TECHNISCHE UNIVERSITÄT
ILMENAU

50. Internationales Wissenschaftliches Kolloquium

September, 19-23, 2005

Maschinenbau von Makro bis Nano / Mechanical Engineering from Macro to Nano

Proceedings

Fakultät für Maschinenbau /
Faculty of Mechanical Engineering

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=15745

Impressum

Herausgeber:	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Peter Scharff
Redaktion:	Referat Marketing und Studentische Angelegenheiten Andrea Schneider
	Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurtz, Univ.-Prof. Dipl.-Ing. Dr. med. (habil.) Hartmut Witte, Univ.-Prof. Dr.-Ing. habil. Gerhard Linß, Dr.-Ing. Beate Schlütter, Dipl.-Biol. Danja Voges, Dipl.-Ing. Jörg Mämpel, Dipl.-Ing. Susanne Töpfer, Dipl.-Ing. Silke Stauche
Redaktionsschluss: (CD-Rom-Ausgabe)	31. August 2005
Technische Realisierung: (CD-Rom-Ausgabe)	Institut für Medientechnik an der TU Ilmenau Dipl.-Ing. Christian Weigel Dipl.-Ing. Helge Drumm Dipl.-Ing. Marco Albrecht
Technische Realisierung: (Online-Ausgabe)	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau
Verlag:	isle Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16 98693 Ilmenau

ISBN (Druckausgabe):	3-932633-98-9	(978-3-932633-98-0)
ISBN (CD-Rom-Ausgabe):	3-932633-99-7	(978-3-932633-99-7)

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=15745

50. Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
19.-23. September 2005

E. A. R. Seabra / J. C. L. Silva

Theoretical and Experimental Investigation on the Mechanical System to Produce File Cutting Edges in a Industrial Machine

ABSTRACT

This paper deals with the research on the mechanical system used to produce file cutting edges (or cutting teeth). A theoretical model was carried out to perform kinematic and dynamic motion characteristics of the mechanical system (cam-follower-spring) of the cutting file machine. With the intent to validate the theoretical model an industrial machine was appropriately re-designed and instrumented to obtain some experimental data.

KEYWORDS

Mechatronics / Instrumentation / Kinematics and Dynamics / Mechanical Design

INTRODUCTION

The experience demonstrates that the most efficient way to produce the file cutting edges is by penetration, due to the impact of a cutting tool which has a reciprocate motion. It should be highlighted that the cutting tool operating rate reaches 200 Hz. This process creates a plastic deformation on the file body, with the shape of sharp edges, which work as cutting edges. For getting this high frequency motion, the cutting bench of the machine has a cam which, due to its eccentricity, and when rotating, causes the elevation of the follower (also called pin throughout this work). The cylinder is elevated in this process, to which the chisel is fixed, and immediately falls down, impelled by the spring and its own weight. Figures 1 and 2 show two schematic drawings of the mechanical system used to produce files teeth.

The impact energy of the chisel depends on the relationship of the regulations of the spring force and the maximum distance between the chisel and the file that is adjusted by the presser foot.

The chisel describes a reciprocating motion that always reaches the same up-dead-point (maximum distance between the chisel and the file), because the pin/follower, attached to the cylinder (which moves the chisel), always passes by the tops of wheel-with-rebounds (cam). On the other hand, the down-dead-point of the chisel is variable, since it depends on the impact energy absorbed by the file body [1-2].

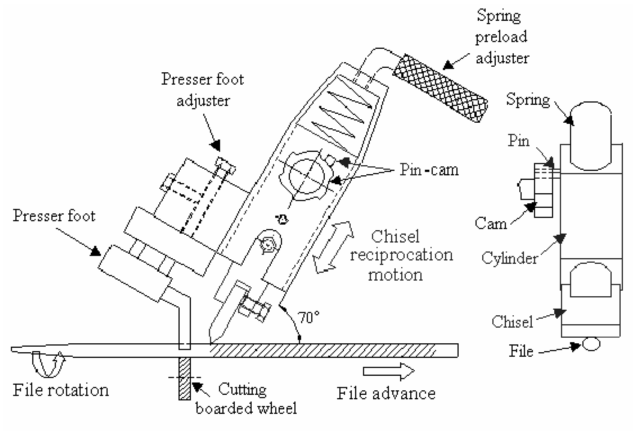

Figure 1 - Schematic representation of the mechanical system (cutting bench).

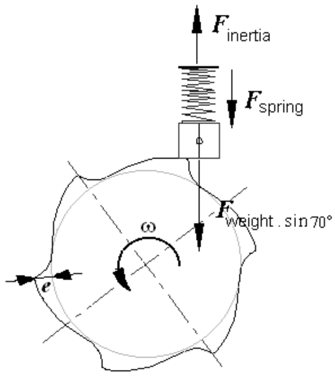

Figure 2 - Kinematic configuration of the cam-follower mechanism.

