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Analyze of the Counter-Rotating Vortices Pair Stability under the External Turbulence Influence

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***Abstract*—The problem developed in this contribution is encountered in airplane aerodynamics and concerns the influence of long life longitudinal wake vortices generated by wing tips or by external obstacles such as reactors or landing gears. More generally it concerns 3D bodies of finite extension in cross flow. At the edge of such obstacles, longitudinal vortices are created by pressure differences inside the boundary layers and rotate in opposite senses. The numerical simulation used for understanding the mechanisms were generally time evolution computation on a fixed space box with periodic boundary conditions using a transformation of the time evolution into a downstream evolution. The flow will be perturbed by prescribed disturbances or by a turbulent field.**

***Index Terms* — Wake Vortex, Turbulence, Large Eddy Simulation, Aircraft.**

I. Introduction

The wake vortex generated by an aircraft is characterized by the presence of the vortices oriented in the direction of flight. [1]. These vortices are due to the flow around the wing-tip generated by the pressure difference between the bottom and top surface [2]. It is due to the lift of each wing and the vortices generated will be more intense if this lift will be great. [3]. As the lift is in relation with the aircraft weight, the intensity of the wake vortex is linked to that quantity [4].

When atmospheric conditions are favorable to the condensation, or when the plume of smoke generated by the reactors comes to mingle with the vortices, we can notice the trace of these vortices in the sky. These vortices have a life that can be quite long. The biggest problem relates to the risk of incidents caused by the meeting of an aircraft with a turbulent wake vortex generated by another aircraft that preceded it. This problem is more important in the phases of takeoff and landing (Fig. 1), where the aircrafts are allowed to follow at a rate close, and where the ground proximity may produce such disastrous incidents.

Fig. 1 Wake vortex in the take-off phase

II. Description of the Basis Flow

The initial conditions for the simulation are the analytical solutions of an array of periodic vortices. The elementary vortex of this array is an Oseen vortex. A solitaire vortex is defined by its circulation Γ_0 , and by its radius r_c corresponding of a maximal velocity. The position of the vortex center has been given by the coordinates (y_c, z_c) in the transverse plane (Oyz). Using a cylindrical system of coordinate (x, r, θ) whose origin is the vortex center, the rotation velocity u_θ and the vorticity ω_x of the vortex, are:

$$u_\theta(r) = \frac{\Gamma_0}{2\pi r}\left(1 - e^{-r^2/r_0^2}\right); \quad (1)$$

$$\omega_x(r) = \frac{\Gamma_0}{\pi r_0^2} e^{-r^2/r_0^2}. \quad (2)$$

For a dipole vortex, we use two longitudinal contra-rotating vortices described above, with the circulation $\Gamma_{01} = -\Gamma_0$, $\Gamma_{02} = \Gamma_0$, situate at distance b_c. In fig. 2 and fig. 3 the distributions of the velocity in this case can be noticed. The referential parameters are the velocity of descending of the vortices, the distance between the vortices and the Reynolds number:

$$U_{ref} = w_d = \frac{\Gamma_0}{2\pi b_c}; \; L_{ref} = b_c; \; Re = \frac{\Gamma_0}{2\pi\nu}. \quad (3)$$

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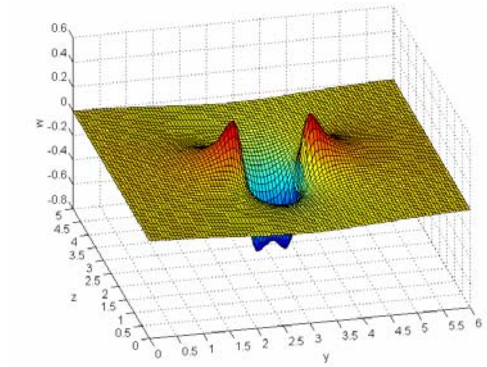

Fig. 2 Distribution of the initial velocity field in a transversal plane for a vortex dipole- velocity w

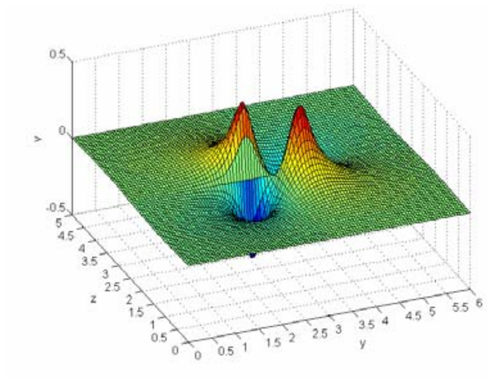

Fig. 3 Distribution of the initial velocity field in a transversal plane for a vortex dipole - velocity v

III. Methods and Tools for Numerical Simulation

To solve the system of non stationary, three-dimensional, incompressible Navier-Stokes equations like equation of advection - diffusion of a scalar on an orthogonal curvilinear grid, which describes the turbulent flow, we used the software called JADIM, developed at IMFT. This software can use the volume finite method, and also the "Large Eddy Simulation" and "Direct Numerical Simulation" methods.

