DYNAMIC MODELLING OF VIBRATIONS ASSISTED DRILLING

Mathieu LADONNE[1],Olivier CAHUC[2],
Jean Yves K'NEVEZ[3], Yann LANDON[4], Mehdi CHERIF[5]

Rezumat. *Numărul de multi-materiale pentru configurarea structurilor aeronautice este în creştere datorită evoluţiei materialelor compozite şi metalice. Pentru găurile de fixare, procesul de găurire asistat de vibraţii (VAD) se extinde rapid, deoarece permite creşterea fiabilităţii operaţiilor de găurire pe structuri multistrat. Printre procesele VAD, soluţia cu vibraţii forţate adăugate găuririi convenţionale, pentru a crea o aşchiere discontinuă, este mai dezvoltată în industrie. Mişcarea înainte şi înapoi permite îmbunătăţirea evacuării aşchiilor prin ruperea acestora. Această tehnologie prezintă doi parametri noi: frecvenţa şi amplitudinea oscilaţiilor. Pentru a optimiza procesul, alegerea acestor parametri necesită modelarea cu precizie a procesului de aşchiere şi a dinamicii maşinii. În această lucrare se propune în primul rând o modelare cinematică a procesului. Limitele modelului sunt analizate prin comparaţie între simulări şi măsurători. Modelul propus este utilizat pentru a dezvolta un model al forţelor de aşchiere pentru estimarea condiţiilor de prelucrare care asigură fragmentarea aşchiilor şi îmbunătăţirea durabilităţii sculei.*

Abstract. *The number of multi-materials staking configurations for aeronautical structures is increasing, with the evolution of composite and metallic materials. For drilling the fastening holes, the processes of Vibration Assisted Drilling (VAD) expand rapidly, as it permits to improve reliability of drilling operations on multi-layer structures. Among these processes of VAD, the solution with forced vibrations added to conventional feed to create a discontinuous cutting is the more developed in industry. The back and forth movement allows to improve the evacuation of chips by breaking it. This technology introduces two new operating parameters, the frequency and the amplitude of the oscillation. To optimize the process, the choice of those parameters requires first to model precisely the operation cutting and dynamics. In this paper, a kinematic modelling of the process is firstly proposed. The limits of the model are analysed through comparison between simulations and measurements. The proposed model is used to develop a cutting force model that allows foreseeing the operating conditions which ensure good chips breaking and tool life improvement.*

Keywords: Vibrations Assisted Drilling; Machining Dynamics; Process Modelling

---

[1]PhD (ABD), Université de Bordeaux, I2M UMR 5295, F3340 Talence, France (e-mail: mathieu.ladonne@ensam.eu).
[2]Prof, Université de Bordeaux, I2M UMR 5295, F3340 Talence, France.
[3]PhD, Université de Bordeaux, I2M UMR 5295, F3340 Talence, France.
[4]PhD, Université de Toulouse, Institut Clément Ader, 31077 Toulouse.
[5]PhD, Université de Bordeaux, I2M UMR 5295, F3340 Talence, France.

1. Introduction

The control of the quality and reliability of drilling operations is a difficult matter, mostly in the aeronautical industry for the realization of fastening holes in multi-materials structures. Among the difficulties, evacuation of dust and chips during drilling is a major issue. It needs to ensure correct breakage of the material into short chips.

During the drilling process, the evacuation of chips is made through the flutes of the drill. In some aeronautical materials such as titanium or aluminium, chips form long helical coils that occupy the flutes of the cutting tool (Fig. 1.a) and can lead to jamming. Due to this phenomenon, there are risks of damage to the machined surface and/or to the drill [1, 2]. Efficient evacuation is a key factor for process reliability. To respond to this issue, solutions have been developed to facilitate chip evacuation. These include the use of tools with a chip-breaker geometry [3], with special coatings [4], or adopting high-pressure lubrication. Another alternative is to change the kinematics of the cutting tool to lead to interrupted cutting. To this purpose, Denkena [5] proposes orbital drilling as a solution. The chip fragmentation can also be obtained using peck-drilling or vibration assisted drilling [6]. The present study will focus on this latter technique.

