POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Motorcycle aerodynamics: a CFD study from airfoil selection to winglet design for downforce increase and lap time reduction

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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Academic year: 2022-2023

1. Introduction

In the last few years a growing interest in aerodynamic is showing in all motorcycle racing teams, especially in the contest of speed race. In past years aerodynamic studies on motorbikes focus only on reducing drag forces and guaranteeing a sufficient cooling. Nowadays, all external fairings are modeled so that they can develop aerodynamic forces and moments that can improve dynamic behaviour of the motorbike. From 2015, a growing interest to the installation of some small wings, improperly called winglets, was expressed from all teams competing in Superbike and MotoGp championship. Due to secrecy reasons there are no publication about the main functionality of these winglets and about a their design methodology. The aim of this work is, through CFD simulation, to design high lift wings, that can operate in a wide range of Reynolds number, for motorbike application and analyze their influence on whole motorcycle aerodynamic and dynamic, with the use of a simplified dynamic model. In this summary, as in the thesis we will refer to that wings with the name of winglets, term probably coined by sports journalists.

2. Winglets design, from airfoil section to a single-element low AR wing

Winglets for motorcycle applications had to respond to some needs, typical of this field of application.

- A wide range of Reynolds number is encountered during real operating conditions
- They had to guarantee high lift force in a wide range of angle of attack
- Their dimensions have to be compatible with the pilot movement and the maximum motorbike lean angle

We started selecting from literature most appropriate airfoil section. Most suitable profile is found to be the MSHD (motor sport high downforce) developed in the work of Sriram, P. S., et al.[4]. Other two airfoils was selected in order to understand how much airfoil chose influence the performance of a low aspect ratio wing. First one is the NACA0012 and the second one the airfoil by Eppler, the E387. A comparison of the $Cl-\alpha$ curve between these airfoils was done both for the 2d-case both for a simple wing with AR2 and rectangular planform through CFD simulation done with OpenFOAM. In particular, we

used the steady incompressible solver, simpleFoam, to simulate all the angles of attack before the stall. Stall and post-stall conditions were simulate through the unsteady solver pimpleFoam.
Selected freestream velocity U is $30m/s$ in standard air, that, with a chord length of $150mm$ results in a Reynolds number equal to 3×10^5. This situation was considered the most representative for real operating conditions because, even if is slower than medium motorbike speed in a track, a lower Reynolds number is more critical for wings behaviour.

2.1. Validation of the models

Regarding 2d studies, we validated our model comparing the obtained $Cl - \alpha$ curve and C_p distribution of the E387 airfoil with results of experimental test at low Reynolds numbers by Nasa [1]. Comparison between experimental and numerical $Cl - \alpha$ is reported in figure 1.

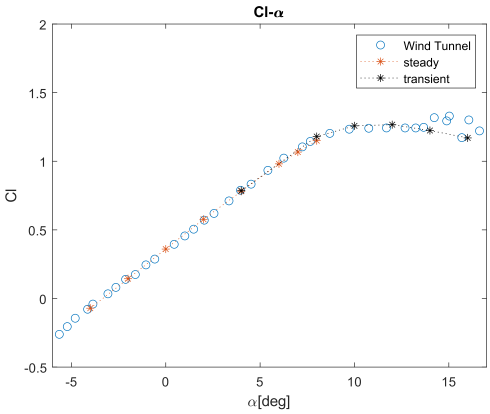


Figure 1: E387 Cl-α

We also report the comparison done at 7° AoA on the pressure coefficient distribution.