THEORETICAL MODEL

As it was referred previously, the file cutting operation is obtain through a peculiar type of cam, known as "wheel-with-rebounds", that originates two different phases for the follower movement (pin) - the elevation and the descent/fall. The first one is obtained according to the principle of a cam-follower mechanism, and the second movement is originated by a free fall body impelled by a spring until the chisel reaches the surface of the file body and hence the cutting operation.

In the present work, the kinematic and dynamic analysis of the cam-follower mechanism was performed in three different stages that are following described:

1- *Graphical and analytic method* – determination of the equation of the follower/pin displacement as function of the cam profile.

2 - *Study of the descent or fall phase* - kinematic and dynamic analysis in order to obtain the contact point from which the pin follows the cam surface.

3 - *Study of the rise phase* - kinematic and dynamic analysis starting from the point of contact cam-follower.

This study does not account with the presence of the file body base during the follower descent movement, because the chisel penetration is governed by other mechanical principle (theory of plasticity), which is out of the scope of the present work.

Graphical and analytical analysis

A graphical method was used to determine the displacement curve of the follower. It was only considered a sixth part of the cam rotation because due to the rebounds that repeats for six times. The displacement curve (profile of the cam for each rebound) was obtained starting from one of the six points more eccentrics of the cam, considering increments of rotation of π/180 rad (1°), using this way 60 relative static positions to the two bodies in contact (cam and follower).

The analytical solution was achieved through a polynomial function of the displacement curve obtained graphically. The best approximation for the polynomial function that expresses the follower displacement is a sixth degree polynomial, which can be written as,

$$s = 0{,}0028 - 0{,}0449.\theta + 0{,}2588.\theta^2 - 0{,}6651.\theta^3 + 0{,}8966.\theta^4 - 0{,}6072.\theta^5 + 0{,}1620.\theta^6 \qquad (1)$$

where s and θ are the follower displacement and the cam angle, respectively.

The figure 3 presents the follower's displacement curve (cam profile) obtained graphically and analytically, being verified the existence of a very good correlation (0,997).

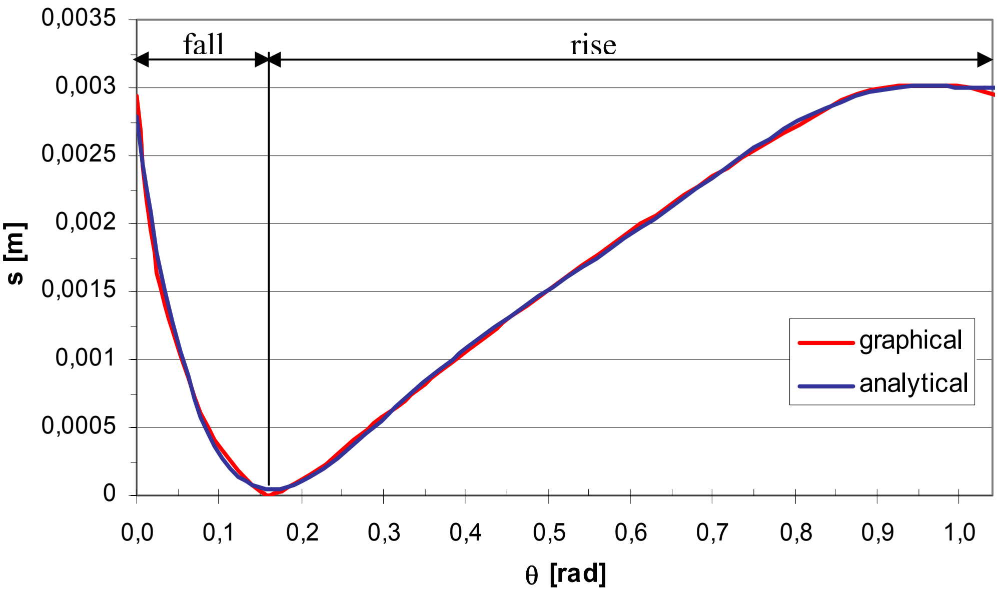

Figure 3 - Displacement diagram of the follower for one rebound.

The follower displacement curve presented in figure 3 is verified just in the case of occurring permanent contact between the follower and the cam surface. This situation doesn't happen in the reality due to the rebounds of the cam conjugated with the high rotation speed corresponding to the regular operation of the machine (1870 rpm). It makes physically impossible the occurrence of permanent contact between the cam and the follower. Figure 4 shows an animation sequence of a virtual simulation of the cam-follower movement during the first instants after the follower reaches the up-dead-point, where it can be verify the existent "jump" on the end of the rising motion.

Figure 4 - Illustration of the contact loss between the follower and the cam.

Analysis of the follower fall

The theoretical analysis of the descent was performed according to the principle of a fall body forced by a spring, until the chisel reaches the surface of the file. This analysis was achieved considering the follower descent movement uniformly accelerated in small intervals of time. Figure 5 presents the flowchart of the theoretical model elaborated to predict the follower motion.