The main idea of the large eddy simulation is to consider that integrality of turbulent agitation ceases being hazardous. Thus, the contributions to the large scales are explicitly calculated, modeling being reserved for the structures whose size is lower than a dimension characteristic of the mesh of calculation. The advantage of this method is to reduce the two defects of the other methods: empiricism of closing in a point of the averaged equations and requirement in computing power of direct simulation.

IV. Calculus Domain

For modeling a longitudinal contra-rotating vortices pair we use a rectangular calculation domain as presented in fig. 4.

The grid parameters of the calculation domain chosen give a total computation cells number $N = nx \cdot ny \cdot nz = 577\ 600$ cells. The boundary conditions used are periodic in Oz and Ox axes, and symmetric in Oy axes. This condition type enables the temporal evolution determination of the studied phenomenon.

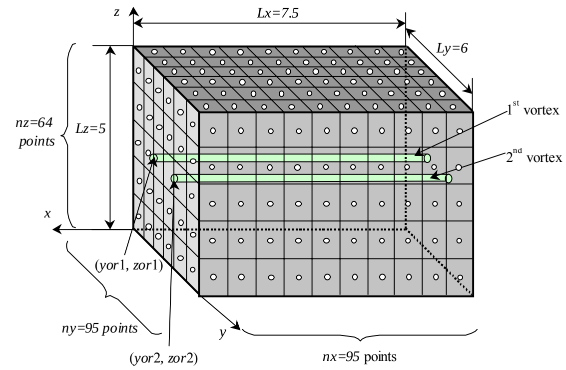

Fig. 4 Grid parameters

V. Disturbances Induced in a Virtex Dipole

In order to study the receptivity of longitudinal vortices contra-rotating at different exterior disturbance, basic flow shall be disturbed.

First disturbance used is the white noise, commensurable to speed basic flow:

$$u = u_0(1+u')\ ;\ v = v_0(1+v')\ ;\ w = w_0(1+w'), \qquad (4)$$

where (u', v', w') are random numbers with uniform casting contained in the range $[-Amp, Amp]$ with Amp the noise amplitude. The white noise is entered continuously after each iteration. Because the values (u', v', w') are randomly established, they don't shall carry out the equation of continuity. This situation can induct noticeable errors only when speed of disturbance has significant values. In the studied case, disturbance entered is small compared to the values basic flow velocities.

Another manner for adding a disturbance is to enter a Crow disturbance (fig. 5). This perturbation is obtained by disturbing the position of vortices centers from basic flow. After the perturbing the basic flow, a number of iteration of accommodation were performed, thus allowing eliminating errors entered by introduction disturbances.

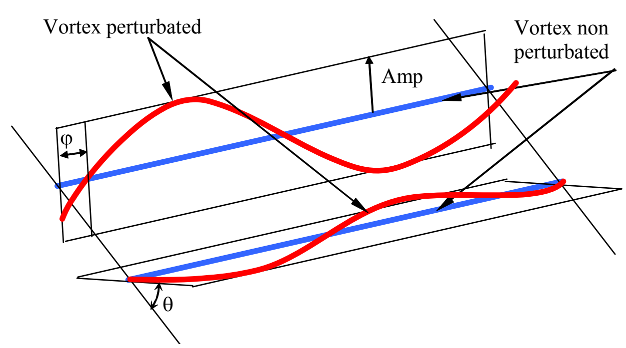

Fig. 5 Crow disturbances

After ending the simulation of accommodation, the field of velocity and pressures obtained will verify the Navier-Stokes equations, and they shall constitute the initial condition for the effectuation of main simulation, for researching the evolutions couples of longitudinal vortices with a Crow disturbance. The vortices filaments shall be perturbed using the following relations:

$$y_{c\_pert} = y_{c\_nepert} + Amp \cdot \sin(kx + \varphi) \cdot \cos\theta$$
$$z_{c\_pert} = z_{c\_nepert} + Amp \cdot \cos(kx + \varphi) \quad (5)$$

where $(y_{c\_nepert}, z_{c\_nepert})$ is the position of unperturbed vortices, Amp is the amplitude of disturbance, k is the longitudinal wave number , φ is the phase, and θ is the disturbance plan angle.

