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On the reduction of windage power losses in gears by the modification of tooth geometry

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Abstract

It has been previously demonstrated both experimentally and numerically that windage power losses (WPL) in high speed transmissions can be mitigated by flanges and/or shrouds close to the gears. However, the gaps between these obstacles and the rotating parts are so small that security during operation can be a problem. In order to overcome this issue, the idea of modifying tooth geometry as proposed by researchers in the early 2010s is investigated in this article. To this end, a numerical approach is first validated based on experimental evidence and then used to study the influence of the size of a tetrahedral shape at tooth edges on WPL. Significant reductions in WPL can be achieved via these tooth modifications but an optimal size has been found beyond which it is not profitable to go since WPL increase for larger modification amplitudes.

Background

Power losses in gear transmissions are traditionally separated into load-dependent and load independent losses. While load-dependent losses are generally dominant in standard applications, load independent losses can become substantial for high-speed gears. Among these losses, the so-called windage power losses (WPL) increase very significantly with velocity, especially for peripheral speeds above 100 m/s, as is the case in high-speed turbomachinery, aerospace or pump transmissions.

From the onset of research on WPL, different techniques were developed in order to mitigate this source of power loss. It was suggested in the pioneering work by Dawson [1] and later confirmed by a number of studies on spur gears, such as [2-5], that windage power losses can be partly reduced by using flanges mounted close enough to the gears. Similarly, several researchers reported the benefit of shrouds in bevel gears [6-9], particularly in aerospace applications. If there is a general agreement on the interest of enclosed gears, which lead to reduced windage losses, general and reliable models are still to be proposed.

It has been demonstrated experimentally [2-4] and numerically [5, 9-11] that, for certain gear dimensions, the positive effect of enclosures is only appreciable for very closely fitted flanges/shrouds. For instance, Hill mentioned clearances of 0.76 mm [10], Marchesse, 1 mm [5], Handschuh, 1.27 mm [3] and Fondelli, 4 mm [11]. The corresponding separations are indeed small compared with typical gear dimensions and the reported improvements appear as highly sensitive to this gap. For example, in [4], a flange at a distance of 1 mm from the pinion with a 288 mm pitch diameter leads to a 40% loss reduction, while a flange at 10 mm generates a 10% reduction only. All these studies suggest, that reducing flange clearance decreases WPL but, on the other hand, gearbox design imposes technical limits for security reasons, especially with high-speed applications for which, unwanted contacts between stationary and rotary parts would be catastrophic.

In order to address this issue, a rather different approach to WPL reduction is presented in this paper, which was initially proposed by Hill [10]. The author investigated four possible tooth shape modifications shown in figure 1, in order to deviate the air flow in an attempt to reduce WPL.

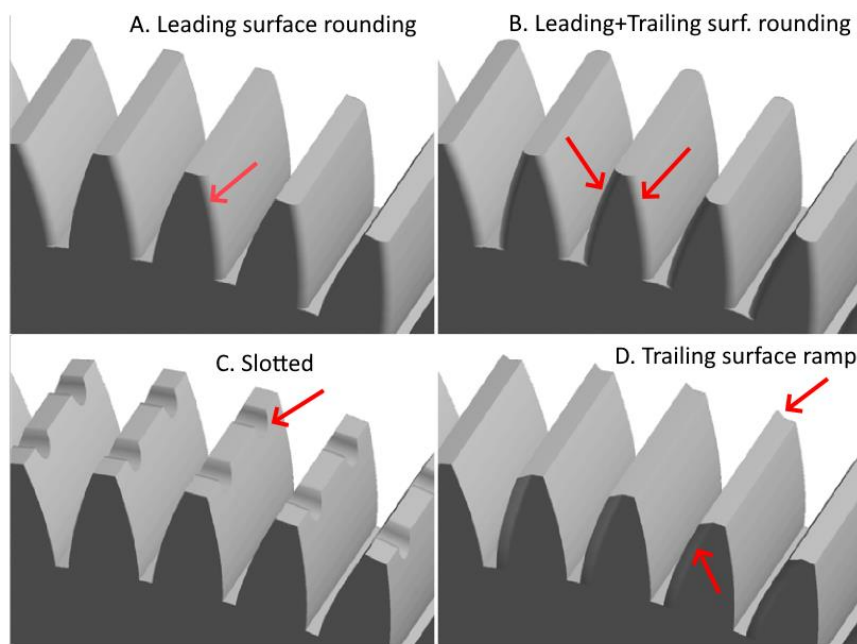


Figure 1 Four tooth modifications investigated by Hill [10]. A - Leading surface rounded, B - Leading and trailing surface rounded, C - Two slots at the tip of the tooth, D - Ramp at the trailing edge.

The effect of these modifications was analysed numerically and the resulting WPL versus angular velocity is shown in figure 2 (reproduced from [10]). It can be noticed that the leading-edge round (case A) and slot (case C) modifications do not change the overall power loss whereas the double rounding (case B) even downgrades the performance over the whole speed range. Only case D, corresponding to ramps at the trailing edges, gives substantial loss

reductions with respect to the baseline configuration. This ramp is supposed to deflect the airflow and prevents it from entering the inter-tooth spaces wherein most of the windage losses occur.

