INLET VORTICES IN A NACELLE OPERATING NEAR THE GROUND

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Abstract
Inlet vortices on a nacelle near the ground have important implications on engine operability, engine life and fan vibration. Three types of vortices occur when an engine is operating near the ground: ground vortex, between the inlet and the ground, able to suck debris into the engine; trailing vortex, the "trails" behind the nacelle and has a strong interaction with the ground vortex; and the attached vortex, a vortex that occurs attached to the nacelle and in some conditions increase the ground vortex strength, in others reduced it. This paper will describe these vortices in more detail. The ground vortex intensity is measured along the vortex core and shown to vary between near the ground and inside the inlet.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>D₀</td>
<td>inlet streamtube diameter</td>
</tr>
<tr>
<td>Dₜ</td>
<td>inlet highlight diameter</td>
</tr>
<tr>
<td>H</td>
<td>distance from the engine axis to the ground</td>
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<tr>
<td>U₀</td>
<td>crosswind speed</td>
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<tr>
<td>W</td>
<td>inlet mass flow rate</td>
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<tr>
<td>ρ₀</td>
<td>air density</td>
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<tr>
<td>Γ</td>
<td>vortex circulation</td>
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Introduction
An engine operating statically near the ground, at high power, has an inlet stream tube that will encompass part of the ground surface, where it will induce flow. Additionally, when a crosswind is present, the nacelle will behave as a finite cylinder in a crossflow: a separated flow region will exist on its leeward side with vorticity that is released to the downstream flow or ingested by the operating engine. These ground flow induction coupled with the separated flow region produce a complex flow structure where different vortices coexist and interact.

The name inlet vortex has been used in different contexts by different authors and, in general, describes any vortex that is caused by the engine and is ingested by the engine inlet. In the context of this work, i.e. nacelles operating near the ground, there are three types of inlet vortices: the ground vortex which forms between the ground and the inlet; the trailing vortex that form on the leeward side of the nacelle and the attached vortex that forms on the windward side of the nacelle.

Although these vortices are not usually visible, under humid ambient conditions the vortex core can condensate, making them visible. The ground vortex is also visible when the engine operates over water standing on the ground.
The three inlet vortices: ground, trailing and attached are shown in Figure 1.

![Figure 1 - Inlet vortices: ground, trailing and attached vortices.](image)

Computational Fluid Dynamics (CFD) will be used to allow a more detailed look into the inlet vortices phenomenon, describing the different vortices: ground, trailing and attached; their correlations and characteristics.

The geometry used in the analyzes is the DLR-F6 wind tunnel model nacelle with a modified inlet lip to ensure that the inlet flow is attached in all conditions.

The CFD analyzes were performed using CFD++, a commercial CFD finite-volume software. The three-dimensional Reynolds-Averaged Navier-Stokes equations are solved for the compressible flow using implicit, second order interpolation, nodal based polynomials and pre-conditioned relaxation. The turbulence model used was the realizable k-ε because previous results showed it predicted inlet separation more precisely.

A hybrid tetra-prism mesh containing approximately six million elements was used. Volumetric mesh densities were used to increase the number of elements in the inlet, ground vortex and nacelle wake regions (Figure 2).

The prism layer contained 25 elements across its height, with a growth ratio of 1.25. The y+ was adjusted to be the order of one on all domain.

![Figure 2 - View of the nacelle and mid volume plane meshes.](image)

**Ground Vortex**

The flow induced on the ground by an operating engine inlet encompasses the existing ground debris. It eventually sucks these debris into the engine and leads to engine damage, the so called foreign object damage (or FOD). Even if the ingested particles are small and do not damage the engine instantaneously, they can increase blade erosion or lead to dust deposits inside the engine, decreasing its life. The sole existence of induced velocities on the ground, however, does not mean that there is the risk of foreign object ingestion, because these velocities alone are not high enough to lift the debris. Actually the main cause of foreign objects ingestion by static engines is the ground vortex: a strong vortex that builds up between the ground and the engine. The ground vortex is able to lift particles from the ground which are much larger than the ones carried by the average inlet flow because of the vortex higher flow speed and lower pressure.
The ingestion of foreign objects by ground vortices has been a concern for more than 50 years. Many authors investigating ways of preventing the appearance of ground vortices. A summary of these existing inventions was published by Trapp and Girardi.

The first author to propose the minimum requirements for a ground vortex to exist was Klein, in 1959, conditioning it to the existence of:

- A stagnation point on the ground (or other fixed structure), where an omni-directional air flow parallel to the surface converges, in a manner similar to a sink;
- An updraft from the stagnation point to the inlet;
- The presence of the ambient vorticity, i.e. any kind of non-uniform flow, generated artificially or by wall shear.