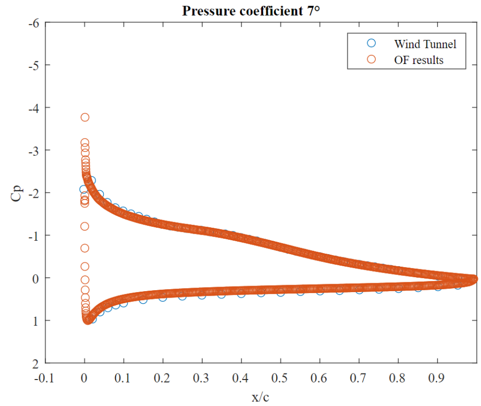


Figure 2: Comparison between numerical and experimental pressure distribution on E387 airfoil at 7° AoA

Same comparison was done also at 0° and 10° AoA with good agreements as for 7° AoA case. Validation of the 3d model was done with two steps:

- a comparison between OpenFOAM results and the ones from non-linear lifting line theory, obtained with XFLR5
- a comparison between the 2d pressure coefficient and the pressure coefficient of a section in the middle of a AR 20 wing, in which we can neglect the tip effects

Good agreement was found comparing lift coefficient results for the E387 at 7° AoA both from OpenFOAM both from lifting-line theory for a wide range of aspect ratio.

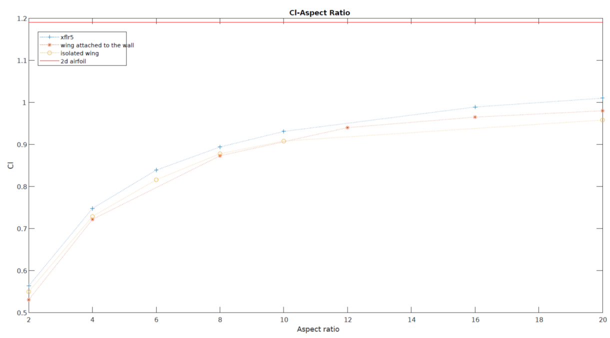


Figure 3: Comparison of lift coefficient for different AR between CFD results and lifting-line theory

Moreover, comparing the pressure distribution on middle section of an AR20 wing with the one of the 2d case we can notice, in figure 4, a good match of the results.

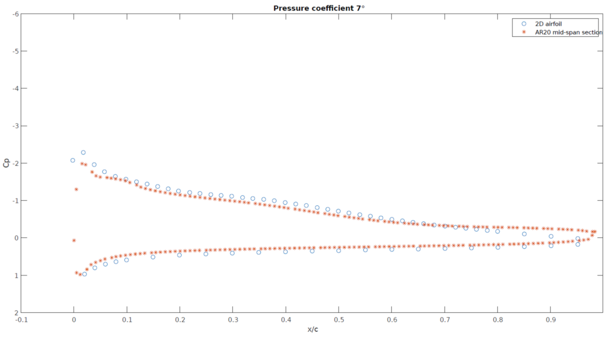


Figure 4: Comparison of pressure distribution between 2d case and middle section of an AR20 wing

Obviously, for each case described so far, a grid convergence study was done before comparing with experimental or theoretical results.

2.2. Effects of low aspect ratio

Once numerical models were validated we started to analyze differences and analogies between the airfoil section and low aspect ratio wings performance. We start showing the $Cl-\alpha$ curves for all three airfoil selected, compared with respective AR2 wing.

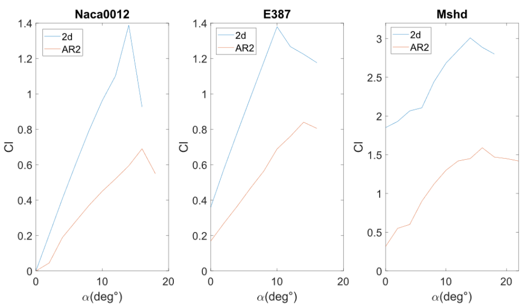


Figure 5: $Cl - \alpha$ curves for chosen airfoils compared with respective AR2 wingCaption

We can notice, for all three airfoils, a maximum lift reduction with an increase of maximum angle of attack and a reduction in the slope of the curve. Moreover after the stall angle we can see a smoother stall, compared with 2d case. However it is clear that 3d wings keep about the same gap of performance, in terms of maximum lift, of the 2d case and we can conclude that selected airfoil has a great relevance on the design process. Lift curve slope of E387 wing was also compared to the theoretical slope proposed by Lowry and Polhamus [2] with a very good match, a part for a little non linearity present at high angle of attack, probably due to the tip vortex. Looking at the Cl distribution over the span of the wing we can notice a progressively reduction of the lift moving from the root to the tip with a high peak on the region of the tip. This behaviour is responsible for the lift reduction described before and it's due to the strong influence of the tip vortex. We report, for different AoA the lift distribution on the MSHD wing in which this phenomena is more evident than in the other two wings.

