Far-Wake - Medium-long-wave instabilities

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Far-Wake - Medium-long-wave instabilities

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Abstract:
This report corresponds to the synthesis of the research activity conducted in the framework of Subtask 1.2.2 of the FAR-Wake project, the title of which being "Medium-Long-Wave instabilities". In this Subtask, the partners investigated different aspects of the major mechanisms which may disorganize an aircraft wake. The activities in the Subtask mainly focused on the so-called 4-Vortex-Systems (4VS) which model aircraft wakes composed of two vortex pairs. A promising counter-rotating configuration has been especially investigated by way of experiments and advanced numerical simulations. Other promising results have been also produced, such as the optimal way to destabilise a 2-Vortex-System (2VS).

Key words:
VORTICES ; TURBULENCE ; AIRCRAFT TRAILING VORTICES ; PIV ; DNS - LES ; VORTEX METHODS ; HYDRODYNAMIC STABILITY ; OPTIMAL PERTURBATIONS
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Duration: 40 months

*Medium-long-wave instabilities*

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1. INTRODUCTION

In the framework of Subtask 1.2.2 the title of which being "Medium-Long-Wave instabilities", the partners investigated different aspects of the major mechanism which may disorganize an aircraft wake. The following subjects have been considered:

- **Theory**
  - Transient growth in dipolar vortices (ONERA)
  - Global stability analysis of 4VS (UPM)

- **Experiments**
  - Produce a 4VS generator and test it in a large towing tank (DLR)
  - 4VS generator in wind tunnel (TUM)
  - LES about turbulence on LW instabilities (TUE)

- **CFD**
  - Temporal-Spatial DNS-LES of 4VS (UCL)
  - LES on 4VS (ONERA)

This report corresponds to the synthesis of this research activity, the numbering of which was provided in the Figure 8 of the Description of Work of the FAR-Wake project, Revision 3 issued on January 11, 2006 [1]

The activities in the Subtask mainly focussed on the so-called 4-vortex-Systems (4VS) which model aircraft wakes composed of two vortex pairs in a co-or in counter-rotating configurations. Realistic landing or taking-off aircraft configuration may produce such 4VS after recombination of the different sources of vortices produced at their flap edges and/or at tail tips. If vorticity is conveniently distributed among the vortices, the system may undergo destructive interactions.

The objectives of the task were:

- to explore further by way of theory the potential of this idea : minimum lifetime, physical mechanisms responsible of the final wake collapse ;
- to test the capacity of modern simulation tools to reproduce the phenomenon ;
- to provide experimental data on 4VS

The reference ‘baseline’ case corresponds to the former "ONERA configuration" scrutinized theoretically by Fabre et al. [2] also referred to as "AWIATOR's benchmark" since used by several CFD partners (CERFACS, DLR and UCL) in the framework of the AWIATOR project. This is four vortex system (4VS) compounded with two vortex pairs of circulations and separations such that $R_1 = \Gamma_1 / \Gamma_2 = -0.3$, $R_2 = b_1 / b_2 = 0.3$, see figure 1.

![Fig. 1 – 4VS model [3]](image-url)
The instability potential of such vortex systems for any values of \( R_t \) and \( R_b \) was investigated by Fabre et al. [2]. The choice of \( R_t = -0.3, R_b = 0.3 \) was considered as a limit for a realistic aircraft wing which is unlikely to support large load at its extremities that smaller \( R_t \) and larger \( R_b \) would imply. With this constraint, at 30 wing spans, the perturbation having the higher amplification, called \textit{optimal perturbation}, grows by a factor \( 10^2 \) to \( 10^4 \) with a wavelength of the order of the wing span. During the linear phase, this ‘explosive’ perturbation mainly affects the secondary vortices. Interaction with the main vortices then occurs leading to collapse of the wake into a single vortex pair. Interaction of the two vortex pairs amounts to a transient turbulent regime during which a significant part of the kinetic energy of the wake is dissipated. A long wave instability then takes place in the system and drives the wake towards final dispersion following the scenario described by Crow [3].