Fig. 1. Chip formation during conventional drilling and vibrations assisted drilling.
a. Conventional Drilling; **b.** Vibration Assisted Drilling.

Vibration Assisted Drilling (VAD) involves adding axial oscillations to the conventional feed movement of the drill in order to interrupt the cutting process and break the resulting chips. The chips generated by this vibration process are smaller and easier to evacuate than conventional long chips (Fig. 1.b).

The vibratory movement can be considered in two ways. A first solution is to generate oscillations with small amplitude (<20 μm) and high-frequency (>5 kHz). These ultrasonic oscillations are achieved by piezoelectric actuators. Without leading the cutter to exit the work-piece, the vibrations have the effect of varying the cut thickness and creating breaking points on the chip [7, 8]. The second approach is to generate a low-frequency oscillation (<1 kHz) whose amplitude is close to the feed rate. A variety of different technologies is used in this second category. For example, it is possible to generate the vibration by imposing an oscillating movement using a piezoelectric system [9], a linear motor [10], an eccentric gear train [11], or cam systems [12]. This is known as forced vibration assisted drilling. The chatter that occurs at high speed can also be used to generate and maintain the oscillations [13]. This self-sustained vibration drilling is driven by the energy from the cutting itself but requires perfect mastery and control of the operating conditions. These technical requirements are difficult to guarantee in industrial conditions.

The present work is focused on vibration assisted drilling with forced low-frequency vibration, as it is the most widely used technology in industry. The vibration device used is a specific tool holder based on a roller bearing with sinusoidal rings [12] (Fig. 2). The oscillations are achieved by the relative rotation of the two rings, with one being driven by the spindle and the other being fixed relative to the spindle frame. The phase difference between the two rings allows the amplitude of the vibrations to be set. The frequency is determined by the number of oscillations of the rings. The system is powered by the spindle movement. Its adaptability and simplicity make it suitable for industrial use, as for research works. The amplitude (A) and frequency (ν) of the oscillations generated by the specific tool holder modify the path of the cutting edges and the dynamics of the cut. However, optimisation of these parameters requires precise modelling of the cutting kinematics in vibration assisted drilling.

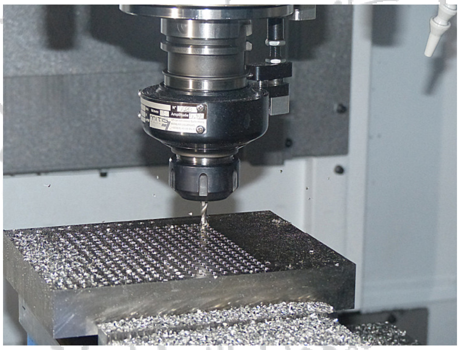

Fig. 2. Specific tool-holder for vibration assisted drilling.

VAD has only recently been brought into operation in industry but has been studied for several years. The various works on the topic include Toews [14] and Deyuan [6], who highlighted the kinematic conditions enabling chip breakage. Laporte and de Castelbajac [15], studying the technology with a cam system, established a link between the design parameters of the vibratory device and the resulting oscillation that is added on to the conventional motions. These studies are based on simple two-dimensional kinematic models of VAD and allow the instantaneous cutting thickness to be calculated. However, such models do not address other phenomena such as ploughing. Axial oscillations lead to considerable variation in the tool speed and effective clearance angle. It is therefore necessary to monitor the ploughing phenomenon during VAD [16-20]. However, this part will not be discussed in this article. All results presented are chosen in specific cutting conditions allowing avoiding ploughing phenomenon.

In order to determine the optimal process parameters, the aim of this works is to develop a model to relate these parameters with the VAD cutting behaviour. An analytical kinematic modelling of the vibration assisted drilling process is developed. A comparison between simulation and experimental results shows that this first model is not adequate to precisely model the VAD process behaviour. The phenomena that have to be integrated into the model to describe VAD behaviour more accurately are then proposed and the influence of each of them on the process is analysed. An advanced kinematic model, taking into account these phenomena is then proposed and validated.