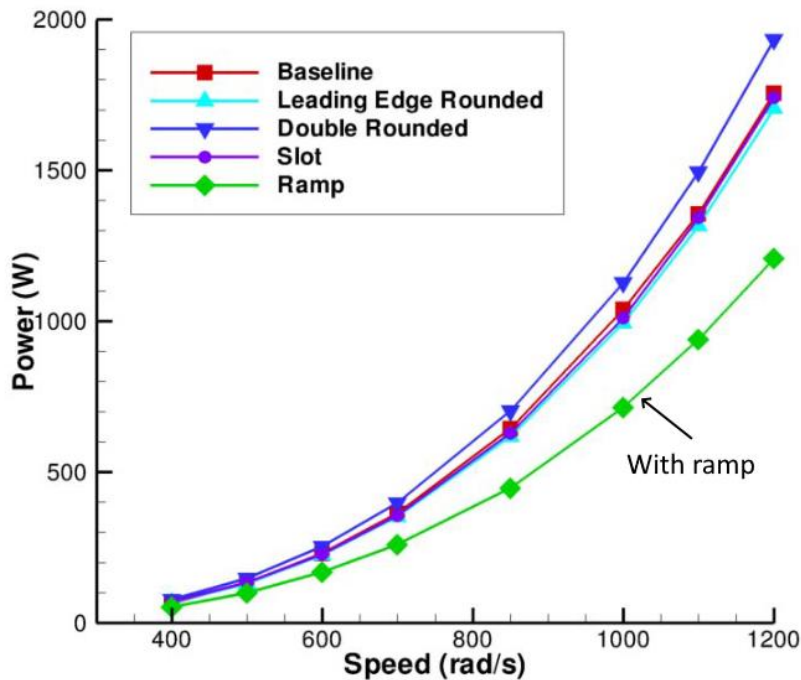


Figure 2 Numerically calculated windage power loss for pinions with different tooth modifications by Hill [10]. Note the case with ramp modification (Fig.1 D).

In spite of its potential interest, this finding with ramps on teeth has never been verified experimentally, partly because of the manufacturing difficulties. Modern 3D printing techniques however, make it possible to generate ramps on tooth edges and to test the actual WPL using printed gears. The major objective of this paper is to compare windage loss measurements and simulations for gears with and without ramps and prove that WPL can indeed be significantly reduced by such a tooth modification. Moreover, the size of this tooth modification varies in our study in order to see if it has an impact on WPL variation.

This paper is organised as follows. The general experimental setup with the geometrical data is presented in the next section, followed by a description of the numerical analyses. Finally, the experimental and numerical results are compared and discussed.

Experimental setup

The experimental measurements of WPL have been performed using the dedicated test rig designed for the purpose of windage power loss estimation (Figure 3) whose operating principles and methodology are described in [12]. No torque sensor is used here since WPL are derived from the Kinetic Energy Theorem and the deceleration curves from a given rotational

speed to rest, having disconnected the power transmission from the motor. Differential measurements are performed with and without gears in order to eliminate the power loss sources associated with the bearings, shafts and timing belt. Two gears can be mounted in order to study the air flow interactions between a pinion and a gear [12] but, in the present study, only the WPL for one single gear is investigated. When making several experiments based on identical rotating gears a standard deviation of 2.5% of the nominal values has been estimated what is more than the uncertainty value (less than 0.5%). The present measurements have been made with the pinion described in Table 1.

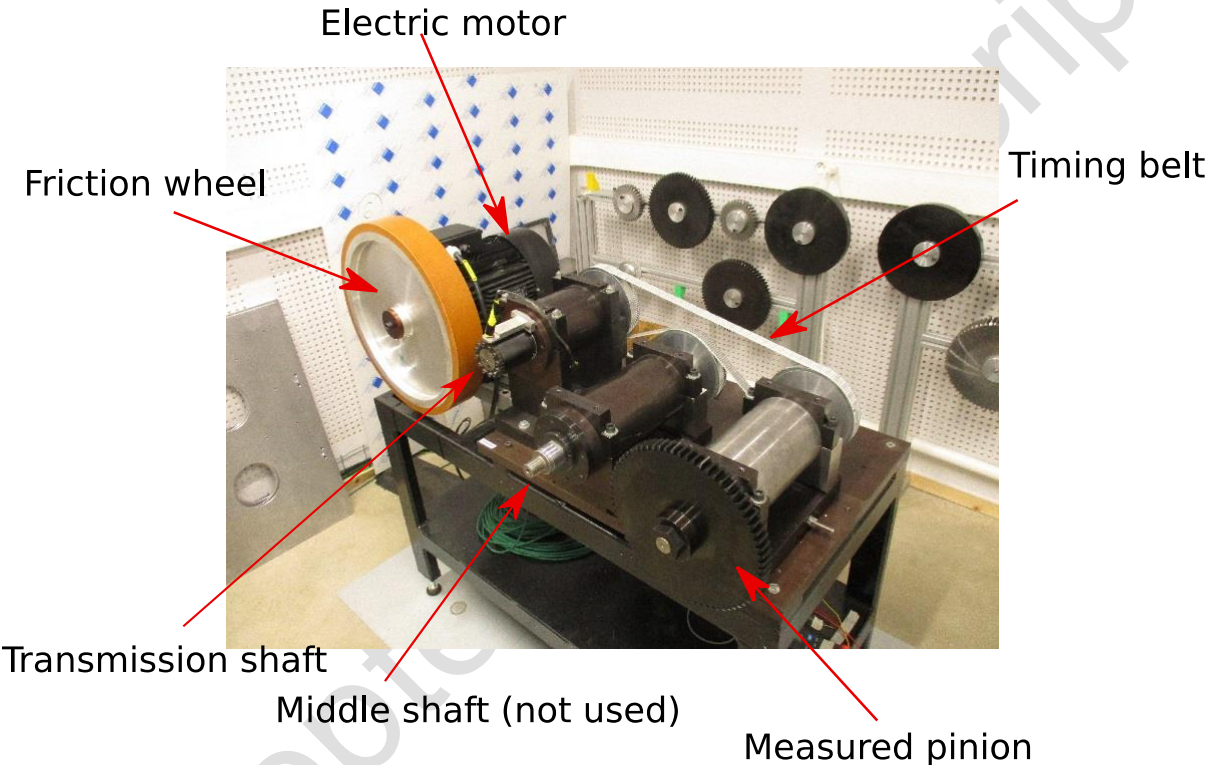


Figure 3 : WPL test rig [4].