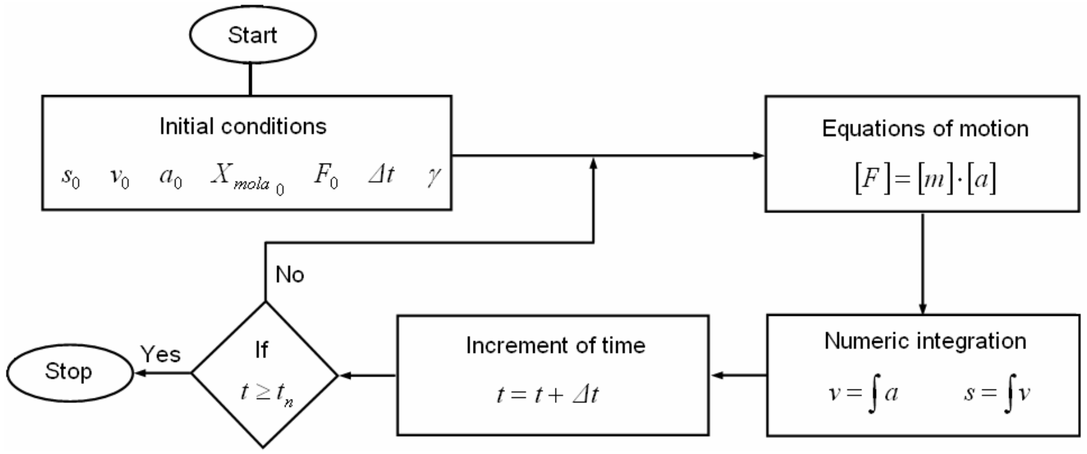

Figure 5 - Flowchart describing the dynamics of cam-follower fall motion.

By knowing the initial state of variables: cam rotation, elastic spring constant K_{spring}, pre-tension of the spring $F_{spring\ pre\text{-}tension}$ (with the follower in the point more eccentric of the cam), the follower mass m, angle of inclination of the cutting bench γ (see figure 1), the values of displacement s, velocity v, acceleration a, deformation of the spring X_{spring} and applied force in the follower F, can be calculated for the instant initial t_0, by using the following equations:

$$s(t_0) = s(\theta = \pi/3) \tag{2}$$

$$v(t_0) = v(\theta = \pi/3) \tag{3}$$

$$a(t_0) = a(\theta = \pi/3) \tag{4}$$

$$X_{spring}(t_0) = X_{spring\ pre-tension} = \frac{F_{spring\ pre-tension}}{K_{spring}} \tag{5}$$

$$F(t_0) = K_{spring} . X_{spring}(t_0) + m . g . sen(\gamma) + a(t_o).m \tag{6}$$

The dynamic analysis is repeated for the next time steps t_i (i = 1, 2, 3,... n.), corresponding the instant n to the initial moment of contact between the follower and the cam after the descent/fall. The acceleration, the displacement and the follower velocity are obtained for the following equations, considering an interval of time Δt, which corresponds to π/180 rad (1°) of cam rotation, that is,

$$a(t_i) = -\frac{F(t_{i-1})}{m} \tag{7}$$

$$s(t_i) = s(t_{i-1}) + v(t_{i-1}).\Delta t + \frac{1}{2} . a(t_i) . \Delta t^2 \tag{8}$$

$$\begin{aligned} &* X_{spring}(t_i) \geq 0 \Rightarrow X_{spring}(t_i) = X_{spring}(\mathrm{t}_{\mathrm{i}-1}) - \lfloor s(t_{i-1}) - s(t_i) \rfloor \\ &* X_{spring}(t_i) < 0 \Rightarrow X_{spring}(t_i) = 0 \end{aligned} \tag{9}$$

$$v(t_i) = v(t_{i-1}) + a(t_i).\Delta t \tag{10}$$

$$F(t_i) = K_{spring} . X_{spring}(t_i) + m . g . sen(\gamma) + a(t_0).m \tag{11}$$

Note*: To avoid the occurrence of negative values of X_{spring} (t_i), what is physically impossible with the *Belleville* spring because it is working in tension. This is due to the fact that the values of pre-tension typically adjusted for the spring, which determine it deformation value $X_{spring}(t_0)$, are less than the maximum displacement of the follower $s(t_0)$, that is 3 mm (value of the eccentricity of the cam e).

This analysis allows obtaining graphically the initial contact point between the follower and the cam. For that, it was necessary to intercept the curves in order at the time of the follower fall displacement (obtained for the analytical method shown in the flowchart of figure 5) and the follower-cam displacement (analytical – figure 3). Theoretically the follower follows the cam surface just starting from the point of interception of the two curves. It shall be remained that this study was performed considering the inexistence of the body base of the file during the descent phase, what corresponds to the obtaining of the maximum follower displacement/stroke.

EXPERIMENTAL MEASUREMENT SYSTEM

In order to validate the theoretical model it was necessary to know how the values of the main parameters were related to the file teeth production, as well as the follower displacement and the spring force.