If vorticity is not present the flow converges, but does not rotate, as shown in Figure 2.

A good correlation between ground vortex strength and engine inlet parameters can be found when comparing the inlet streamtube interference with the ground and a non-dimensional vortex circulation. The streamtube interference is calculated by the ratio between the ideal inlet streamtube diameter \(D_0\) and the diameter of an imaginary cylinder of radius equal to the distance from the engine axis to the ground \(H\). The ideal streamtube is the axis-symmetrical streamtube of an isolated nacelle, undisturbed by the ground. This definition implies that when the streamtube diameter ratio (SDR) is greater than one the inlet streamtube is in contact with the ground and a ground vortex possibly exists. The equation for the SDR is given by

\[
SDR = \frac{D_0}{2H}
\]

Considering that the ideal diameter is a function of the inlet mass flow rate \(W\), crosswind speed \(U_0\) and air density \(\rho_0\), the SDR equation becomes

\[
SDR = \frac{1}{H} \sqrt{\frac{W}{\pi \rho_0 U_0}}
\]

The non-dimensional vortex circulation is calculated by

\[
\Gamma' = \frac{\Gamma}{U_0 D_H}
\]

Where \(\Gamma\) is the vortex circulation and \(D_H\) is the inlet highlight diameter.

The result of the non-dimensional circulation, measured near the ground and plotted as a function of SDR is shown in Figure 4 for the following cases: (a) 10 m/s crosswind, inlet height ratio of 1.03, different engine mass flow rates; (b) 10 m/s crosswind, height
ratio of 1.13 and different engine mass flow rates; (c) inlet mass rate of 0.40 kg/s, height ratio of 1.13 and different crosswind intensities; (d) inlet mass rate of 0.34 kg/s, height ratio of 1.13 and different crosswind intensities.

![Ground vortex non-dimensional circulation as function of the SDR, with different scenarios.](image)

Figure 4 - Ground vortex non-dimensional circulation as function of the SDR, with different scenarios.

Figure 5 - Cut planes perpendicular to the ground vortex core, SDR 2.3, slipping ground.

It can be seen that the results of these four sets of data become superimposed, showing that the correlation is able to fairly predict vortex intensity based on engine distance to the ground, ambient and inlet conditions. Based on this, the CFD results to be presented in the following section will use SDR as the reference parameter.

Another interesting aspect of the ground vortex is that its intensity changes when measured inside or outside the inlet. Plane cuts can be used along the vortex core length to verify how the intensity changes as the vortex is ingested by the engine. Different planar cuts were made from the ground (0%) to inside the inlet (100%) for the SDR 2.3 case, as shown in Figure 5. The measurement planes are perpendicular to the vortex core.

The results for this case are shown in Figure 6. It can be seen that the vortex circulation outside the inlet, decays slowly, from the ground (0%) until 30% of the length. It then starts to decays more abruptly up to 40%, when the plane starts intercepting the nacelle wall. At this point it changes its tendency, to then raise abruptly, as it gets into the inlet (about 54% of the length).

Inside the inlet the vortex starts to decay again. It must be pointed
out that the vortex cross-section area is difficult to determine when it is entering the inlet, due to the high curvature and high velocity gradient. Nevertheless it is clear that, as the vortex gets inside the inlet, the vortex has gained circulation – reaching a peak non-dimensional circulation of 6.2. This means that there is some mechanism near the inlet by which the ground vortex gains intensity. It is near the inlet that the ground vortex gets in closer contact with two other inlet vortices that we will discuss in the next sections: the trailing vortex and the attached vortex.

![Figure 6 - Circulation along the vortex core and vortex core angle relative to the longitudinal axis.](image)

**Trailing Vortex**

The trailing vortex was first detected by De Siervi. It originates at the inlet and trails downstream of it, having approximately the same circulation as the ground vortex, when measured outside the inlet, but opposite rotation. More recently, Brix performed an extensive wind tunnel test campaign on a scaled model nacelle. The ground and trailing vortices’ speeds were measured inside the inlet using two rotating probes with hot wire anemometers: one probe measured the axial and tangential inlet velocities; the other measured axial and radial velocities. Different ground and trailing vortex combinations were shown to appear depending on the mass flow ratio, wind speed and direction. Brix also measured the circulation of the trailing vortex, showing that its circulation was considerably smaller than the ground vortex circulation, when measured inside the inlet. As the ground vortex, the trailing vortex also has different intensities inside and outside the inlet.