Pitch diameter [mm]	Tip diameter [mm]	Face width [mm]	Module [mm]
288	296	30	4

Table 1 Geometry of the test pinion.

This pinion was employed in several studies [2, 9-11] and its WPL are well known. Unlike in the previous experimental analyses based on a steel pinion, PLA plastic has been used here in 3D printing to manufacture (i) a baseline configuration corresponding to a pinion with no ramps and (ii) a pinion with ramps located on the teeth side (Figure 4). The latter was printed from two symmetrical halves subsequently glued (the junction between the two halves is visible in Figure 4). Since it is very difficult to build the ramp as it is in Hill investigations due to 3D

printing precision it has been decided to print a ramp occupying the entire surface of the side of the tooth (the ramp studied by Hill occupies only one part of the side of the tooth, see Figure 1). The ramp geometry is approximately composed with a rectangular surface $1.6 \text{ mm} \pm 0.2 \text{ mm}$ thick at the leading edge, with this thickness decreasing steadily down to the trailing edge (Figure 5.b).

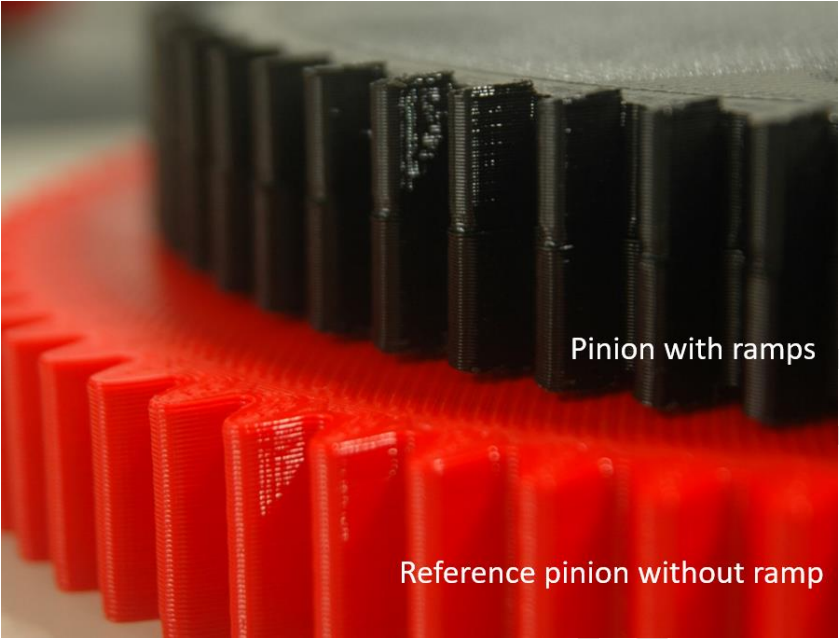


Figure 4 : Two 3D-printed pinions; below, the reference pinion and above, the pinion with ramps.

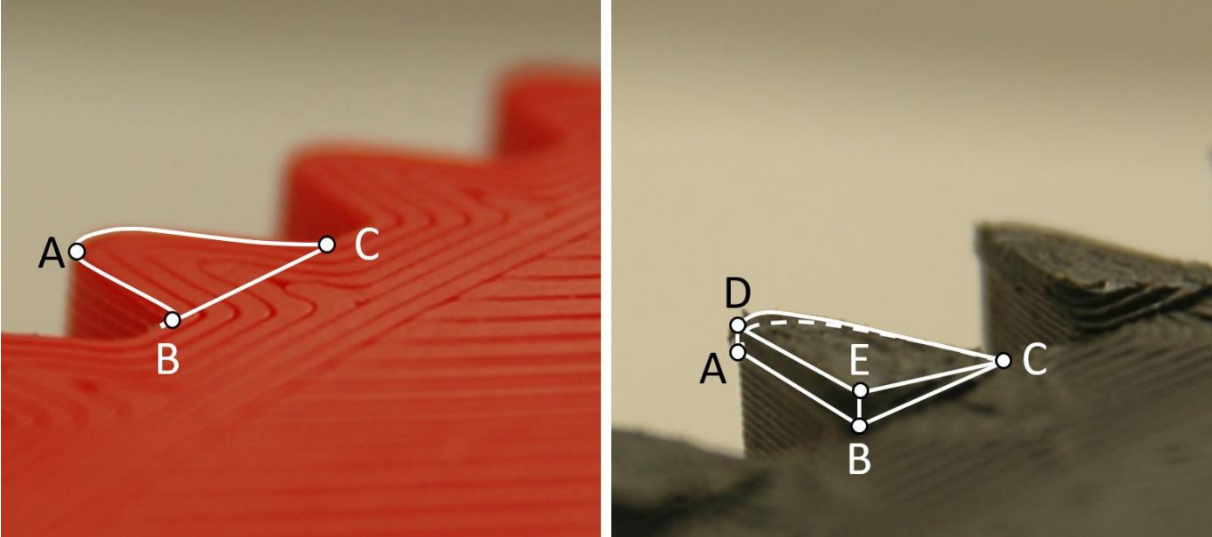


Figure 5 Two 3D-printed pinions. (a) the reference pinion and (b) the pinion with ramps. The width of the pinions is 30 mm, the size of the ramp is approximately $1.6 \pm 0.2 \text{ mm}$.