For that reason, an *LVDT* transducer (Linear Variable Differential Transformer) was selected to quantify the displacement of the cutting beater. This type of sensor has a good accuracy and works quite well even under severe conditions, such as of high vibrations/frequencies and accelerations, because the measurement is performed without direct contact [3-4]. To measure the spring force a piezoelectric force transducer was chosen, due to the fact that this technology is the most appropriated to measure dynamic forces at high frequencies [5-6]. Figure 6 shows the transducers' arrangements in the cutting bench of the file machine. The detailed description of the instrumentation of the cutting file machine can be found in references [7-8].

A Pentium based *PC*, with a data acquisition board and specific software developed in *LabVIEW* environment, was employed to acquire, store and analyse the acquired data. This software were developed with base in a computing design performed to achieve the automatic machine control, that realized the acquisition and treatment of the transducers data, as well as the control of the main regulations of the machine, in order to keep the depth of penetration of the chisel under values that guaranteed the production of the teeth in the quality limits [8].

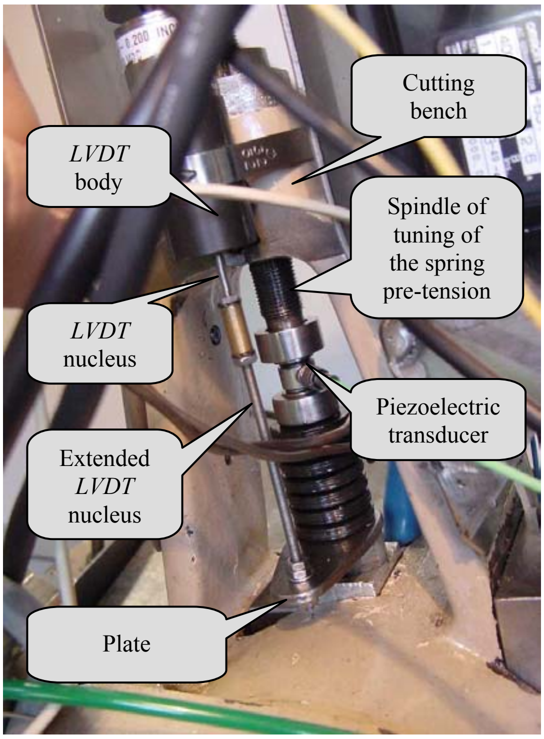

Figure 6 - Layout of the transducers.

RESULTS AND DISCUSSION

Theoretical results

The kinematic analysis of the follower descent motion was performed to study the influence of the main parameters that controls its behaviour, namely: the cam rotation, the pre-tension of the spring and the follower mass. Through the obtained graphs it can be determined the point of interception of the curves previously referred, as well as, the curves of velocity and acceleration of the follower.

Influence of the cam rotation

This analysis was performed with a spring pre-tension (elastic constant 240 N/mm) of 335 N, that corresponds to a typical value of machine operation, and considering the follower mass of 0,5 kg. Figures 7, 8 and 9 present the results for cam rotation, respectively, for 380, 1120 and 1870 r.p.m, being this last case the most common speed of machine operation.

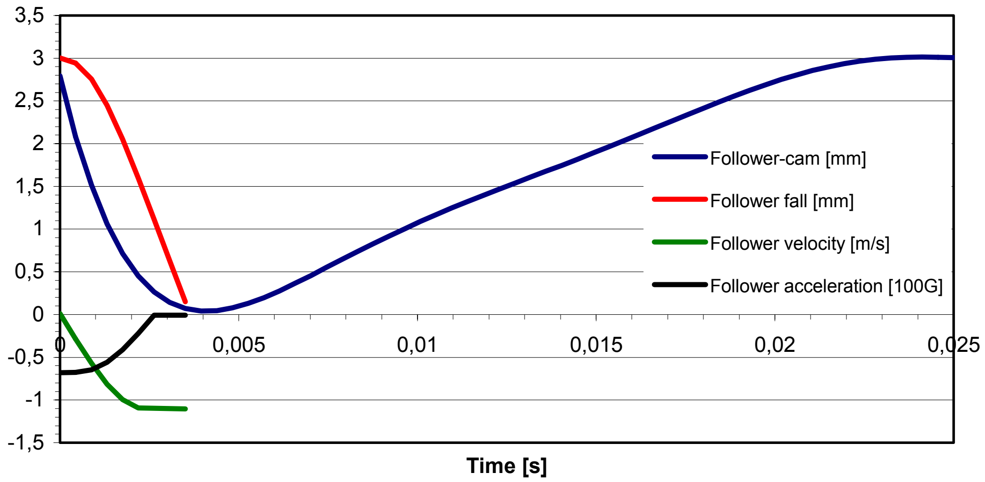

Figure 7 - Global results for cam rotation speed of 380 r.p.m.