2. Kinematic Modelling of the VAD process

The process parameters determine the tool's path in relation to the work-piece. Conventional parameters such as feed rate (*f*) and rotation speed (*N*) describe the cutter's constant translation movement and rotation. Assuming the vibration device generates a perfectly sinusoidal oscillation, it is then possible to describe the axial position ($Z_{tool|spindle}$) along the drilling axis of a point of the tool (considered to be a rigid body, at each instant (t), using its amplitude (*A*) and the frequency (ν) (eq. 1).

$$Z_{tool|spindle}(t) = -\frac{A}{2}.\sin(\omega.t) \tag{1}$$

$$\text{with } \omega = 2.\pi.\upsilon \tag{2}$$

It enables to calculate the axial position (Z_{tool}) and angular position (θ_{tool}) for each point of the cutting edge (i), at radial position (r), for each instant (*t*), using equations (3) and (4) (fig. 3.a and fig. 3.b).

$$Z_{tool}(t,i,r) = Z_{tool,0}(i,r) - \frac{f.N}{60}.t - \frac{A}{2}.\sin(\omega.t) \tag{3}$$

$$\theta_{tool}(t,i,r) = \theta_{tool,0}(i,r) - \frac{2.\pi.N}{60}.t \tag{4}$$

Knowing the tool path, the next step is to model the cutting action of the edge inside the material. In order to describe VAD behaviour, an indicator (*W*) corresponding to the number of oscillations per revolution, is introduced (5).

$$W = \frac{\nu_{oscillation}}{\nu_{rotation}} = \frac{\nu.60}{N} \tag{5}$$

If the oscillation amplitude remains below the limit defined by equation (6), there will be no intersection between the sinusoidal paths of the different cutting edges [21] (Fig. 3.a). Cutting is then continuous, with vibratory assistance allowing merely to vary the thickness along the length of the chips generated. The oscillations will thus create more fragile points for the chips to be broken as they are deformed by the flute of the tool.

$$A < \frac{f}{.N_z .\left|\sin\left(\frac{W.\pi}{N_z}\right)\right|} \tag{6}$$

In the case of a perfectly symmetrical cutter with (N_z) cutting edges and a regular rotary movement, the cutting height can be determined using equation (7) (taken from works by Toews [14]).

$$H_{cut}(t) = \frac{f}{N_z} + \frac{A}{2}.\sin\left(\frac{W.\pi}{N_z}\right).\cos\left(\omega t - \frac{W.\pi}{N_z}\right) \quad \forall i, r \tag{7}$$

The height of the surface down-hole ($Z_{surface}$) machined by the edge (i) can be described at each instant (t) using the equation for the tool axial position (eq. 8).

$$Z_{surface}(t, \theta(t,i,r), r) = Z_{tool}(t,i,r) \tag{8}$$

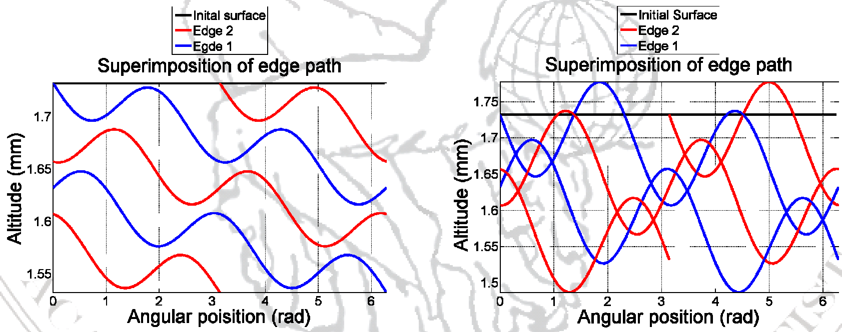

Fig. 3. Successive trajectories.
a. Without cutting interruption; **b.** With cutting interruption.