There are several differences between steel and PLA wheels. (1) The flank of the wheel made of steel is smoother than the PLA flank surface, which is likely to generate more losses due to the

viscous effect. However, many previous studies [5,10] have shown numerically that the contribution of viscous loss to total windage loss is small. (2) As it has been said the dimensions of the teeth are more difficult to satisfy precisely in the case of the PLA wheel because of the 3D printing effect. This last point could be behind the 10% difference in losses from the two kind of wheel without any ramp (Figure 6) what is higher than the uncertainty and the standard deviation values. The authors have previously emphasised that a slight modification of the tooth height leads to a WPL variation [13] what would be a consequence here of the height uncertainty for the PLA wheel. (3) The inertia of the 3d-printed pinions is not as well-known as that of the steel pinions. This is due to not homogeneous distribution of the matter in the volume of the pinion. Due to the 3d-printing technique, the inertia of the pinions is likely to be slightly underestimated, which may also explain somewhat lower values of the apparent WPL.

Further, the WPL are measured from a steel pinion and from the baseline PLA pinion in order to verify the capability of employing 3D printing when studying windage phenomenon. Next, the WPL are measured from both PLA pinion without and with ramps in order to investigate the capability of using ramps for mitigating WPL. In what follows, rotational speeds have been limited to 3000 rpm for security reasons and not damaging the plastic gears (N. B.: higher speeds up to 9000 rpm had been already reached with the steel pinion).

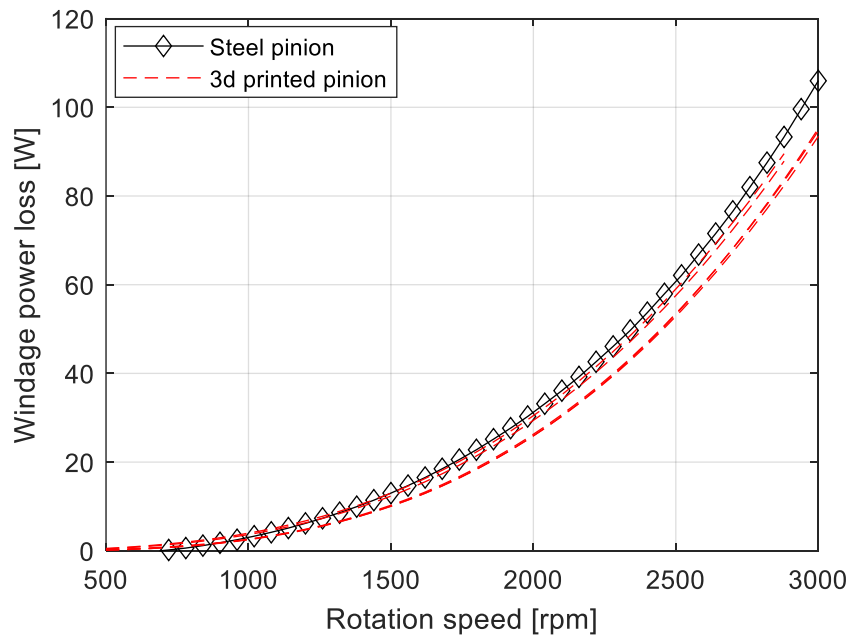


Figure 6 Experimental comparison between the plastic and the steel pinions without ramps in terms of windage power loss. Multiple red lines are indicating the scatter of individual measurements.

Numerical approach

The numerical method used in this study is detailed in [14]. In all the computational results in this paper, a three-dimensional domain is considered, which comprises one single tooth and

the associated fraction of the blank (Figure 7). One notices in figure 3 that one square-shaped surface is located behind the wheel. However, the WPL is mainly due to the airflow in the vicinity of the teeth that is drawn into the space occupied by the air between two consecutive teeth [5, 10] before being ejected. Therefore, the square-shaped surface should not have great influence on the airflow and should not act as a flange. Consequently, the numerical domain is simplified as mentioned above as in other investigations [5, 10-11]. The radial dimension of the domain is taken as 15 times the tooth height, while the axial dimension is 3 times the tooth width. Because of the problem symmetry, only one-half of the real tooth width is considered in order to reduce the model size. The mesh is composed of a structured mesh near the walls sufficiently fine to capture the near-wall turbulent region. For that, the dimensionless wall parameter y^+ equals 1 at the first grid points away from all the walls whatever the rotational speed (for example the height of the first cell equals 4.4×10^{-6} m when $N = 9000$ rpm). Beyond this first mesh layer, an unstructured mesh is constructed from tetrahedrons evolving with 1.1 growth rate. Simulations based on the Reynolds-Averaged Navier-Stokes (RANS) theory have been carried out using the SST $k-\omega$ low-Reynolds turbulence model proposed by Menter [15] and using ANSYS CFX 2020R2 code. Angular frequencies of 50 Hz, 100 Hz and 150 Hz (*i.e.* 3000 rpm, 6000 rpm and 9000 rpm) are used in the numerical calculations. The equations for incompressible airflows are solved as a simplification even if the maximum local Mach number was found to be equal to 0.4 for a rotational frequency of 150 Hz. This assumption seems reasonable since previous investigation [12] have shown that the WPL evolves with the angular velocity power 2.9 even at 150 Hz. Doing so the relative difference between the measurements and the numerical predictions remains nearly constant for both low and high speeds and is thus not far higher for the latter velocity range. Solutions are sought in a rotating frame for steady state flows with the Coriolis and centrifugal effects being considered. For all the computations, a nil velocity is imposed at all the nodes located on the gear tooth surfaces and periodic conditions are applied to the radial edges at the limits of the computational domain (Fig. 7). The surrounding fluid is supposed to be pure air whose physical properties at 25°C (*i.e.* $\rho = 1.185$ kg/m³ and $\mu = 1.831 \times 10^{-5}$ Pa.s) are considered. Convergence is reached when both the equation residuals are low, and the drag torque caused by windage keeps a nearly constant amplitude.