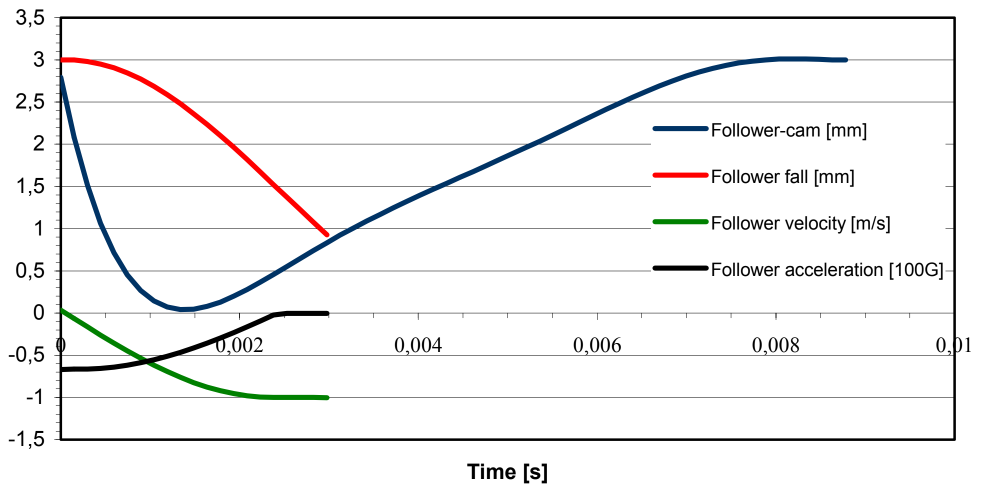

Figure 8 - Global results for cam rotation speed of 1120 r.p.m.

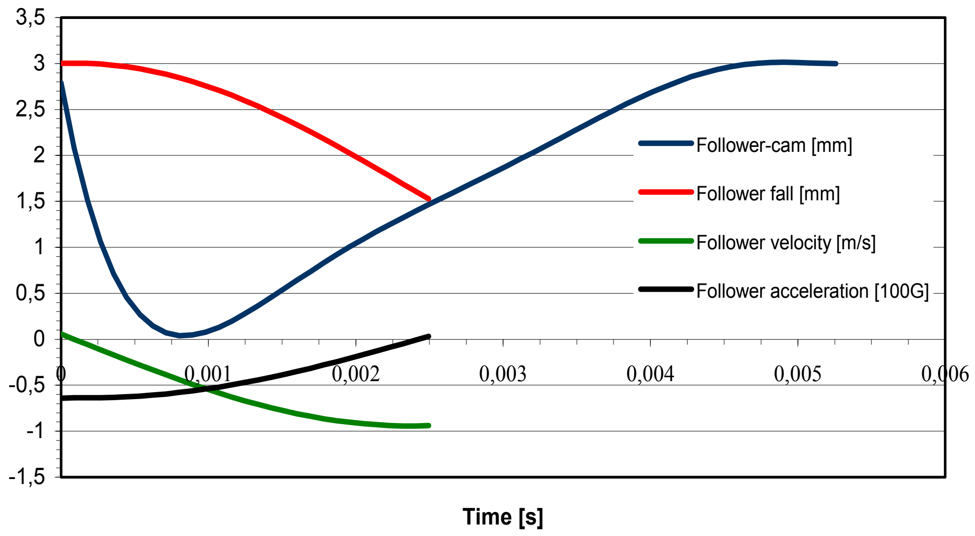

Figure 9 - Global results for cam rotation speed of 1870 r.p.m.

Table 1 presents the values of the more relevant kinematics parameters involved in the cutting operation of the industrial file machine used in this study.

Cam rotation [r.p.m.]	**Cam rotation angle (contact cam-follower) [º]**	**Follower fall stroke [mm]**	**Maximum velocity [m/s]**	**Maximum acceleration [100G]**	**Maximum kinematic energy [J]**
380	8	2,9	1,1	-0,67	0,3025
1120	20	2,2	0,99	-0,66	0,2450
1870	28	1,5	0,94	-0,63	0,2209

Table 1 – Main results obtained of the analysis of the influence of the cam rotation.

It can be concluded, analysing figures 7, 8 and 9 and table 1, that when the cam rotation is higher the displacement/stroke of the follower descent/fall decreases. Due to this reason, the cutting frequency operation of the machine is limited, associated to the cam rotation speed, because it is necessary a minimum stroke for the chisel to obtaining files with quality teeth (acceptable chisel penetration depth). Additionally, it can be concluded that increasing the cam rotation, due to the occurrence of smaller displacements, the velocity, the acceleration and the kinetic energy of the follower decreases.

Influence of the spring pre-tension

This analysis was done considering the same follower mass of 0,5 kg and a cam rotation speed of 1870 r.p.m. Figures 10 and 11 present the results obtained, respectively, for the spring pre-tension of 200 and 400 N. Table 2 shows the main values of the most relevant parameters of this study.