Beyond the limit defined in equation (6), the paths intersect each other (Fig. 3.b). The cutting edge will then pull out from the work-piece during the process and cutting will be discontinuous. Equation (7) therefore fails to correctly define the cutting height. To reflect the discontinuity of the VAD, a formula covering the different configurations is needed. When the tool is engaged in the material, the cutting height will correspond to the distance between the surface down hole and the cutting edge. When the tool is outside the material, there will be no cutting and the cutting height will be zero. Thus, the different cutting heights can be expressed by equation (9).

$$H_{cut}(t,i,r)=\begin{cases} Z_{surface}(t-dt,\theta(t,i,r),r)-Z_{tool}(t,i,r) \\ \quad if\, Z_{tool}(t,i,r)<Z_{surface}(t-dt,\theta(t,i,r),r) \\ 0 \quad else \end{cases} \tag{9}$$

Then, the surface position is updated at each instant (t) of the calculation, taking into account both configurations (eq. 10).

$$Z_{surface}(t,\theta(t,i,r),r)=\begin{cases} Z_{tool}(t,i,r) \\ \quad if\, Z_{tool}(t,i,r)<Z_{surface}(t-dt,\theta(t,i,r),r) \\ Z_{surface}(t-dt,\theta(t,i,r),r) \quad else \end{cases} \tag{10}$$

This modelling affords a better understanding of the influence of vibration assistance on cutting behaviour. It is able to detect when the tool is cutting and when it egresses from the material (Fig. 4.a). It also allows to be calculated the instantaneous cutting height (Fig. 4.b).

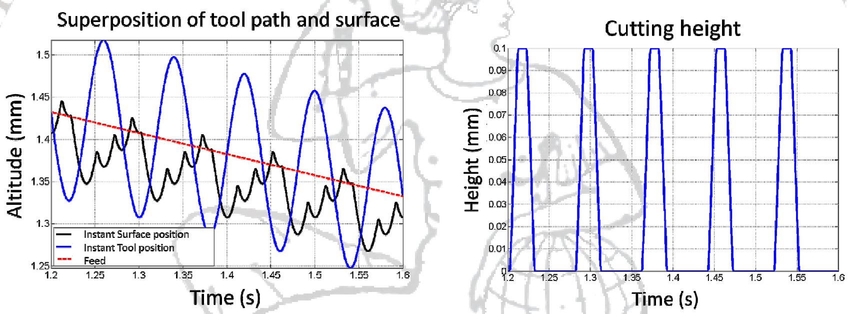

Fig. 4. Results of simulation.
a. Trajectory and surface down-hole position; **b.** Cutting heigh.

To validate the model developed, the simulation results were compared with experimental measurements.

3. Experimental Setup

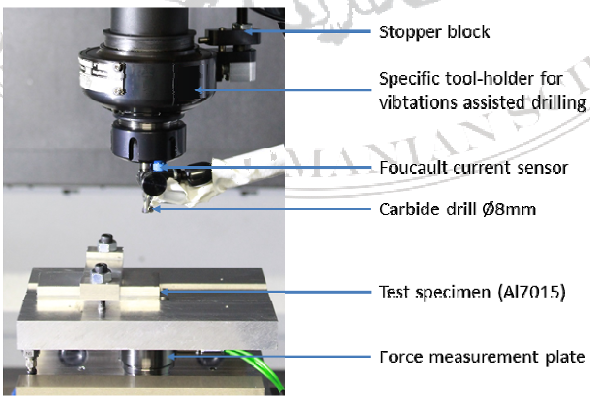

Fig. 5. Experimental Setup.

The aim of the experimental tests campaign was to measure real displacements of the tool during VAD operation. Tests were performed on 3-axis machine-tool (Mori-Seiki NVX5060). An 8 mm diameter drill was used. The drill was mounted using a collet chuck on a vibratory tool-holder (MITIS PG8040). The material used for the drilling tests was an aluminium alloy (Al7015) 15 mm thick plate. The operating parameters are presented in Table (1). During the test, the axial force was measured using a force measurement plate (Kistler 9345B). The axial oscillations are recorded using a Foucault current sensor (Keyence EX-305) that measures the instantaneous position of the tool-holder relative to the spindle (Fig 5).