An important objective of this study consists in the research of the influence of the external turbulence field on a pair of longitudinal contra-rotating vortices. For that we achieved a procedure of generating a turbulent field consisted of the Oseen vortices each having the ray $R \in [R_{min}, R_{max}]$ and circulation $\Gamma \in [-\Gamma_{max}, \Gamma_{max}]$ randomly generated. Also, the orientation, position of each vortex center and its length randomly generated. The intensity of turbulent fields thus generated may be controlled through the intensity, length and maximal ray of component vortices, as well as through their number. The characteristic parameters used-up for generating the field of external turbulence are: vortices' ray $R \in [0.01,\ 0.1]$, intensity $\Gamma \in [-0.01,\ 0.01]$ and length $L = [2,\ 8]$ cells.

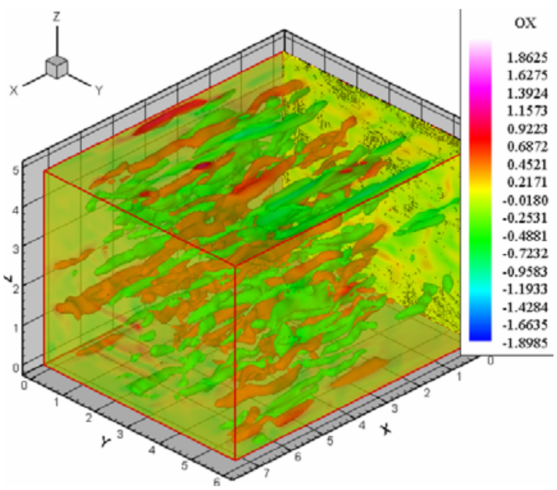

Fig. 6 Characteristics distribution ω_x for an external turbulence

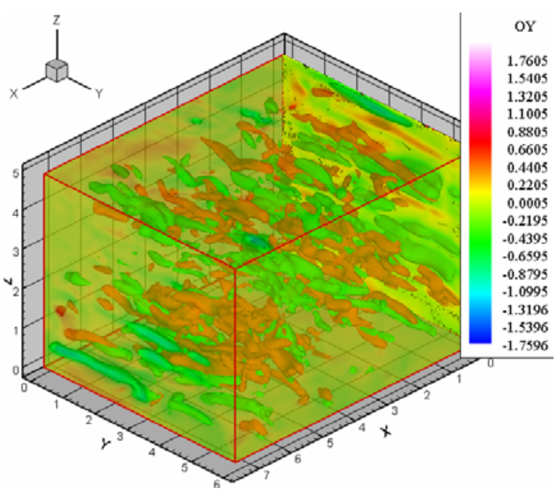

Fig. 6 Characteristics distribution ω_y for an external turbulence

The vortices generated in the manner presented previously were used as initial condition for a calculus of accommodation. After a certain number of temporal iteration (over 500), the obtained field of velocity and pressure represents the field of external turbulence which shall be overwritten on the longitudinal contra-rotating vortices, and thus we can get to research of an external turbulence influences on a pair of longitudinal contra-rotating vortices.

VI. Numerical results

We have first tested the laminar solution starting from the analytical flow field is numerically stable. The diffusion process is weak and both the maximum vorticity and effective vortex radii undergo small changes for computational times long compared to the time scales of the disturbances introduced for forcing the initial flow.

A. *Periodic Crow instability*

The instability mechanism induces large oscillations that result in vortex rings. This mechanism is known to be faster to modify the vortex pair than the high wave number elliptic instability. The results of this study are comparable to the ones of literature reported in [5].

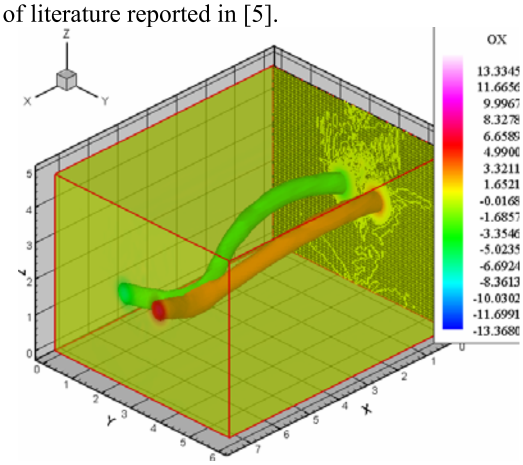

Fig. 7 Iso ω_x surface in Crow instability development at T=8

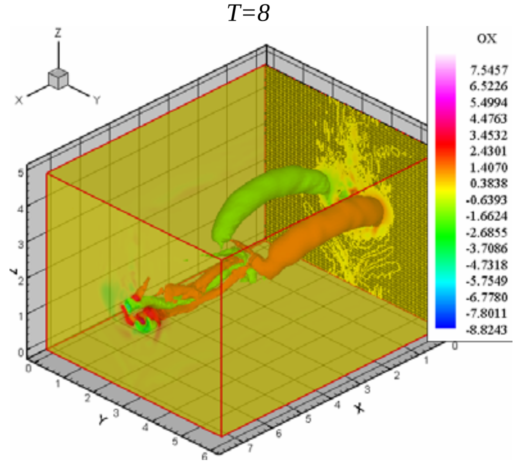

Fig. 8 Iso ω_x surface in Crow instability development at T=12

During the phase of the long wave instability the vortex tubes close to each other then the reconnection mechanism takes place between the two tubes.