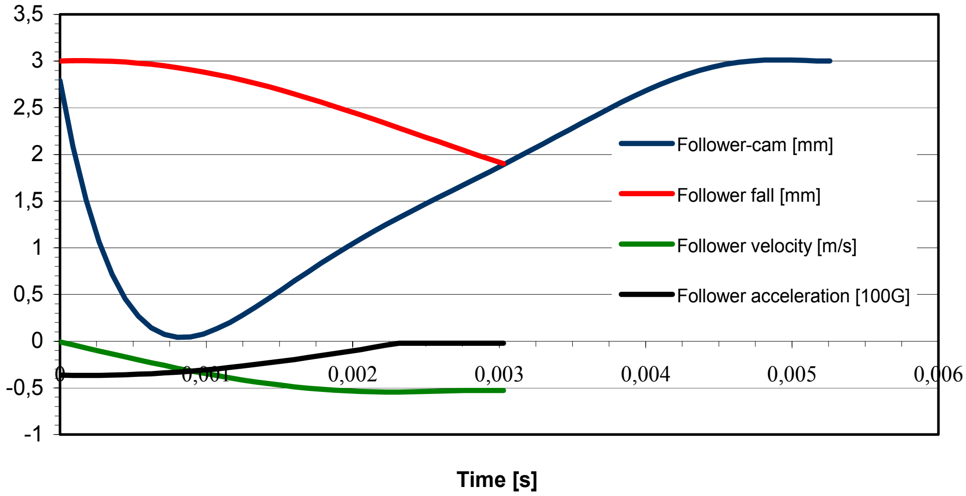

Figure 10 - Global results for spring pre-tension of 200 N.

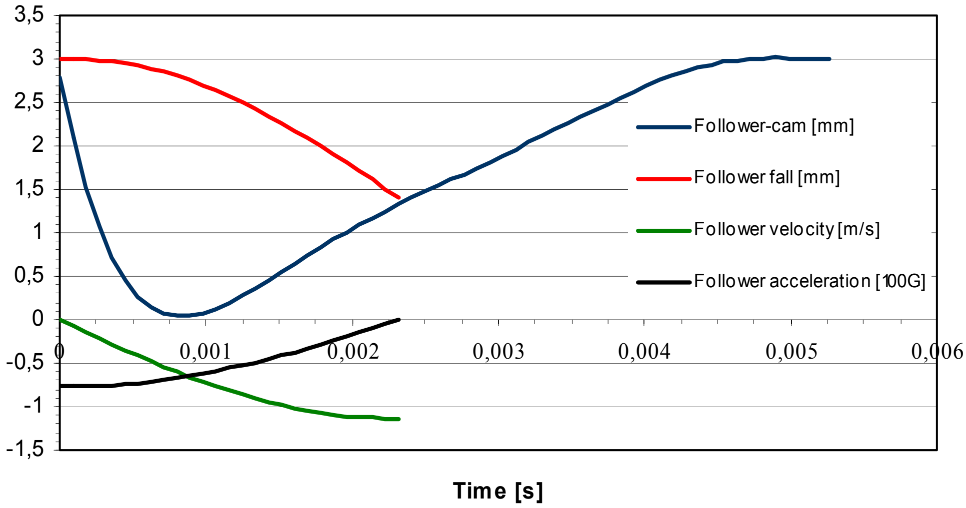

Figure 11 - Global results for spring pre-tension of 400 N.

Spring pre-tension [N]	Cam rotation angle (contact cam-follower) [º]	Follower fall stroke [mm]	Maximum velocity [m/s]	Maximum acceleration [100G]	Maximum kinematic energy [J]
200	33	1,1	0,53	-0,37	0,0702
335 (fig. 9)	28	1,5	0,94	-0,63	0,2209
400	26	1,6	1,13	-0,77	0,3192

Table 2 – Main results obtained of the analysis of the influence of the spring pre-tension.

Influence of the follower mass

This analysis was performed taking into consideration the cam rotation speed of 1870 r.p.m and a spring pre-tension of 335 N. Figures 12 and 13 present the results obtained, respectively, for the follower mass of 0,3 and 0,4 kg. Table 3 summarize the values of the most relevant parameters of this analysis involved in the cutting operation.

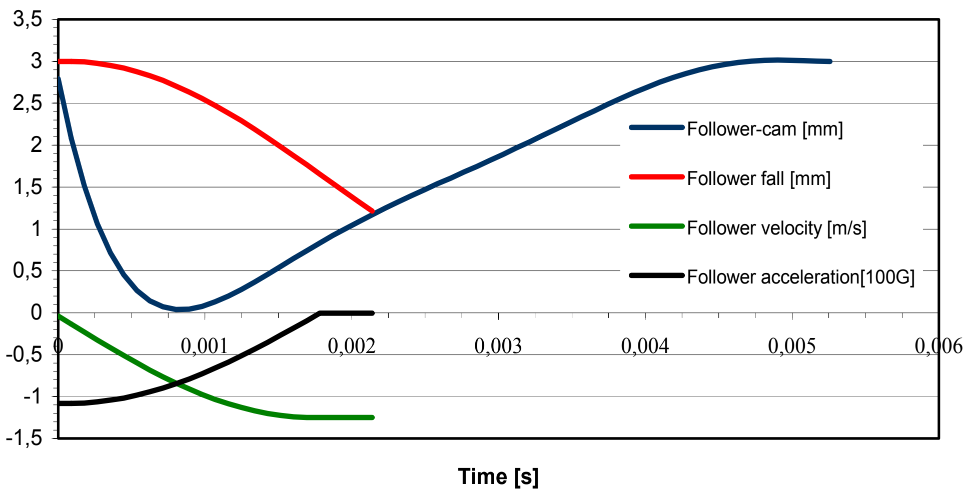

Figure 12 - Global results for follower mass of 0,3 kg.