The above described physics amounts to a scenario of \textit{‘passive control’} as regards to the objective of reducing the strength of a wing wake because background noise, once such a 4VS has been produced by the wing plan form, suffices to ‘seed’ the optimal perturbation. Another scenario also proposed in reference [2], is an \textit{‘active control’} scenario based on the forcing of the long wave length corresponding to the dominant instability that takes place after collapse of the two vortex pairs. Linear theory predicts that the optimal growths obtained by means of this long wave forcing are much less than that of the optimal perturbation. But they lead to significant improvement with regards to the basic two vortex case. As a comparison, at 30 spans the initial modal perturbation is amplified more than 10 times whereas this needs nearly 100 spans in the case of a classical vortex pair. This is comparable to the growth of a factor 10 at 30 spans for the longwave transient growth mechanism characterizing the co-rotating configurations considered by Crouch [4]. But further downstream, if linear mechanism are still considered, the counter-rotating systems forced at a long wave length exhibits more larger amplifications than the co-rotating ones. Whether these instabilities can effectively lead to a reduction of the wake vortex danger will depend upon the subsequent nonlinear regime. But forcing the long waves in a four-vortex system gives a better guarantee of final dissipation of the wake by transport of vorticity through the plane of symmetry whatever the outcome of the nonlinear interaction between the two initial vortex pairs.

2. SCALING

A main objective of the work synthesized in the present report was to evaluate the gain of a 4VS configuration with respect to an equivalent 2VS. Given an aircraft with a forward velocity \( U \) and having its different surface elements set so as to produce a lift \( F_z \) which counterbalances its weight, one considers the variations in the lifetime of its vortex wake when its plan form is changed so as to produce different vortex configurations, in particular a 4VS. The lift \( F_z \) must be kept constant for such a comparison. A 4VS is supposed to favour a \textit{reduction in the lifetime} when compared to an equivalent 2VS and it is our purpose to quantify this reduction.

Given an aircraft producing a global circulation \( \Gamma \) distributed around two centroids separated by a distance \( b \), a meaningful time scale is \( t_0 = 2\pi b^2 / \Gamma \). This time scale is the characteristic time scale on which cooperative linear instabilities develops in two vortices of circulation \( \pm \Gamma \) separated by a distance \( b \). Physically, this corresponds to the inverse of the rate of shear felt by a vortex in the presence of its neighbour. For a 2VS, observations suggest that nearly \( 6t_0 \) are necessary for a complete dissipation of a 2VS, see Spalart [5]. Considering different vortex systems having the same lift \( F_z = \rho U T b \). One has \( t_0 = 2\pi \rho U T b \). By consequence, if the forward speed \( U \) is kept constant, the reference instability time scale above defined evolves as the cube of the centroid separation distance.

Let suppose now that modifications of the aircraft plan form leads, after some transient, to formation of a 4VS comprising 2 vortex pairs as schematized in Fig.1. Neglecting influence of the vortex core thicknesses, one gets the following relations:
The impulsion reads \( \Gamma b = \Gamma_1 b_1 + \Gamma_2 b_2 = \Gamma_1 b_1 \left( 1 + \Gamma_2 b_2 / \Gamma_1 b_1 \right) \). Accordingly, with \( R_1 = \Gamma_2 / \Gamma_1 = -0.3 \) and \( R_2 = b_2 / b_1 = 0.3 \), introduction of the second counterrotating vortex pair decreases the main wing circulation by 30\% (\( \Gamma/\Gamma_1 = 0.7 \)) and increases the centroid separation by the same proportion (\( b/b_1 = 1.3 \)). Impulsion of the total system \( \Gamma b \) is nearly 10\% less than that of the initial 2VS (\( \Gamma b/\Gamma_1 b_1 = 0.91 \)). Consequently, the reference instability time scale \( t_0 = 2\pi \rho U b^3 / \rho U' b \) of an equivalent 2VS having the same lift as that of the 4VS is increased by a factor \((1.3)^3 / 0.91 = 2.4 \).

