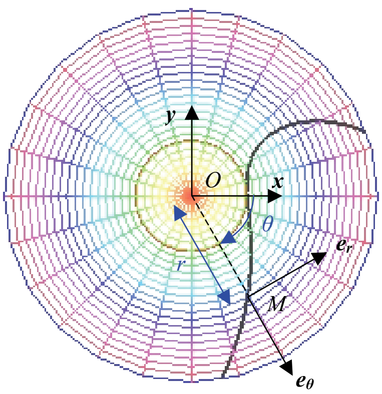



**Fig. 4.** Local and global frame attached to the tool.

In the frame $(O,\boldsymbol{x},\boldsymbol{y})$, micro screws can be added to obtain forces and torques along the cutting edge. Equation (4) displays regression coefficients which allow calculating mechanical efforts according to geometrical parameters.

Unlike for DOE, coefficients are not adimensioned but correspond to the real amplitude (here, in N, N/°, N/°²) due to variation of the parameters on the studied domain.

$$\begin{bmatrix} Fe_r \\ Fe_\theta \\ Fz \end{bmatrix} = \begin{bmatrix} 19.907 & 61.597 & -294.887 \\ 0.748 & 3.067 & -0.211 \\ -0.15 & -1.676 & 3.742 \\ 0.916 & 0.073 & -1.128 \\ 2.274 & -22.55 & 46.895 \\ -0.004 & -0.026 & 0.011 \\ -0.019 & 0 & -0.01 \\ 0.064 & -0.144 & -0.096 \\ 0.007 & -0.038 & 0.062 \\ -0.04 & 0.293 & -0.542 \\ -0.161 & 0.372 & -0.477 \end{bmatrix}^T \cdot \begin{bmatrix} 1 \\ \lambda \\ \kappa \\ \gamma \\ r \\ \lambda\;\kappa \\ \lambda\;\gamma \\ \lambda\;r \\ \kappa\;\gamma \\ \kappa\;r \\ \gamma\;r \end{bmatrix} \tag{4}$$

For a better interpretation of the results, a two dimensional display of the mechanical effort repartition has been developed.

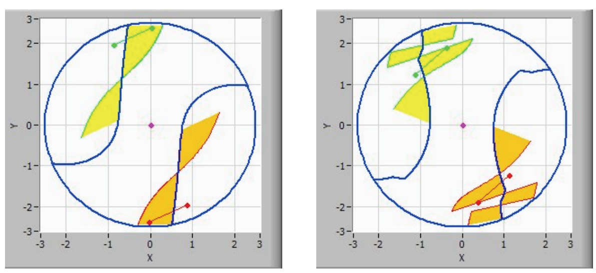
Therefore, it is possible to analyze different tool tip configurations such as, classic drill point geometry (Fig. 5.a) or step drill geometry (Fig. 5.b).

In Fig. 5.a, a variation in radial force direction can be observed. A positive torque is generated near the web due to the great negative rake angle and low cutting speeds. This phenomenon is not described in “orthogonal cutting models” or “oblique cutting models” because the influence of the ship coiling around two axes is not taken into account.

Indeed, for these classical models, each part of the cutting edge is considered independent form the others.

Experimentally, the iterated segmentation of the edge allows determining the contribution of the chip coiling on mechanical actions.

Practically, drill points are often split nearby the web which generates a secondary cutting edge. As a consequence, influence of the chip coiling (that mainly occurs in this zone) is less observable.



a) b)

**Fig. 5.** Radial efforts repartition for different type of drill point geometry.

## 3. CONCLUSION

The behaviour model directly shows the mechanical action repartition along the cutting edge according to the geometrical parameters of the drill. Information concerning the stress state on the cutting face (traction, compression, shearing) is now accessible. This information can deliver indications concerning the breakage modes of drills. In particular for step drills (industrial issue), the existence of a remaining breakage in the middle of the cutting edge has been explained by the model that predicts this particular location matches with a shearing zone. Effects of shearing in this zone most often entail a pilling of the cutting edge.

Presented works illustrate the direct method which intends to set a model of mechanical actions along the edge according to geometry. Yet, the reversed model is easily realizable thanks to the linearity of the matrix (4). Therefore, point design can be improved to solve mechanical action repartition issues. These further works are parts of the perspectives.

When comparing this model to more elaborated numerical or analytical models, the main advantage consists in its easy implementation. This works can be used as an efficient help for the design of new tool point geometry. A LabVIEW © program also permits to visualize the influence of the concentricity default of the drill holding and its consequences on the mechanical efforts along the cutting edge.

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