Table 1. Experimental parameters

	Property	Value	Unit
Material	Aluminium	Al7015	(-)
Tool	Diameter	8	(mm)
Conventional parameters	Spindle speed	300	(rev/min)
	Feed rate	0.05	(mm/rev)
Vibratory parameters	Number of oscillations per revolution	2.5	(-/rev)
	Amplitude	0.2	(mm)

Force and displacement measurements were synchronized in order to be able to correlate observations on the displacement signal during the different drilling stages (Fig. 6.a to Fig. 7.b).

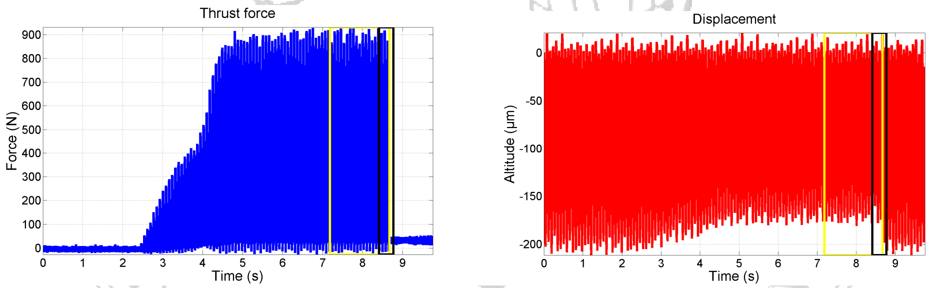

Fig. 6. Example of recorded signal.

a. Oscillation of the tool; **b.** Thrust Force.

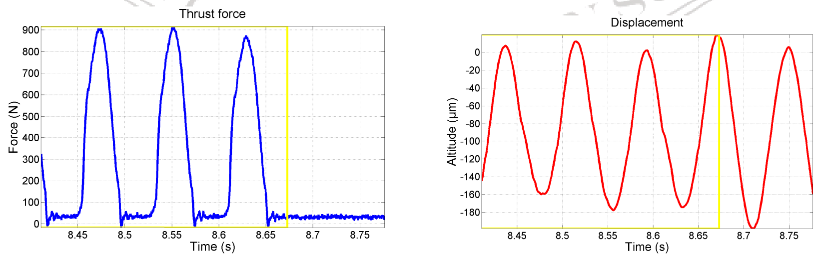

Fig. 7. Detail of the measurement signal.

a. Oscillation of the tool; **b.** Thrust Force.

4. Results and discussion

From the displacement measurements made, it can be noticed that there are irregularities in the pattern of oscillation resulting from the vibrating tool holder's rotation (Figure 8). The machining system cannot be considered to be geometrically perfect. This variation in the pattern is induced by the geometrical defects on the sinusoidal cam profile.
From the measurements recorded during the drilling tests, observation can be made on the behaviour of the system, looking at the displacement signal (Figure 9). The beginning of drilling is recorded at $t = 2.6$ s (Figure 7). Before the contact between the tool and the work-piece, the displacement signal shows an oscillation of 0. mm, which corresponds to the amplitude set (Figure 6). As the tool enters the material, the amplitude of measured oscillations is decreasing with the increase of thrust force. A decrease of 15% of the nominal value is observed.
A renewed increase in amplitude appears when the drilling operation is interrupted. A comparison of the oscillations signals with and without drilling clearly shows the difference (Figure 9). This observation highlights the fact that a purely kinematic model is not suitable to predict all the phenomena associated with the process (error of 6,2%). The machining system cannot be considered infinitely rigid.