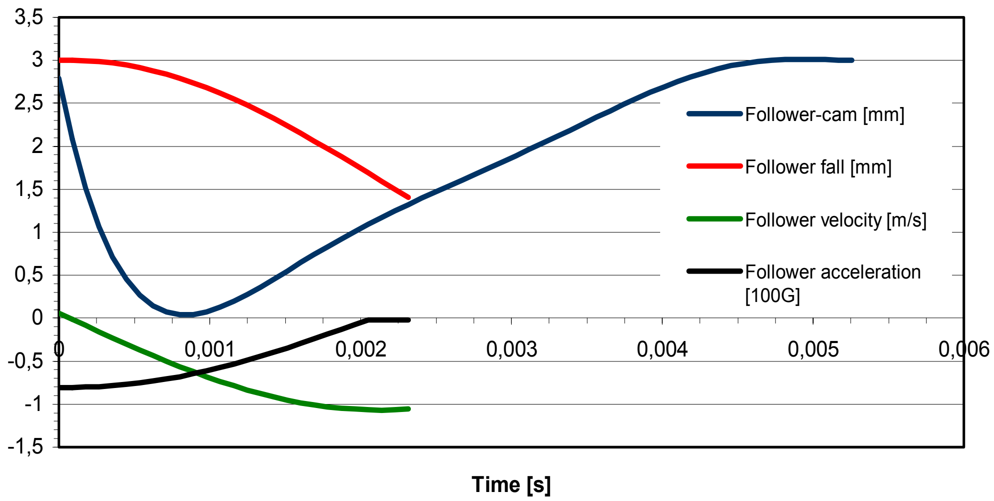

Figure 13 - Global results for follower mass of 0,4 kg.

Follower mass [kg]	**Cam rotation angle (contact cam-follower) [º]**	**Follower fall stroke [mm]**	**Maximum velocity [m/s]**	**Maximum acceleration [100G]**	**Maximum kinematic energy [J]**
0,3	23	1,8	1,23	-1,08	0,2269
0,4	26	1,6	1,06	-0,80	0,2247
0,5 (fig. 9)	28	1,5	0,94	-0,63	0,2209

Table 3 - Main results obtained of the analysis of the influence of the follower mass.

Analyzing the results presented in table 3 it can be concluded that the follower kinetic energy is independent of the mass, because the influence of mass is compensated by the increase of the follower velocity.

Figure 14 shows the cam rotation angle where the contact cam-follower occurs after the fall, as function of the three variables studied that is, cam rotation, spring pre-tension and follower mass. This parameter is very important because it determines the descent displacement of the follower/chisel. As referred previously, for obtaining a correct depth of penetration, a minimum stroke for the chisel must be obtained through the mechanism cam-follower.

It can be concluded that the main limitation of the machine cutting frequency is associated with the reason of the increase of the cam rotation to implicate a decrease of the descent stroke of chisel. This fact can be contradicted with the increase of the pre-tension of the spring and the decrease of the follower mass. They are limited, respectively, due to the resulting kinetic energy (occurrence of excessive cutting) and to constructive reasons.

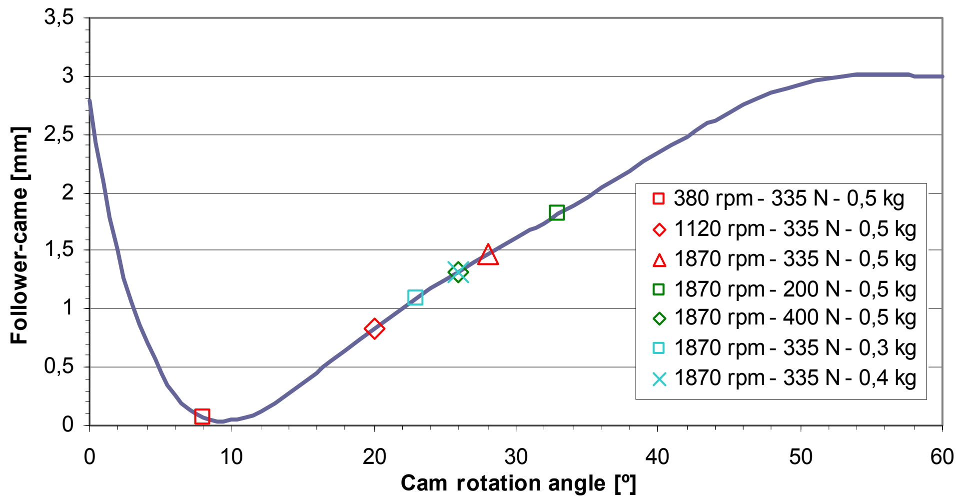

Figure 14 - Theoretical location of the initial contact cam-follower.