Accordingly, a convenient way to compare different vortex configurations with regard to vortex wake alleviation issues amounts to normalize time by the reference time scale \( t_0 = 2\pi \rho b^2 / \Gamma \) characterizing a reference 2 vortex system having the same lift \( F_z = \rho U T b \). In the following we will note this reference time scale as \( t_{0,2VS} \). Considering a 4VS defined by (1), this reference time will be calculated as:

\[
t_{0,2VS} = 2.4 \times \frac{2\pi b^2}{\Gamma} \tag{2}
\]

Nota – Somehow different time normalisations have been considered by the partners in their report. Several are using recommendations made in [6]. The above described principles make comparison between the different contributions of this subs-task easier. They are also thought to be well suited to evaluate the potential of 4VS with regards to minimum lifetime.

3. EXPERIMENTS (PARTNERS: TU-MUNICH, DLR)

Two detailed experimental investigations have been conducted by two different partners using the same model, the DLR F13 model, which produces a 4VS system with counter-rotating neighboured vortices. This model set-up was chosen on the condition to create the most promising four vortex system to accelerate wake vortex decay by optimal perturbations enhancing inherent instability mechanisms, as described in [2] and [3]. A first experiment is conducted in the wind tunnel of TU-Munich. The second one, conducted by DLR, is a bigger experiment which took place in a large tow tank of SVA (Schiffbau-Versuchsanstalt Potsdam GmbH) with the objective to explore the flow further downstream and to preclude flow disturbances caused by end- and wall-effects.

3.1 Model

The F13 model represents a generic configuration consisting of a rectangular cambered wing and tail plane linked by a fuselage sting, Fig.TUM-DLR-1. Typically, the wing of the F13 model produces positive lift and the tail plane negative lift. The geometric data of the wing are: span \( b_w = 0.3m \), chord \( c_w = 0.05m \), aspect ratio \( AR_w = 6 \).
The geometric data of the horizontal tail plane are: span $b_{\text{HTP}} = 0.09\text{m}$, chord $c_2 = c_{\text{HTP}} = 0.035\text{m}$ and aspect ratio $AR_{\text{HTP}} = 2.75$. The span ratio of horizontal tail plane and wing is therefore $R_o = b_2/b_1 = 0.3$. The circulation ratio of the trailing vortices emanating from horizontal tail plane and wing is set to $R_T = \Gamma_2/\Gamma_1 = -0.3$.

![Image](image-url)

**Fig.TUM-DLR-1** - *DLR F13 model (from [DLR-1])*

### 3.2 Parameters

Three experiments have to be compared here, the one in the wind tunnel (4VS) and the two others in the towing tank (2VS and 4VS). They all have approximately the same chord based Reynolds number, $Re_c = 810^4$. Other characteristic parameters are compared in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>$U$ $(\text{ms}^{-1})$</th>
<th>$x^* = x/b_w$</th>
<th>$t^* = tU/b_w$</th>
<th>$\Gamma_1$ $(\text{m}^2/\text{s})$</th>
<th>$t_{0.2VS}$ $(\text{s})$</th>
<th>$\tau = \frac{t}{t_{0.2VS}}$</th>
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<tr>
<td>WT</td>
<td>2VS</td>
<td>24</td>
<td>/</td>
<td>/</td>
<td>~0.76</td>
<td>~0.60</td>
</tr>
<tr>
<td>TUM</td>
<td>4VS</td>
<td>24</td>
<td>≤ 48</td>
<td>≤ 48</td>
<td>~0.76</td>
<td>~1.44</td>
</tr>
<tr>
<td>TT</td>
<td>2VS</td>
<td>1.71</td>
<td>/</td>
<td>≤ 440</td>
<td>~8.48$^{(*)}$</td>
<td>≤ 9.10$^{(*)}$</td>
</tr>
<tr>
<td>SVA</td>
<td>4VS</td>
<td>1.71</td>
<td>/</td>
<td>≤ 608</td>
<td>0.054</td>
<td>20.35</td>
</tr>
</tbody>
</table>

$^{(*)}$ with $t_{0.2VS} = t_0$

**Table 1** - Characteristic flow parameters for the wind tunnel and the towing tank experiments

The angle of attack of the main wing is fixed at $\alpha_w = 10^\circ$ in the two experiments, so that one may suppose that the values of the lift coefficient $C_{\text{c,W}}$ of the main wing are comparable. The ratios $R_T$ and $R_o$ obtained with addition of the HTP are shown to be close to -0.3 and 0.3 by means of velocity contour integrations of PIV data.