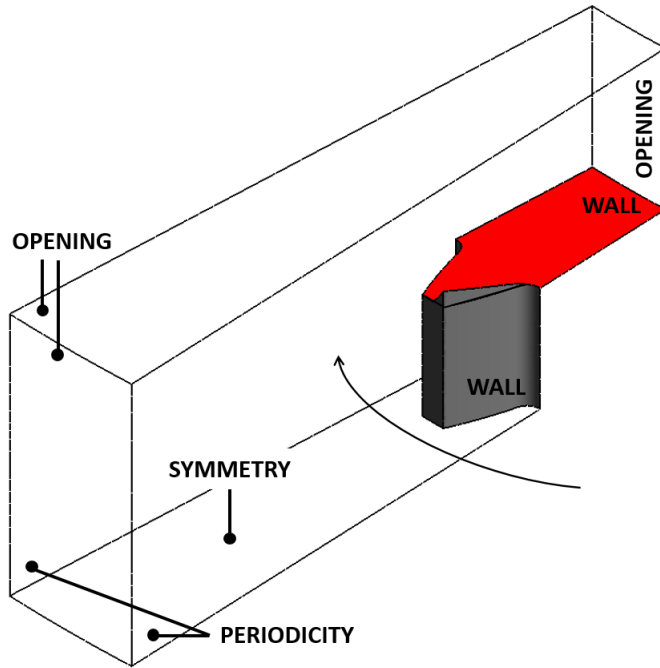


Figure 7 : Schematic of the CFD domain and location of the ramp at the trailing edge of the tooth.

As mentioned previously, the numerical approach aims at investigating the capacity of modifying the tooth shape by adding a ramp at its trailing side, and not necessarily one with a shape similar to Hill's [10] or similar to the present experimental approach, in order to reduce WPL. For that, the ramp proposed by Hill is simplified by constructing a tetrahedral shape, ABCD (Figure 8). Point C is located at the middle of the linear segment DE and remains unchanged as well as the other two points A and D. Only point B can be moved in order to modify the ramp geometry. Various simulations have been performed for different values of parameter Δ defined as the length between points B and D: $\Delta = \{0; 0.25; 0.50; 1.00; 2.00\}$ mm. The case when $\Delta = 0$ corresponds to an unmodified tooth shape. It should be noted that the geometry of the ramp numerically analysed by Hill [10] is slightly different from that used here since, in his work, point A is not located on the red plane in Figure 7 as it is also the case in the present experiments.

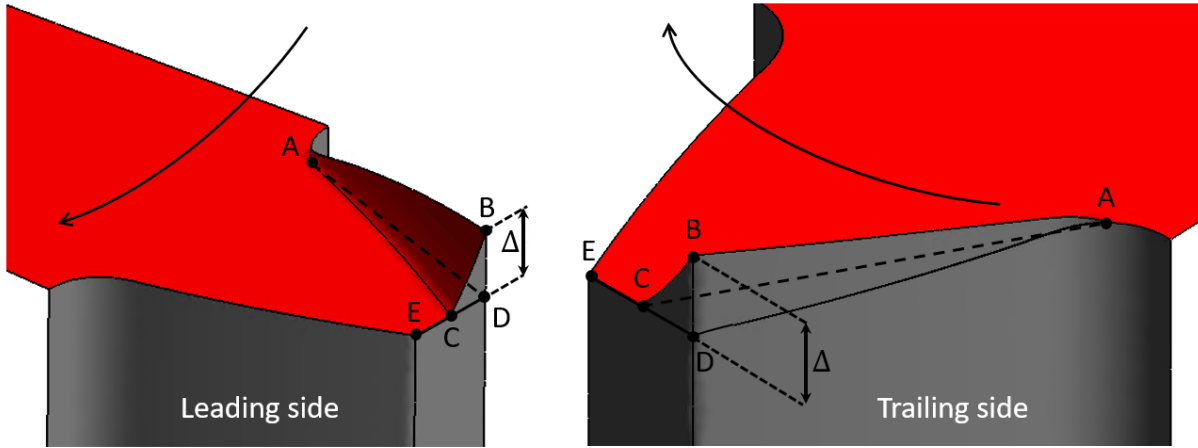


Figure 8 : details of the ramp geometry (from the leading side and the trailing side point of view).