Experimental results

Figures 15 and 16 show typical results obtained by using the experimental and theoretical approaches with the typical values of operation of the cutting file machine.

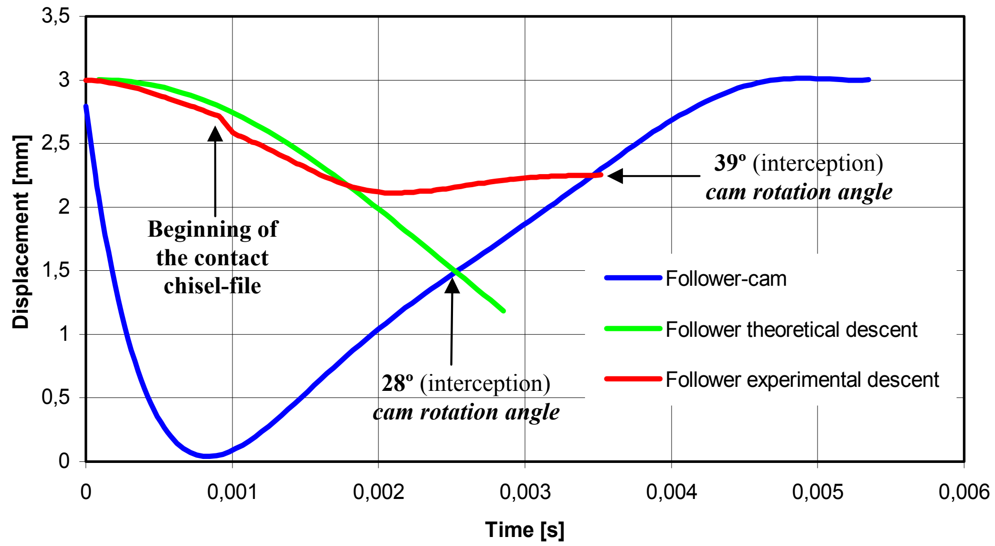

Figure 15 - Theoretical model results versus experimental data for the follower descent.

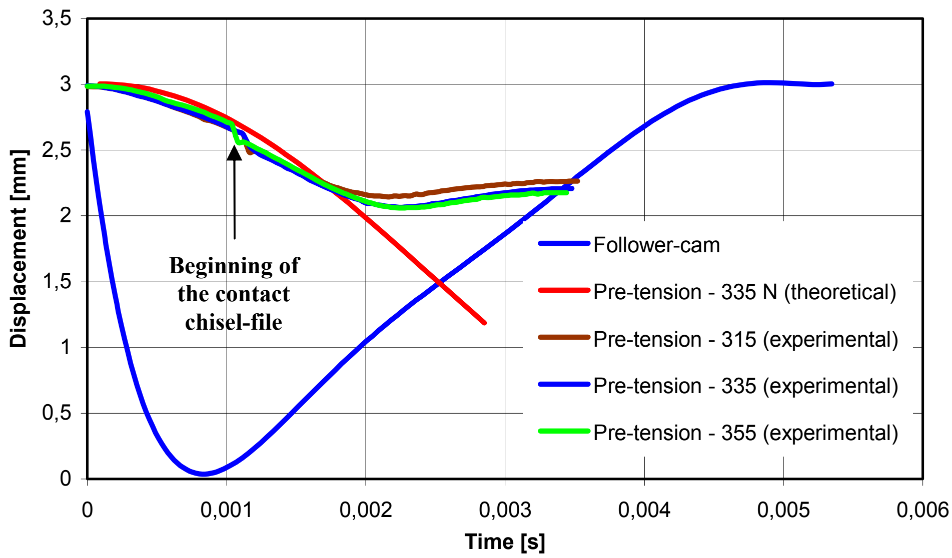

Figure 16 - Theoretical model results versus experimental data for the follower descent for different values of spring pre-tension.

From the results presented in figures 15 and 16, it can be concluded that a very good correlation is obtained between the theoretical and experimental results for the follower descent until the beginning of the contact between the chisel and the file base body.

CONCLUSIONS

The system currently used to produce files (mechanism, cam-pin-spring) is a very efficient way to generate discontinuous teeth, being the more effective for the forces and, especially, for the rates involved in the cutting process.

The maximum frequency that the chisel can operate is conditioned by the mass of the cutting body of the machine, commonly designated by crusher, and that it is composed by the pin, cylinder and chisel.

The main restriction of the machine cutting frequency is that the increase of the cam rotation implicates a decrease of the descent displacement of the chisel.

The cutting frequency can be increased with the decrease of the follower mass, due to the reason of the follower kinetic energy being almost independent of its mass.

The measurement system used to evaluate the process behavior has been developed and proposed. The waveforms obtained suggested that this system is adequate to measure the main parameters involved in the cutting operation and to understand the process itself.

The present research has been demonstrated to be successful using the theoretical model proposed to describe the follower descent.

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