In the towing tank, the wake is surveyed on distances $x^* = x/b_w$ nearly 10 times larger than in the wind tunnel. (440 versus 48). The model scale used in all experiments being the same, the circulation $\Gamma \sim U b$ and the time scale $t_0 = 2nb^2/\Gamma$ are set by the velocity which varies by a factor 14 between the wind tunnel and the towing tank.
Starting from the value $\Gamma_1 = 0.054 \text{m}^2/\text{s}$ measured by PIV in the towing tank for the circulation of the main wing, one gets $\Gamma_1 = 0.76 \text{m}^2/\text{s}$ in the wind tunnel. Separation $b_1$ is evaluated as $b_1/b = 0.9$ by DLR (to be compared for instance to the elliptic loading value $\pi/4$). This gives $t_0 = 8.48s$ for the 2VS in the towing tank and $t_0 = 0.60s$ in the wind tunnel. The reference time scale for the 4 vortex system, see (2), is $t_{0,2VS} = 20.35s$ in the towing tank and $t_{0,2VS} = 1.44s$ in the wind tunnel. The ‘vortex age’ $\tau = t/t_{0,2VS}$ attainable in each facility is indicated in the table. Note that the big towing tank allows a gain of nearly a factor 13 for this vortex age parameter of the 4VS (5.33 versus 0.42).

### 3.3 Experiment on a 4VS in a Large Tow Tank (Partner: DLR)

Four different configurations are considered in the experiments. One will consider the two first ones: the case of a 2VS with no horizontal tail wing and a 4VS case, with attached horizontal tail wing. The inclination of the tail wing was determined to achieve a circulation ratio of $R_f = -0.3$. This was verified by force measurements and by velocity contour integrations [DLR1].

Figure DLR-1 shows the plots for the 2VS case. The colour in the background of the vectors is related to the out-of-plane vorticity. Significant distortions of the vortex pair are visible at $t^* = 166$ ($\tau = 3.43$), a distance where we expect to feel the effects of the crow instability. Dispersion of the vortex system is evidenced at $t^* = 288$ ($\tau = 5.95$). This is in qualitative accordance with the observations of Spalart [5]. The results of figure DLR-1(d) suggest that this plane could be located between such two vortex rings formed by the Crow instability.

Fig. DLR-2 shows plots for the 4VS case. The inner vortex pair can be clearly identified between the outer tip vortices in the first plot starting to orbit around the tip vortices. At $t^* = 14$ ($\tau = 0.12$) and $t^* = 30$ ($\tau = 0.26$), the inner vortices have passed an angular position of about 45° and 100° respectively. Their deformation indicates a strong interaction with the tip vortices after which the inner vortices vanishes in the plots. Also the tip vortices are disturbed. A new 2VS of reduced circulation and increased spacing is formed and is visible up to $t^* = 375$ ($\tau = 3.23$). At this position, the vortex pair is subjected to strong perturbations which are likely attributable to a mature Crow instability. The vortex system then seems to be completely dissipated at $t^* = 608$ ($\tau = 5.24$).