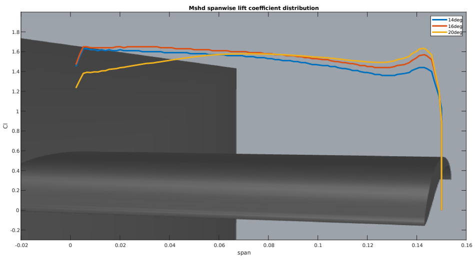


Figure 6: Mshd Cl distribution

We can notice also that the stall starts at the root, where tip vortex has less influence. For this reason, as said before, the stall is slower with respect to the 2d case. Regarding the peak present at the tip, we can see from figure **??** that tip vortex generates a low pressure region, deflecting streamlines towards the center of the vortex. For better understanding, in next figure, are reported for the MSHD at 14○ AoA a pressure contour of the wake and the streamlines near the wing.

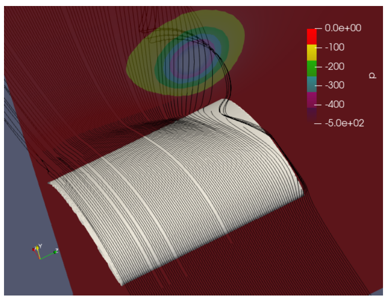


Figure 7: MSHD wing wake pressure contours and streamlines

This low pressure region affects both upper and lower surface of the wing, however in the suction side this phenomena has a higher intensity, resulting in the peak shown in figure 6.

2.3. Winglets design

During winglets design following geometrical parameters were anlyzed:

- **Simple planar endplates**, obtained with an offset of the airfoil. This kind of solution was inspired by the configuration used by Ducati in 2015 Gran prix world championship. We tested different offset dimensions from 5 to 20 mm. We noticed that increasing the endplate dimension an higher pressure is reached on the lower side of the tip region. This effect is already visible for the 5mm endplate but becomes stronger when dimension is increased to 20mm. This increase in lower side pressure should take advantages in therms of lift, however, in the suction side we experienced a strong reduction of the low pressure region generated by the tip vortex. This reduction implies the anticipation of the stall because reducing low pressure region an higher adverse pressure gradient is reached with consequent flow separation. This phenomenology has led to higher Cl at equal AoA but a anticipated stall, without consistently improvement of the researched performances, a part a very little increase in efficiency.
- **Taper ratio** from 0.2 to 0.6. We found that this parameter influence Cl and Cd with any changes in the stall angle. More interesting solution is that with 0.6 taper ratio for which higher lift with higher efficiency is obtainable
- **Sweep angle**. Sweep angle is primarily used in transonic and supersonic field, instead in subsonic field it generally does not take any advantages. However we considered it as possible interesting parameter because moving the tip back, or forth in case of negative sweep angle, with respect to the root, also the tip vortex position will change and that could have some influence on wing performance. For this test we selected sweep angles from $-10°$ to $30°$ with a step of $10°$. No significant influence was found also for low AR wings.
- **Shaped endplates** that has the aim of reduce the pressure loss on the lower surface of the winglets without losing the low pressure peak on the upper surface.

Final solution presents an endplate consisting of two parts. The upper part (the one facing to suction side of the winglet) endplate section consists of an airfoil, in particular the E387 with the suction side towards the root. At the contrary, in the lower part the suction side of the endplate airfoil is facing outward. The upper part is able to generate the same low pressure peak done by the tip vortex, instead the lower part can generate an high pressure region that reduce the flow from the pressure side to the suction side.