Discussion of results

The experimental evidence in Figure 9 clearly reveals an influence of the ramp on WPL since at 3000 rpm (maximum speed) a reduction of 35 percent in windage losses is reported (*i.e.* $P_{ramp} = 0.65 \times P_{max}$ where P_{max} is the power measured when there is no ramp), thus confirming the numerical findings of Hill [10]. This experimental observation confirms also the capability of using a ramp in order to mitigate WPL. One observes moreover that if the rotation is reversed the WPL values increase highlighting the importance of the relative position of the ramp in comparison with the pinion rotation. This is mainly due to the pressure stagnation point that probably appears in the front of the ramp. The numerical simulation results based on the model described in the previous section are plotted in Figure 10 and, here too, a significant influence of the tooth ramp (via parameter Δ) can be observed. Interestingly, the reduction in WPL seems to be larger for $\Delta = 0.5$ mm and $\Delta = 1.0$ mm (68 %) than what has been found when $\Delta = 0.25$ mm and $\Delta = 2.0$ mm (35% only). It can be noticed that for the latter value of Δ , the numerical predictions are in good agreement with the measured WPL considering $1.6 \text{ mm} \pm 0.2 \text{ mm}$, *i.e.* nearly 35% reduction for the two approaches. It has been found that all the numerical WPL curves varies proportionally to approximately $\Omega^{2.9}$ (Figure 10), where Ω is the angular velocity so that the higher the pinion speed, the larger the losses regardless of the ramp geometry. However, the same relative loss reduction is observed whatever the angular velocity (Fig. 11) suggesting that the same influence of the geometry is observed at all speeds. The ramp contribution appears as non-monotonous with a clear optimal value of Δ close to 0.5 mm above which, the ramp efficiency in terms of WPL is downgraded.

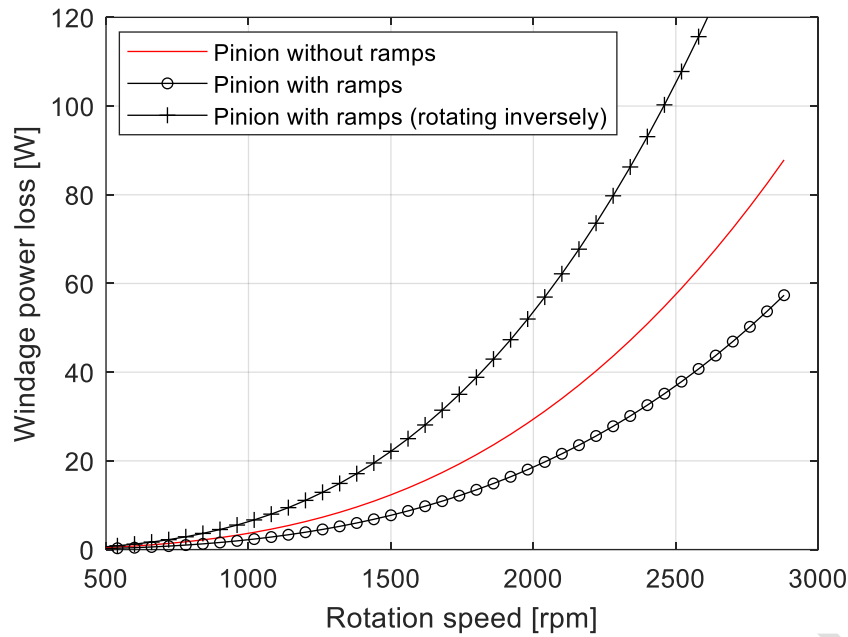


Figure 9 : Influence of a ramp on WPL (data from the measurement using pinion made with PLA).

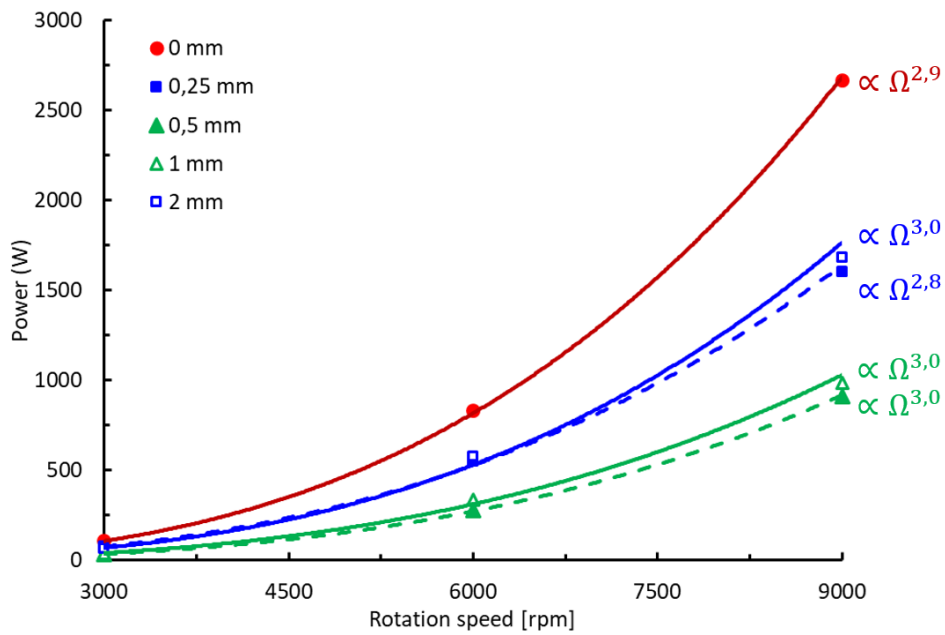


Figure 10 : influence of the ramp geometry on WPL (the symbols are data from numerical approach and the lines correspond to power regression).