These results show that a 4VS system evolves following two successive regimes. The first regime corresponds to the rapid development of the optimal perturbation. This regime ends with the formation of a new 2VS. It takes place within a “aging time” smaller than 0.5. Observations of the vortex pair of figures DLR-1(b) ($\tau = 1.43$) and DLR-2(e) ($\tau = 1.94$) suggests that the 2VS system issuing from this interaction is weaker, so less hazardous, than that obtained with the standard 2VS of equivalent aging. The second regime is a Crow instability. Comparing figures DLR-1(d) ($\tau = 5.95$) and DLR-2(h) ($\tau = 5.24$) shows that the final dissipation resulting from this unstable regime is achieved earlier for a 4VS.
3.4 Experiments on a 4VS in a wind tunnel (Partner: TU-Munich)

As in the preceding experiment, the required circulation ratio $R_t = -0.3$ for the DLR-F13 model is obtained based on force and flow field measurements [TUM1]. The value of the circulation ratio has also been proven by integrating the corresponding induced velocity fields. The wake vortex formation and evolution from the near-field up to the far-field is studied using smoke visualisations and hot-wire anemometry (PIV has also been used for complementary tests) [TUM2], [TUM3].

The vorticity distribution of the overall flow field is illustrated in Fig.TUM-1 which depicts all measured cross flow planes (note that the model is mounted inverted in the wind tunnel so that the vortices move upwards). According to Fig.TUM-1, the vanishing of the inner vortices which results from the linear instability regime corresponds to an ‘aging time’ of nearly 0.20. Then the Crow instability develops as revealed by the smoke visualisation results depicted in the right of Fig.TUM-1.
The wind tunnel experiment looks in good qualitative agreement with the one conducted in the towing tank. Moreover the hot wire measurements have provided time resolved results allowing some quantification of unsteady properties of the vortices (meandering, instability, turbulence).

![Flow field development: non-dimensional axial vorticity pattern (left) and schematic representation (right). See text for the definition of \( \tau \). Note that the model is mounted inverted in the wind tunnel so that the vortices move upwards.](image)

3.5 Experiments on wake vortex alleviation by differential and oscillating flap setting (Partner: DLR)

A third series of experiments have been devoted to the problem of wake vortex alleviation using Differential Flap Setting (DFS) and Oscillating Flap Setting (OFS). These concepts have been applied to a rectangular wing equipped with a flap partitioned into three equal parts which can be moved independently or not, see Fig.DLR-3.

The experiments were conducted in a water towing tank at DLR Göttingen. The different configurations tested are listed in the following table. Configuration 00 denotes the baseline configuration without flap moving, configuration 01 and 02 represent an outboard loading with DFS and OFS respectively to trigger long wavelength instabilities like Crow. The configurations are listed in Table 2 below. In the towing tank a free stream velocity of 2 m/s was chosen in order to achieve a Reynolds-number of 100 000 based on chord length of the wing. The frequency which was chosen for flap motion is 0.8 Hz.
The results, very preliminary, showed that the segmented flap with differential settings accelerates vortex mitigation thanks to interactions among the different vortices. The oscillating mechanism proved also to be operational. However, a quantitative analysis of these preliminary results is not yet feasible.

Steady and unsteady Euler calculations in near-field with DLR-Tau code, accounting for flap movement with Chimera technique, have been attempted.

### 3.6 Conclusions

The experiments on counterotating 4VS conducted in the course of the project have confirmed that these vortex configurations are less hazardous than equivalent two vortex systems. The results shows that dynamics of a 4VS is characterized by a rapid turbulent merging of the two vortex pairs which reinitiates a new two-vortex system with lower circulations, larger lateral separations and more perturbed and diffused cores. This new 2VS system is then rapidly dissipated by a Crow instability. The data provide good evidences that the lifetime of the 4VS wake vortex is reduced, at least, by a factor 2 compared to an equivalent 2VS. These results are well supported by the numerical simulations presented in the next section..

However, the towing tank experiment has been completed very late in the course of the project. Further analyses of the data is planned which should provide us with more quantitative conclusions in a near future.

At last, an experiment on the DFS and OFS approaches has been developed in the DLR-Göttingen water towing tank and can be used now for future investigations on the subject.
4. SIMULATIONS (Partners: UCL, ONERA)

4.1. Numerical simulations of 4VS (Partner: UCL)

The purpose of UCL was to numerically investigate, and thus further characterize, the potential of counter-rotating four-vortex systems (4VS) for rapid wake vortex demise. The ‘reference’ (baseline) case is the 4VS $R_T = -0.3, R_b = 0.3$, see Fig. 1. The main objective of the simulation is to describe the non-linear interactions that lead, first, to the merging of two vortex pairs, then to final dispersion. Some parametric variations have been considered by changing $R_T$ while keeping the geometry the same and the ratio $R_b$ constant.