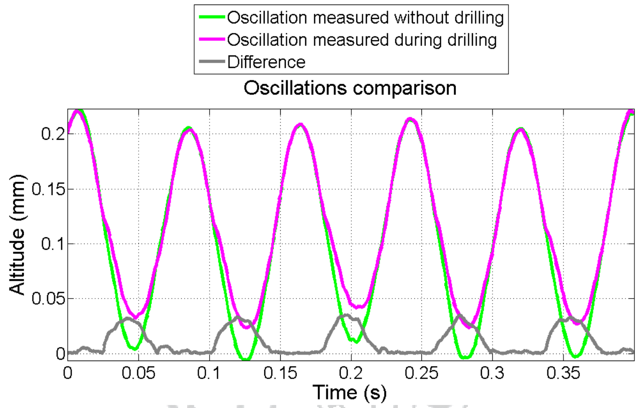

Fig. 8. Comparison of oscillations signals with or without drilling.

As a first conclusion, the most significant deviations derive from two main sources that are a defect in the pattern of oscillation from the cam and the dynamic behaviour of the machining system during drilling that must be taken into account. In the following part, these two phenomena are integrated into the model and their impact is assessed by comparison with experimental data.

4.1. Geometrical defect of the oscillation

To reflect deformities of the sinusoidal pattern of the cam in the model, theoretical sinusoidal oscillation is compared with the measurement of oscillation when the drill is outside the hole (Figure 14). The overlapping of the sine oscillation and the measured oscillation shows that a mechanical device, such as MITIS tool-holder, can generate minor irregularities in oscillation pattern (error of 5.1%). In order to take into account this geometrical defect of the cam, the theoretical sinusoidal oscillation is replaced into the modelling by the oscillation measurement without drilling.

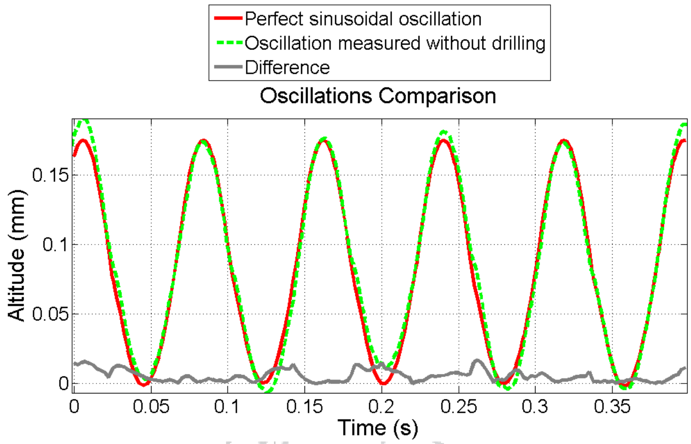

Fig. 9. Comparison of the theoretical sinusoidal oscillation with the measured displacement signal without drilling.

4.2. Dynamic behaviour of the machining system

To take into account the lack of rigidity of the machining system, a new dynamic model is introduced. The machining centre, the work-piece and its setup are considered to be infinitely rigid. The tool-holder is modelled as a 1-degree flexible system, admitting a given stiffness (measured in this case K_{th}=26 kN/mm) and a damping effect responsible for the dynamic behaviour of the machining set-up (Fig. 10). These dynamic parameters were identified by numerical method using the difference between the displacement measurement during drilling and without drilling. They were confirmed by specific identification tests in static.
The path of the drill is then depending on the displacement due to the stiffness of the tool-holder ($Z_{tool\text{-}holder}$) (eq. 11).

$$Z_{tool}(t,i,r) = Z_{tool,0}(i,r) - \frac{f.N}{60}.t - \frac{A}{2}\sin(\omega.t) + Z_{tool-holder}(t) \tag{11}$$

The displacement can only be determined by resolving the equation of the machining system's dynamics. If the tool-holder, with a mass (M_o), has a stiffness (K_{th}) and damping (C_{th}), the displacement can be calculated by solving equation (12).

$$M_o.\ddot{Z}_{th} + C_{th}.\dot{Z}_{th} + K_{th}.Z_{th} - F_z(t) + M_o.\frac{A.\omega^2}{2}\sin(\omega.t) = 0 \tag{12}$$

The axial force (F_z) due to tool-material interactions needs to be known to solve the equation. For this, the forces measured during drilling are considered. A modified simulated trajectory is then obtained (Fig. 11).