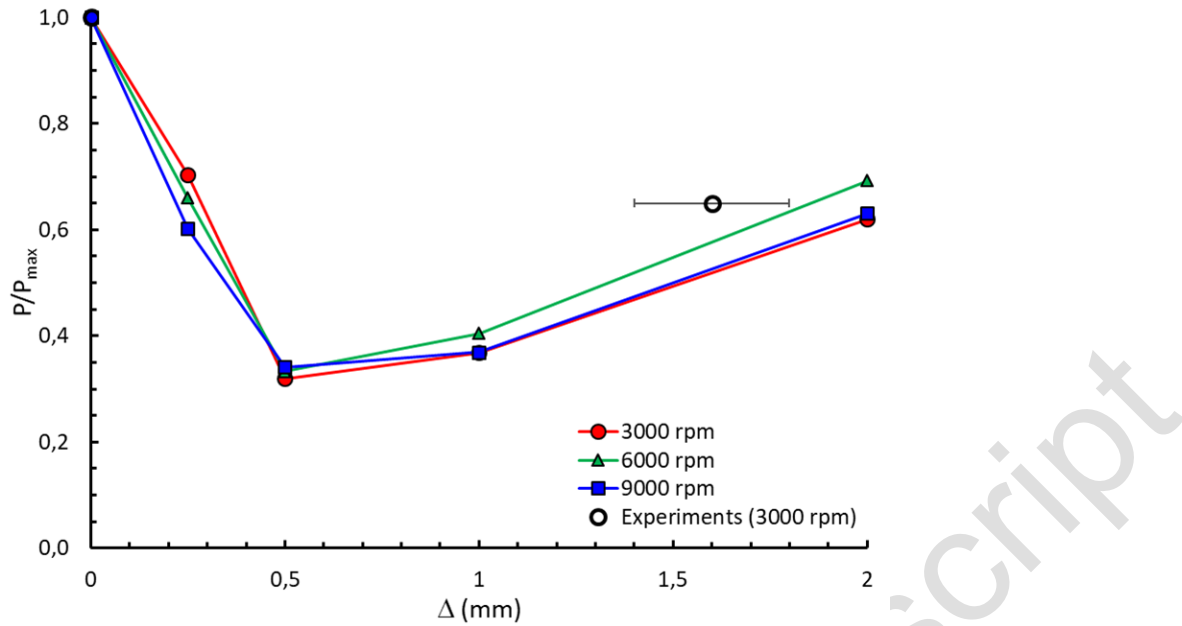


Figure 11 : influence of the ramp geometry on WPL decay (P_{max} corresponds to the maximum value of the power observed in the speed considered, i.e. when the ramp is absent).

This behaviour can be explained by considering the pressure coefficient $C_p = (p - p_\infty)/(0.5\rho V^2)$ where p_∞ is the pressure at a location far from the simulated tooth (i.e. at the radial opening boundary condition) and V , the tip tangential velocity. In the absence of a ramp ($\Delta = 0$ mm), the pressure coefficient distribution is independent of speed as illustrated in the first row in Figure 9, thus highlighting that the air flows pattern is similar for all speeds. This conservation of flow pattern is also reported in the presence of a ramp whatever the value of Δ . As a consequence, an increase in angular speed always leads to an increase in windage torque. Focusing on the influence of the ramp dimensions the distribution of pressure coefficient (columns in Figure 12), it is noticed between $\Delta = 0$ mm and $\Delta = 0.25$ mm that the pressure coefficient distributions are similar and differ mainly in terms of amplitudes. When looking at the streamlines this time, one notices in the two cases that the air above the tip radius is sucked into the region between two consecutive teeth before being expelled near the symmetry plane (streamlines in blue colour in Figure 13). Moreover the air from the gear side, that is drawn axially inside the teeth region when $\Delta = 0$ mm, is drawn in much less when $\Delta = 0.25$ mm or $\Delta = 0.50$ mm (streamlines in red colour). This is mainly due to the presence of the ramp that slightly deviates the airflow, preventing it from entering the cavity. Even if the streamlines are similar, the pressure coefficient distribution is drastically different for $\Delta = 0.50$ mm, as the region with overpressures due to the air flow impingement has disappeared compared with the results with smaller ramps. Moreover, the low-pressure area, which was located at the foot of the volume between two consecutive teeth, has moved up towards the tooth heads. The combination of these two phenomena leads to a minimum in the WPL curves. Increasing further the ramp parameter Δ appears not beneficial since the pressure coefficient

highly increases due the impingement of the flow onto the ramp and the corresponding windage torque becomes larger. One observes that the location of the region expelling the air has moved from the symmetry plane to the edge of the tooth decreasing the pressure coefficient in that region (Figure 13). So the numerical approach predicts that the size of the ramp plays a role in the shape of the flow and therefore in its parietal stresses. This reduction in WPL needs however to be validated by experiments using steel pinions.