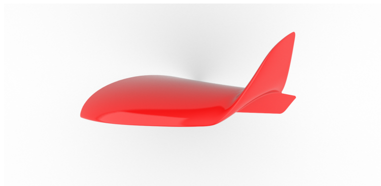


Figure 8: JG5 wing

This configuration reached a maximum Cl of 2.00 with a Cd of 0.44, thereby increasing the Cl with respect to the simple rectangular planform wing of about 20% with a 10% increase in drag.

3. Motorcycle studies

After completing the design and analysis of the individual winglet, we moved on to the analysis of the entire motorcycle so that we could compare the results and evaluate the actual change in performance given by the addition of the winglets. This study was divided into three main parts:

- Model validation
- straight motion configuration
- leaning configuration

3.1. Validation of the model

As for the validation of the model, we relied on the comparison of our CFD results with the experimental lift and strength values of the motorcycle obtained during tests at the wind tunnel of the Polytechnic University of Milan. The aerodynamic model was built specifically for the validation: the CAD geometry implanted in the OpenFOAM case consists of a faithful reconstruction of the walls of the test chamber of dimensions 4x3.86x6m with the simplified CAD model of the motorcycle without the rider on it positioned in the center. To be able to capture the entire wake and have a uniform Inlet condition, two extensions were added to the test chamber: the first upstream of the test chamber, the second in the wake. A domain-independence study was performed by going to change the section in the wake from 15m to 20m and 25m, In the last two cases we noticed that the wake was well captured, the sections far in the wake showed a quite uniform distribution in terms of velocity and, moreover, aerodynamic coefficients of motorcycle remain unchanged. Regarding the mesh, a mesh convergence study was done with the same set-up: the domain presents a first level of cell partitioning in the entire control volume, two consequent refinement boxes extend partially in the front of the bike and to the far wake, finally surface refinements were added on each component of the motorcycle, as in the test section walls. Having fixed the speed at 50m/s we obtained the results shown in the following table.

	Wind tunnel	**CFD**
Drag force	337.2	368
-	-	

Table 1: Results comparison between wind tunnel and CFD

The discrepancy in the results is mainly due to the quality of the CAD model of the motorcycle geometry, which in multiple components is highly simplified and not faithful.

3.2. Rectilinear motion

In order to analyze the motorcycle under real-life conditions, we made some modifications to the validation model used: primarily the removal of the test section walls, the addition of the rider on the motorcycle, and the speed condition fixed on the floor to simulate asphalt. In addition, to reduce the computational cost, half the domain was simulated, since the motorcycle, while not symmetrical, the small asymmetries would not lead to bias in the results. Initially, we did a first simulation without winglets. Its results was used both for comparative purposes, both to, through Paraview visualization, understand which position on the fairings was the most convenient to place winglets. In order to do that, we visualized the p_{tot} on some plane, parallel to the ground, at various height: We can notice, descending with height, the growth of an high total pressure area that we expect to be beneficial for the functioning of the winglets.

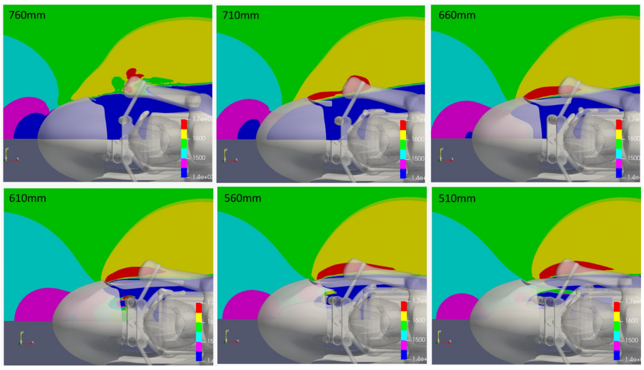


Figure 9: p_{tot} contours

Another parameter to take into account is the local flow direction. In particular the flow could not be aligned with freestream flow, acquiring a speed both in y both in z direction. An induced velocity in z direction would change the effective angle of attack of the winglets, instead an induced y velocity would generate a not desired sweep angle. To take into account of this flow direction changes, we plot on the same plane used for the p_{tot} the side and the 'vertical' angle.