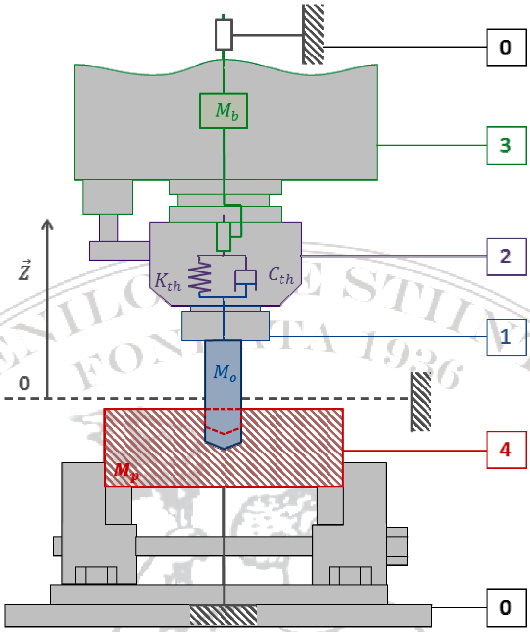

Fig. 10. Schematic representation of the flexible machining system.

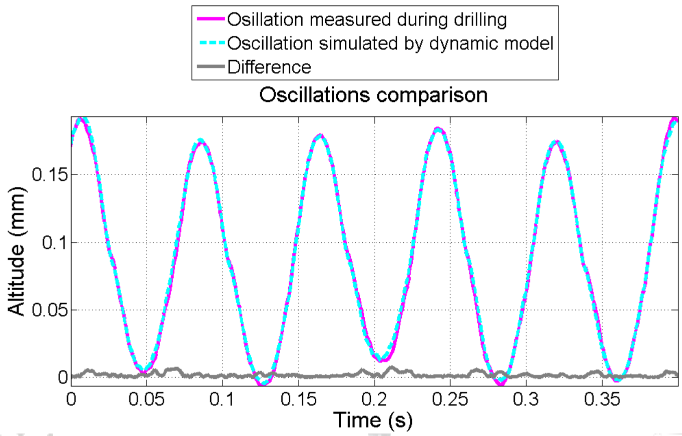

Fig. 11. Comparison of oscillations obtained with dynamic modelling and with displacement measurement.

The measured oscillation (during drilling) and the oscillation from the dynamic model are then very close. The difference between the two signals is negligible (mean error of less than 1%). The engagement of the tool, at each oscillation, is characterized by a deformation of the oscillation (example at $t = 0.025$s). Taking into account the dynamic behaviour of the machining system allows predicting the actual trajectory of the tool.

To further improve simulation of the process, other sources of variance need to be considered, such as other flexibilities in the machining system (work-piece, tool).

5. Conclusion

In this paper, the sensitivity of VAD process modelling was studied through comparison of simulated and measured oscillations.

- It is shown that a purely kinematic modelling is not suitable to correctly describe the process and various associated phenomena.
- Sources of deviations between the model and the test results were analysed and the most influential phenomena were identified.
- In order to improve the modelling, the flexibility of the machining system needs to be taken into account. The first one is the flexibility of the tool-holder. A model that caters this aspect was developed and used to more accurately describe the VAD process.

This model may be used to optimise the operating parameters (vibration parameters and cutting parameters) on a criterion of process reliability.

Abbreviations

VAD: Vibrations Assisted Drilling

R E F E R E N C E S

[1] F. Dargnat, "*Modélisation semi-analytique par approche énergétique du procédé de perçage de matériaux monolithiques*", Université Bordeaux 1, 2006.

[2] E. Brinksmeier and R. Janssen, "*Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys*", CIRP Ann. Technol., vol. 51, no. 1, pp. 87–90, 2002.