It was already shown using CFD by Trapp & Girardi and Murphy that each trailing vortex is made of two parts one that is ingested by the inlet and the other that is carried by the freestream, while one is captured back to the inlet in a more concentrated form through the vortex nucleus, the other keeps flowing downstream, occupying the core of the vortex, downstream of the ingested trailing vortex.

On Figure 7 it is shown the SDR 1.7 case, with stream ribbons that pass through the ingested trailing vortex core, colored by vorticity intensity, together with a plane cut inside the nacelle with longitudinal vorticity contours. It can be seen that the stream ribbons upstream of the nacelle do not contain vorticity and that they only gain strength on the back of the nacelle. These vorticity reduces as they flow to the ingested vortex most downstream point. There they are collected into the vortex core and sucked by the engine. As they flow back, their vorticity slowly increases, reaching a maximum strength near the inlet.
A detailed analysis of the trailing vortex flow shows that the trailing vortex has at least 6 different components, which are shown together in Figure 8: (a) vorticity from the upper part of the nacelle (green streamlines); (b) vorticity from the bottom part (orange streamlines); (c) the ingested trailing vortex (blue streamlines); (d) the trailed trailing vortex (grey streamlines); (e) the vorticity film (black streamlines); (f) the channeled vorticity (purple streamlines).

These ingested parts of the trailing vortex interact inside the inlet with the ground vortex, given that the inlet walls put these vortices in close contact, which may explain the increase in ground vortex intensity seem in Figure 6.

**Attached Vortex**

The attached vortex appears on the bottom the of the nacelle windward side, channeling vorticity into the inlet. This vorticity in some conditions add to the ground vortex intensity, in others reduce it.
The crosswind component over the nacelle produces an effect similar to that of the crossflow over a circular cylinder: the crosswind component interacts with the nacelle walls and creates vorticity in the longitudinal direction that accumulates behind the nacelle, similarly to the wake behind the cylinder. The external vorticity accumulated in a wake is sucked by the inlet, gets further concentrated and is intensified by vortex stretching. Most of this wake was shown to end up constituting the trailing vortices, described in the previous section. In this section it will be shown what happens to other part of this vorticity.

The flow on the external nacelle wall creates vorticity in one direction that, when ingested by the inlet, inverts its longitudinal direction, as it is shown in Figure 9 which contains a sketch of the crosswind flow externally with the direction of the vorticity being created at the walls and ingested by the inlet.

In Figure 10 it is shown results for the case with SDR 2.3, it contains isocurves of constant vorticity on planes passing to the center of each sector. The external vorticity downstream of the nacelle, like in a cylinder, accumulates in a wake and is progressively ingested by the inlet. While it is being sucked, the wake gets further concentrated and the vorticity is intensified by vortex stretching.

![Figure 9 - Crosswind flow over the nacelle with the direction of the vorticity being created on the external wall.](image)

The isocurves in Figure 10 depict the location of the wake behind the nacelle and how this wake is further concentrated on the forward portion of the inlet. The location of the center of the top wake, which forms the trailing vortex, moves to the back of the nacelle, as the flow approaches the inlet lip.

![Figure 10 - Bottom view of the nacelle with isocurves of constant axial vorticity at different longitudinal planes, SDR 2.3.](image)
Another situation is when the ground vortex is at its peak strength, at SDR equal to 1.70 (Figure 11). It then becomes so strong that it interacts with the nacelle bottom surface and produces vorticity that, when ingested by the inlet, opposes the ground vortex vorticity. It merges with the ground vortex inside the inlet and reduces its circulation.

Figure 11 contains ground vorticity isocontours at a plane at 11% of the inlet length, positioned so that it does not intersect the nucleus of the inlet vortex outside the nacelle. Even without intersecting the ground vortex, the cut plane contains a region of high longitudinal vorticity on the bottom windward part of the nacelle. This vorticity is being created by the high intensity ground vortex that induces velocity below the nacelle and produces vorticity on its bottom walls. In this region the velocity is opposite to the freestream flow direction.

As this attached vortex vorticity goes into the nacelle it weakens the ground vortex. Nevertheless, despite this attached vortex having vorticity opposite to the ground vortex vorticity when they interact inside the inlet, the ground vortex is the strongest possible.

Conclusions

The three major inlet vortices that occur when a nacelle operates near the ground were described. The ground vortex is the most important of them because it has the potential to disturb engine operation and even damage it. The trailing and attached vortices, on the other hand, are not directly harmful. However, given that they interact with the ground vortex, they must be considered when designing experiments or performing analyses.

The ground vortex was shown to vary its intensity when measured outside or inside the inlet. The reason for this variation is the interaction with the trailing and the attached vortex. While the trailing vortex circulation is always opposite to the ground vortices’, the attached vortex can have circulation opposite or in the same direction as the ground vortex.

References