Thanks to these simulations, our comprehension of the flow dynamics of the 4VS has been considerably improved. In the first part of the work, the vortex filament method (thus inviscid) was used to perform an efficient and parametric analysis of many cases ($R_T = 0, -0.1, -0.15, -0.20, -0.25$ and $-0.30$). All cases were initially perturbed using a random perturbation of the vortex centerline position at a very low level. The computational periodicity length was one Crow instability wavelength of the equivalent 2VS. The obtained wavenumber of the most unstable medium wavelength instability ($\lambda = b_0$) is smaller when the circulation ratio is higher, and the associated growth rate is higher, see Table 3. These results for the $R_T = \Gamma_2/\Gamma_1 = -0.3$ case are very close to those obtained by Fabre et al. [3].

\[
\begin{array}{|c|c|c|}
\hline
\Gamma_2/\Gamma_1 & \sigma^* & k b_1 \\
\hline
-0.10 & 6.7 & 8.20 \\
-0.15 & 7.2 & 7.21 \\
-0.20 & 7.5 & 6.27 \\
-0.25 & 7.7 & 4.78 \\
-0.30 & 7.9 & 4.53 \\
\hline
\end{array}
\]

Table 3 - Growth rate and wavenumber of the most unstable medium wavelength instability

In the second part of the work, the pseudo-spectral method with dealiasing was used (thus no numerical diffusion and no numerical dispersion). UCL performed large-scale large-eddy simulations (LES), using a high order spectral hyperviscosity as subgrid-scale (SGS) model: being high order, this model only acts at the highest wavenumbers of the computational grid. The initial vorticity field was the same as that used in the vortex filament method simulations. Simulations focused on the two most promising cases in terms of expected wake vortex demise: LES of $R_T = -0.3$ and of $-0.20$. Both simulations were performed using approximately 51 million grid points. The two cases were perturbed by adding a very low level random perturbation to the initial field. The global wake vortex dynamics were investigated for each case, using flow visualizations of vorticity fields. Indeed, the medium wavelength instabilities ($\lambda/b_1 = O(1)$) identified by both linear theory and by the vortex filament method, appear at first. This instability develops in anti-symmetrical or symmetrical ‘Ω-loops’ on the weaker vortex. Short wavelength core instabilities (‘elliptic instabilities’) on the weaker vortex were also captured. When the ‘Ω-loops’ instabilities have developed, the secondary vortices partially reconnect with the primary ones producing small scales and ‘vortex bursting’ events (which themselves also produce small scales).

A detailed energy analysis was also carried out: total energy, modal energy, energy spectrum. As a net result of the violent generation of turbulence, the total energy of the wake vortex system is seen to rapidly decrease. As shown in figure UCL-1, for $R_T = -0.2$ (resp. $R_T = -0.3$), nearly 50% (resp. 65%) of the 2D kinetic energy of the flow is lost at $\tau = t/t_0 = 7$. Here $t_0 = 2\pi b^2/\Gamma$ (see section 2).
Variations of modal energies are depicted in figure UCL-2. The obtained mean growth rate of the Crow instability for the 4VS is found to be up to ten times higher than the one for a 2VS, even for a low circulation ratio ($R_t = -0.1$). This is explained by the fact that the 4VS creates medium-wave instabilities that eventually (i.e. after some delay) also excite the Crow mode. Spectral analyses showed that the finally obtained turbulent 2VS is also seen to have a Kolmogorov-type spectrum for a significant range of wavenumbers.