[3] L. Benezech, Y. Landon, and W. Rubio, "*Study of Manufacturing Defects and Tool Geometry Optimisation for Multi-Material Stack Drilling*", Adv. Mater. Res., vol. 423, pp. 1–11, Feb. 2012.

[4] N. Guibert, "*Etude et modélisation de l'influence des phénomènes de coupe sur les performances du forage vibratoire*", Université Joseph Fourier - Grenoble 1, 2008.

[5] B. Denkena, D. Boehnke, and J. H. Dege, "*Helical milling of CFRP–titanium layer compounds*", CIRP J. Manuf. Sci. Technol., vol. 1, no. 2, pp. 64–69, Jan. 2008.

[6] Z. Deyuan and W. Lijiang, "*Investigation of chip in vibration drilling*", Int. J. Mach. Tools Manuf., vol. 38, no. 3, pp. 165–176, Feb. 1998.

[7] S. S. F. Chang and G. M. Bone, "*Thrust force model for vibration-assisted drilling of aluminum 6061-T6*", Int. J. Mach. Tools Manuf., vol. 49, no. 14, pp. 1070–1076, Nov. 2009.

[8] R. Neugebauer and A. Stoll, "*Ultrasonic application in drilling*", J. Mater. Process. Technol., vol. 149, no. 1–3, pp. 633–639, Jun. 2004.

[9] G. F. Moraru, P. Veron, and P. Rabate, "*Drilling Head with Axial Vibrations*", US 2012/0107062 A12012.

[10] K. Okamura, H. Sasahara, T. Segawa, and M. Tsutsumi, "*Low-Frequency Vibration Drilling of Titanium Alloy*", JSME Int. J. Ser. C, vol. 49, no. 1, pp. 76–82, 2006.

[11] G. F. Moraru and D. Brun Picard, *"FR2892959A1 - Dispositif de perçage a oscillations axiales*", 28929592005.

[12] G. Peigne, "Ring-Rolling Bearing with Axial Displacement and Shaping Tooling Equipped with Such a Bearing", US 2010/0003096 A12010.

[13] N. Guibert, H. Paris, and J. Rech, "*A numerical simulator to predict the dynamical behavior of the self-vibratory drilling head*", Int. J. Mach. Tools Manuf., vol. 48, no. 6, pp. 644–655, May 2008.

[14] H. G. Toews, W. D. Compton, and S. Chandrasekar, "*A study of the influence of superimposed low-frequency modulation on the drilling process*", Precis. Eng., vol. 22, no. 1–9, p. 9, 1998.

[14] S. Laporte and C. De Castelbajac, "*Major Breakthrough in Multi Material Drilling, Using Low Frequency Axial Vibration Assistance*", in SAE Int. J. Mater. Manf., 2012, pp. 1–12.

[15] D. Bondarenko, "*Etude mésoscopique de l'interaction mécanique outil/pièce et contribution sur le comportement dynamique du système usinant*", Institut Polytechnique de Grenoble, Université Technique Bauman de Moscou, 2010.

[16] P. Naisson, "*Développement de portes outils, d'outils et de modèles pour la maîtrise du perçage vibratoire*", Université de Grenoble, 2011.

[17] C. F. Bisu, "*Etude des vibrations auto-entretenue en coupe tridimensionnelle : nouvelle modélisation appliquée au tournage*.", Université Bordeaux 1, 2007.

[18] G. F. Moraru, "*Etude du comportement du système 'pièce-outil-machine' en régime de coupe vibratoire*", Ecole Nationale Supérieur d'Arts et Métiers, Université Polytechnique de Bucarest, 2002.

[19] N. Guibert, H. Paris, J. Rech, and C. Claudin, "*Identification of thrust force models for vibratory drilling*", Int. J. Mach. Tools Manuf., vol. 49, no. 9, pp. 730–738, Jul. 2009.

[20] J. Jallageas, M. Chérif, J.-Y. K'nevez, and O. Cahuc, "*Modélisation du perçage vibratoire sur UPA*", in 20ème Congrès Français de Mécanique, 2011, pp. 1–6.