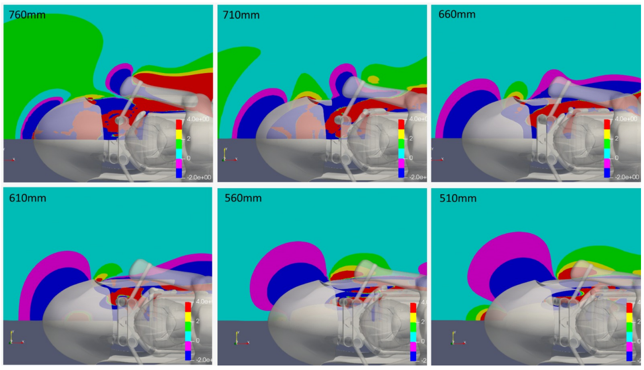


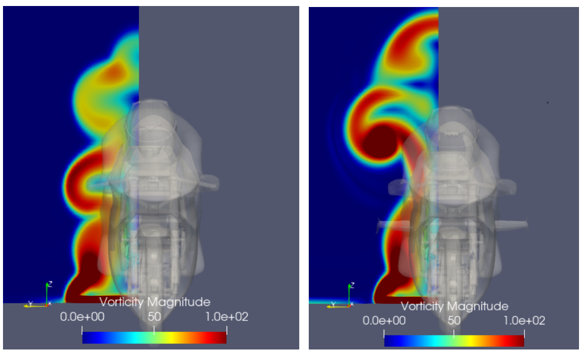
Figure 10: Sideslip angle contours

In some cases it was not possible to place the winglets in the desired place because the shape of the fairing did not allow it or, in the case of high leaning angle contact with ground would have been a problem. In the following table all the data are collected and the more intresting and suitable configuration is h=610mm.

height	Cl	Cd	Cl wing	Cd wing
without	-0.045	0.43	-	-
610	-0.27	0.47	-1.92	0.421
660	-0.25	0.48	-1.88	0.421
710	-0.15	0.46	-1.39	0.338
760	-0.17	0.46	-1.52	0.354

Table 2: motorbike with winglets

In the followuing figure we can see that winglets make the wake narrower in the zone behind the pilot and tends to move the wake upward. This can be an advantage because during competition, in particular during long straight, it is common practice to use the wake of the bike in front to decrease drag force. Finally we can see that the whole wake is dominated by the wing tip vortex. From that, we can understand that winglets could be optimized, instead of to maximize the lift, to control wake shape, reducing in size or moving where is convenient.

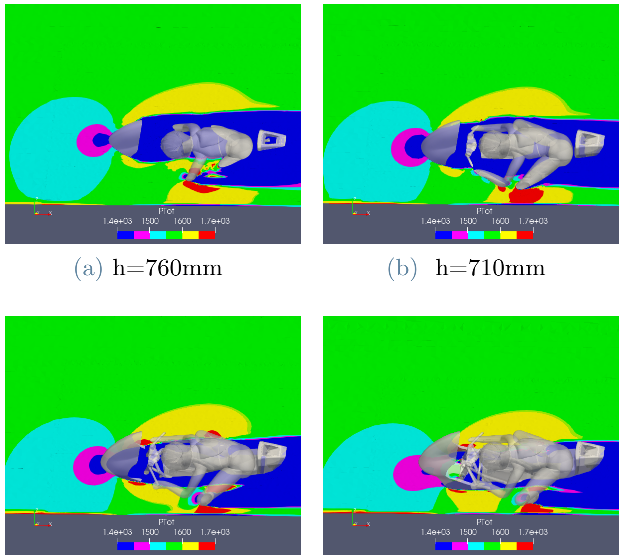


(a) without winglets (b) with winglets

Figure 11: Wake vorticity comparison

3.3. Cornering

To analyze the bike under cornering conditions, we had to make additional changes. First of all, the bike was tilted 50 degrees from the vertical, and consequently the rider's position in the saddle was changed drastically to suit the case. In addition, since motorbike no longer lies on vertical plane, the symmetry of the problem is lost, therefore we had to use the entire domain. Before proceeding testing the winglets we decide to repeat the pressure contour study made for placement choice, in figure **??**. In this way we can analyze if some locking occurs.