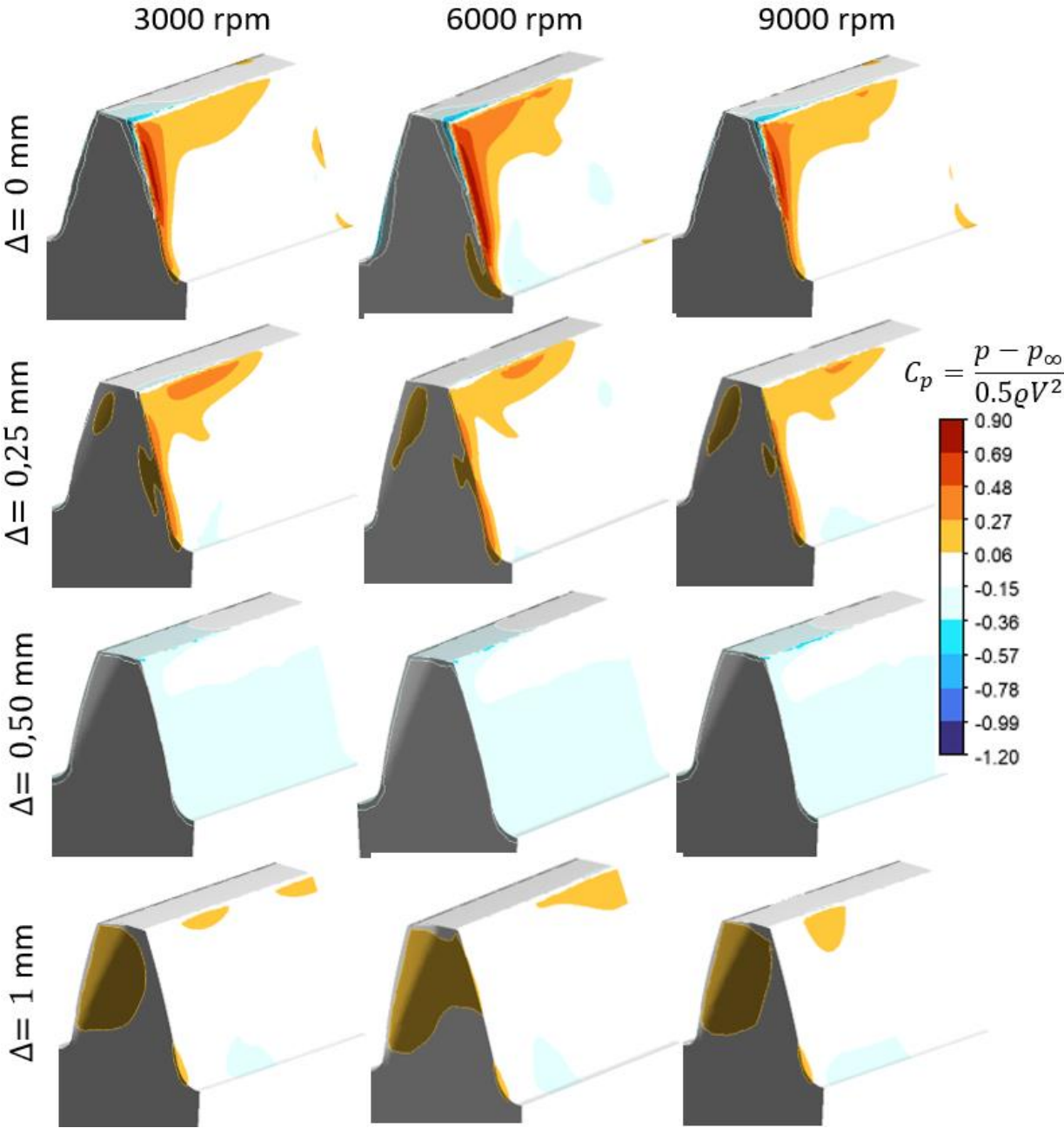


Figure 12 : predicted pressure coefficient distribution over half the width of the tooth according to the numerical value of Δ (lines) and the angular velocity (rows).

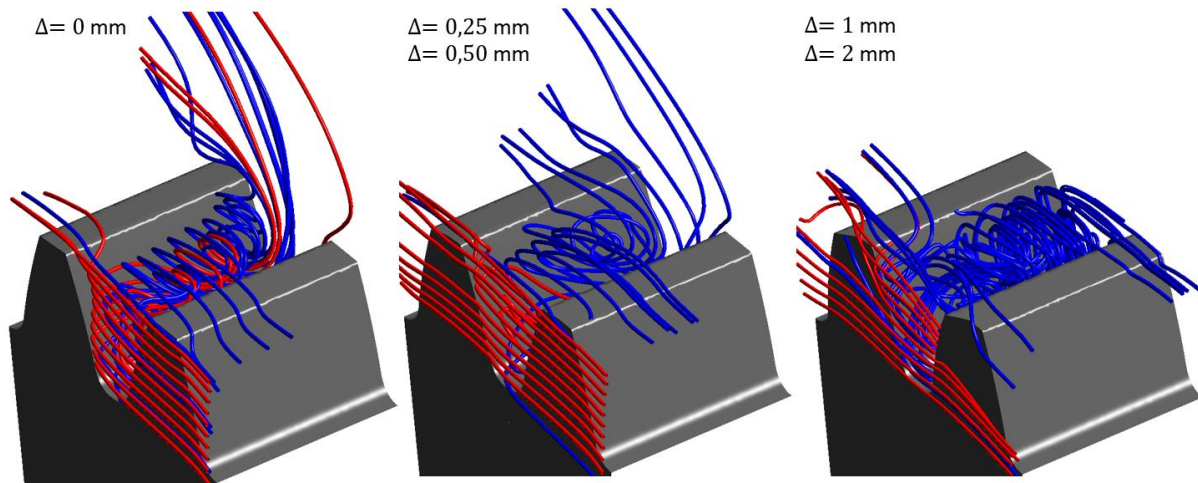


Figure 13 : predicted streamlines when the size of the ramp (Δ) is modified.

Discussion and conclusion

Both the experimental and the numerical results in this paper confirm the interest of a ramp manufactured on the teeth with regard to windage power losses. The experimental and numerical findings about WPL variations agree well and it can be concluded that the proposed numerical simulation procedure is accurate enough for analysing the WPL characteristics associated with modified teeth. The simulation results emphasize the existence of an optimum ramp parameter Δ , for which WPL reduction is maximum (up to 65 % for $\Delta = 0.50$ mm in the examples treated). Compared with the WPL improvements possibly brought by using shrouds [4], a maximum of 38% reduction only has been reached with symmetrical flanges positioned at 1 mm from the test pinion, which is potentially dangerous from an industrial point of view. If the numerical results are experimentally confirmed using steel gears, either manufactured by conventional machine tools or by 3D metal printing, the slight tooth modification investigated in this paper could be a simple, safe and effective solution for increasing high-speed gear efficiency.

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