Note that figure UCL-2 provides an excellent illustration of the two different regimes characterizing the 4VS dynamics: linear regime dominated by a medium-wave ($\lambda/b \approx O(1)$) – non linear saturation due to merging of the two vortex pairs – Crow instability on the finally formed 2VS.
Finally, in the third part of the work, a space-developing LES of the baseline 4VS was done (combining a ‘vortex-in-cell’ method, the parallel fast ‘multipole method’ and a “multiscale” SGS model). This simulation was done using 111 million grid points using a very high, and unrealistic, value of $C_L/AR = 1.35$ so as to limit the extent of the computational domain required for attaining sufficient development of the 4VS into a fully developed turbulent flow. Such a simulation was developed as a proof of concept of what is possible to do in space-developing simulation as of today.

4.2. LES of ‘most promising’ 4VS (Partners: DLR-ONERA)

DLR and ONERA have scrutinized, by way of LES, the ‘active control’ scenario described in [2]. This consists in forcing a 4VS at the Crow wavelength in order to promote the Crow instability which develops naturally in the last period of the flow evolution. Forcing the Crow wavelength in a 4Vs with $R_f = -0.3, R_b = 0.3$ leads to energy gain which are larger than that those resulting from the Crow instability on a 2VS.

The collaborative work by ONERA and DLR focused on the non-linear interactions between the two vortex pairs. The development of the flow is described in figure ONERA-DLR-1. Due to the large value of the forced wave length ($\lambda/\delta = 8$) the vortices remains more parallel than in the case of a free 4VS interaction. No ‘$\Omega$-loops’ form and the merger is different. The forced Crow wave emerges after one period, figure (c). Merger is due to secondary instabilities which develop on the closest vortex parts, see figure (d). The mechanism then propagates rapidly along the vortex cores, producing a new vortex pair with a total energy reduced by nearly a factor 2. The final Crow instability so obtained has a larger amplitude than that corresponding to a dipole equivalent to the 4VS of figure (a). Careful comparisons between this ‘active control’ and the ‘passive control’ scenario detailed in the previous subsection remain to be done in order to rank the respective configurations with regards to vortex wake minimization potential.

![Image](a)(b)(c)(d)(e)(f)

*Figure DLR-ONERA-1 - LES of the 4VS forced at the Crow wavelength. Red and blue: longitudinal vorticity, white: azimuthal vorticity*

4.3. Simulation of DFS and OFS (Partner: DLR)

Simulations of the DFS/OFS model described in section 3.5 have been conducted with the DLR-Tau code. An unstructured Euler grid from CATIA-V5 construction data of F13 model have been constructed with grid
5. THEORY (Partners: ONERA, DLR)

5.1. Optimal amplification of the Crow instability (Partner: ONERA)

A perturbation optimizing the amplification rate of the Crow instability has been found by using a global mode analysis. The technique detailed in Brion et al. [ONERA1], [ONERA2], is based on the resolution of an adjoint problem using a finite element method for the flow field and an Arnoldi Method for solving the eigenvalue problem. If the dynamics of the flow is driven by the most unstable direct eigenmode at large time, here the Crow mode, it can be shown that a specific initialization which consists in the adjoint mode of this most unstable direct mode will yield the perturbation with the maximum energy at large time, (see Schmid and Henningson [7]).

The basic flow considered here is two-dimensional. The pair of vortices is characterized by an aspect ratio $a/b = 0.2$ where $a$ is the radius of the vortices and $b$ is their separation distance. Importantly, this flow, on which the stability analysis is applied, is a realistic one, i.e. a solution of the 2D incompressible steady Navier-Stokes equations. It is obtained by a two-dimensional DNS started with an initial dipole composed of two Lamb-Oseen vortices with $a/b = 0.1$. During the simulation the two vortices basically diffuse under the effect of viscosity and adapt under the strain mutually induced by one vortex onto the other. The first effect, diffusion, is characterized by the viscous time $T_v = 2\pi a^2/\nu$. The second effect is characterized by the time $T_{3D} = 2\pi b^2/\Gamma$ of the three-dimensional perturbations. The first is larger than the second by a factor $\Re(a/b)^2$ with $\Re=3600$. Consequently, the base flow obtained when $a/b$ has grown up to 0.2 can be considered as quasi-steady for the forthcoming stability analysis. Using $T_{3D}$ and $b$ as reference time and length scales, time $t = 1$ is the time needed to have order 1 deformation of the vortices by the Crow instability.