(a) h=760mm (b) h=710mm (c) h=660mm (d) h=610mm

Figure 12: p_{tot} contours in cornering condition

Leaving aside the area in the wake, there are no areas on the sides of the fairing where there is a consistent reduction in total pressure due to the rider. The only area would be in front of the inner knee but we discard this immediately because it is a smaller area than the winglet planform and in a position where the wing would bother the pilot. This can be view also from figure.

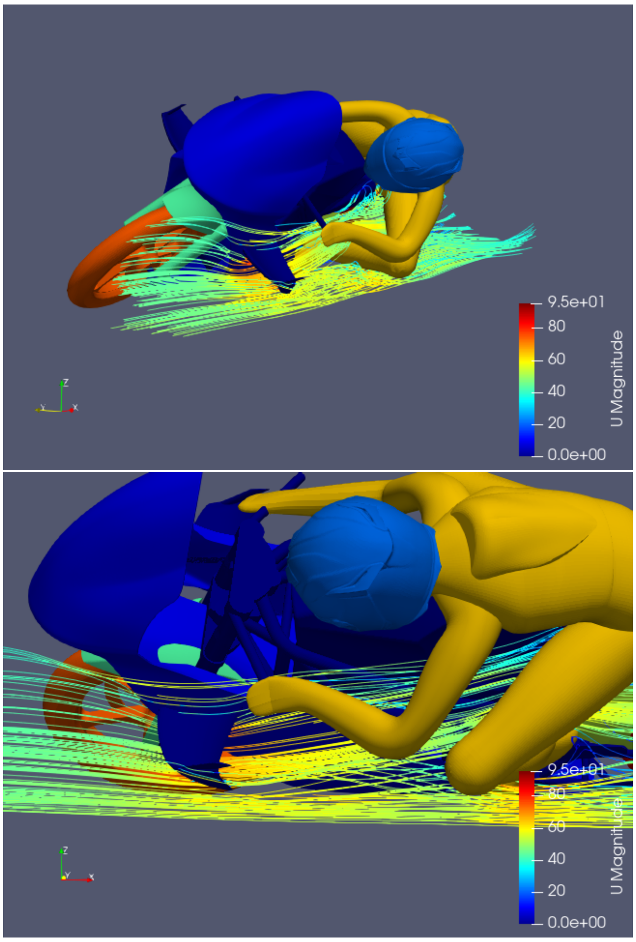


Figure 13: streamlines visualization during cornering motion

This analysis showed us that installing winglets with a dihedral angle, as proposed in the work done by Vojtech Sedla [3], would not produce any advantages so we maintained the original position and orientation to the wind.
In the Table 3 below, the aerodynamic coefficients of the entire motorbike with and without winglets are collected; they have also been written in body axes, thus following the 50-degree rotation with respect to the x-axis.

	ground axes			body axes	
	Cl	**Cd**	**Clat**	**Cl**	**Cd**
no winglets	0.12	0.73	0.00	0.08	0.73
winglets	0.00	0.74	0.08	-0.06	0.74

Table 3: aerodynamic coefficient in cornering

4. Dynamic model

In order to evaluate if in real operating condition winglets can take some advantages, a simplified dynamic code was developed to have an estimation both of maximum acceleration and deceleration in rectilinear motion both of mid-corner speed. From this simple work we obtained some indication of the effect of the winglets on the dynamic behavior of the motorbike. It was possible to try different positioning, concluding that by mounting them far forward favors maximum acceleration, at the expense of braking. Vice versa, installing them in a more backward position it is possible to increase maximum deceleration capabilities. The latest feature of this algorithm is to provide an estimate of the lap time so that we can effectively understand if we can get some benefits from the work done. We would like to point the hypothesis of this model:

- Motorbike with pilot are considered as rigid body. We only considered a variation of center of gravity position between acceleration and braking phase due to the driver movement.
- Rear and front suspension are modeled as simple shocks, without damping. A look-up table was implemented in order to consider the effects of rear suspension kinematic.
- All rotational inertia was neglected because we considered just slow variation of pitch angle.
- A simplified tyre model was used, in which we neglect rolling resistance and we modeled maximum driving and braking force as linear with the vertical load.

$$F_{\mathrm{x_{max}}} = \mu F_{\mathrm{z}} \qquad (1)$$

- Squat ratio is supposed to be negligible.
- A simplified aerodynamic model was used, in which we considered constant aerodynamic coefficients for all motorcycle trim in rectilinear motion that differs only with respect to the one of the cornering motion.

5. Final performance analysis

Data from aerodynamic studies was inserted in the dynamic model just described in order to have a complete overview on final motorbike performance variation. Final evaluation was done using data that characterize a high power motorbike, similar to the ones that race in Superbike championship. This choice is due to the fact that high lift winglets can be counterproductive if installed on motorbike with medium or low power because of their increase of drag, though not excessive. We report here a comparison between the base case without fins and the one with our winglets design installed.

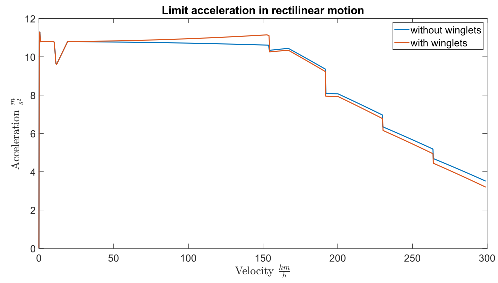


Figure 14: Limit acceleration during rectilinear motion

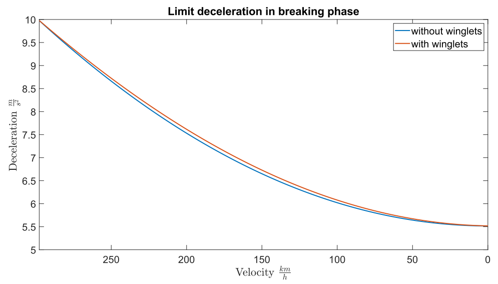


Figure 15: Limit deceleration during rectilinear motion

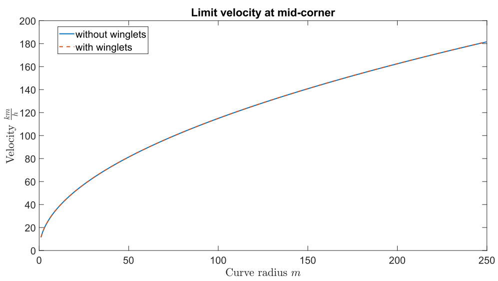


Figure 16: Limit velocity at mid-corner

We can see that:

- during acceleration phase some advantages can be obtained while speed remain lower than 150km/h. Over this speed additional drag contribution is unfavorable. However winglets at this speed range could improve motorbike handling and stability, but this is beyond the scope of our study.
- during deceleration phase winglets take a performance increase at all speed range
- during cornering any changes are manifested

This situation of uncertainty was solved using our simplified lap time simulator that estimate a decrease in lap time of 5 tenth of second considering a high average speed track.

6. Conclusions

High lift winglets were designed and installed onto an example motorbike to evaluate their influence on global performance.
We can conclude by saying that winglets designed for high lift purpose, can be beneficial only in straight part of the track and mainly on high power motorcycles. Advantages decrease as power decreases. Regarding cornering motion, as long as active aerodynamics is not considered, there seems to be no advantage.

References

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