This optimal perturbation of the Crow instability is shown in the left side of figure ONERA-1 by contours of $x$-vorticity (spanwise vorticity, oriented in the $x$ direction) while theCrow instability is shown in the right side by contour of $z$-vorticity (axial vorticity, oriented in the direction of the columnar vortices). The complete perturbation can be obtained by symmetry of the contours drawn here about the symmetry axis $x = 0$ of the dipole. In this figure the lines represent the streamlines of the base flow which is composed of two planar counter-rotating vortices. The vortices are supposed to be columnar which allows the study to be two-dimensional. The Reynolds number of the study is $\Re=3600$. We are interested in the perturbation of the pair of vortices at the wavelength of $\lambda = 2\pi/k$ where $k$ is the wavenumber corresponding to the Crow instability.

In Fig. ONERA-2 we compare the energy growth of the optimal perturbation compared to the modal growth of the natural Crow instability. It is clear that the gain obtained by using the optimal perturbation is subsequent. After 2 time units (1 time unit correspond to a visible Crow instability), the gain is equal to the value of the norm of the optimal perturbation and is 36. This corresponds to an acceleration of the appearance of a strong Crow instability of 2.5 time units.
The mechanism of this optimal amplification, as explained in Brion et al. [ONERA1], [ONERA2], is illustrated in Fig.ONERA-3. The spanwise vorticity $\omega_z$ is the component that allows an initial strong amplification of energy through the bottom hyperbolic point where it is strongly amplified by stretching. This spanwise vorticity amplification then bends, by induction, the vortex core in the planes where stretching by the mean flow usually develops the Crow instability (i.e. fixed orientations around nearly $\pm 45^\circ$). Once modulating this initial perturbation with the Crow wavelength, one triggers this, in an optimal way, the Crow instability.

To generate such a perturbation one must produce very elongated (flat) distributions of longitudinal vortcity $\omega_z$ with a sinusoidal modulation in the longitudinal direction $z$. Moreover, this must be done in a narrow region, close to the symmetry plane. Actuation from the vertical tail plane and fuselage could be considered. Better, one may think to a system deployed below the aircraft (landing gears?) that would put the perturbation closer to the bottom hyperbolic point of the vortex wake. The strength of this perturbation cannot be fixed a priori. In the case computed here, what we know is that this perturbation is amplified 36 times more than the basic Crow mode.
5.2. BiGlobal stability analysis of 4VS (Partners: UPM)

Numerical tools providing global temporal ‘BiGlobal’ linear instability analysis of multipolar vortex systems have been developed by UPM in order to improve understanding of vortex instability mechanisms. These tools have not been used by the partners, but could be used for future advanced investigations of the topic.

6. CONCLUSIONS

By combining experiments, CFD and theory, the collaborative work described in this report has provided some decisive clarifications concerning the properties of the counter-rotating two vortex systems (2VS) and four-vortex systems (4VS) in a counter-rotating configurations.

The main results are:

- The lifetime of a 4VS is significantly smaller that that of an equivalent 2VS. A reduction by a factor 2 is attained, at least.
- The mechanism by which the lifetime is reduced is a non linear amplification of the Crow instability mediated by a rapid merger between the two vortex after development of an optimal perturbation of the initial configuration.
- The mechanism by which energy is transferred from the initial optimal wavelength to the Crow wavelength looks to be a turbulent one, but this remains to be clarified.
- The 4VS system may be view as a passive control mean (no energy input needed, except noise). An active control scenario based on the forcing of the Crow wave length in the 4VS, following see [2], has been also investigated. It looks rather efficient, but more quantitative investigations are necessary to evaluate properly the potential of this solution compared to that of the ‘passive’ 4VS case.
- Another way of accelerating ‘passively’ the Crow instability has been found by solving an adjoint problem giving the optimal perturbation of this instability. This optimal mechanism has been physically described. It allows a reduction of more than a factor 2 of the life time of a 2VS.

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7. REFERENCES


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