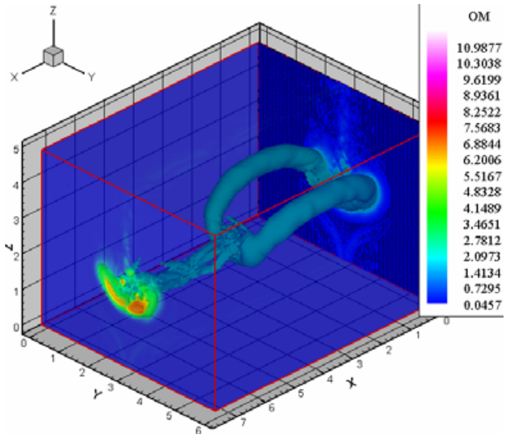

Fig. 9 Iso vorticity surface in Crow instability development at T=12

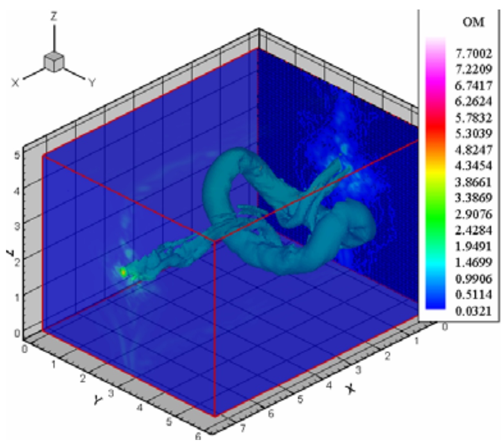

Fig. 10 Iso vorticity surface in Crow instability development at T=16

During that period the phenomenon of bounding occurs between the non connected tails of the tube along with the creation of threads with the remanents of the vortex tubes. It can be shown that enstrophy increases during the reconnection. But after reaching a local maximum both energy and enstrophy are destroyed by viscous dissipation of the small scales.

B. Random white noise

Concerning the white noise level imposed it is shown to be sufficient to trigger the instability and provoke a continuous decrease of energy in time.

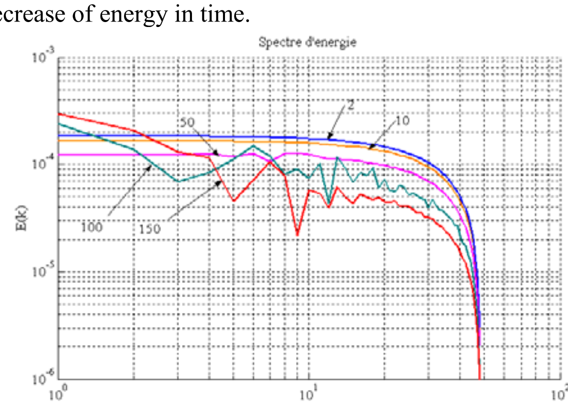

Fig. 11 Spectrum evolution of energy in noise effect

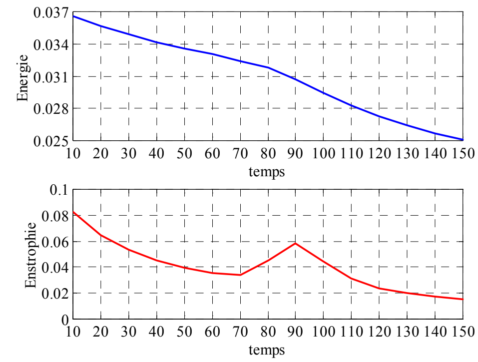

Fig. 12 Energy and enstrophy time evolution in noise effect

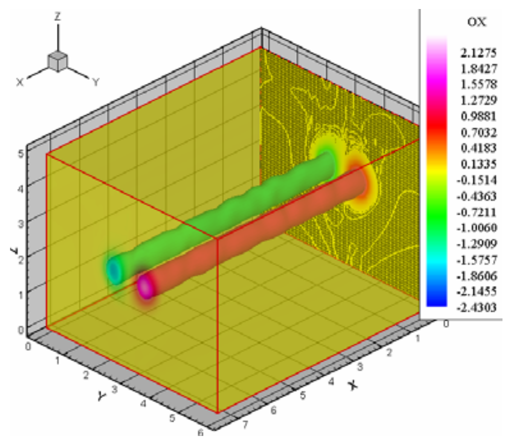

Fig. 13 Iso ω_x surface in noise effect at t=50

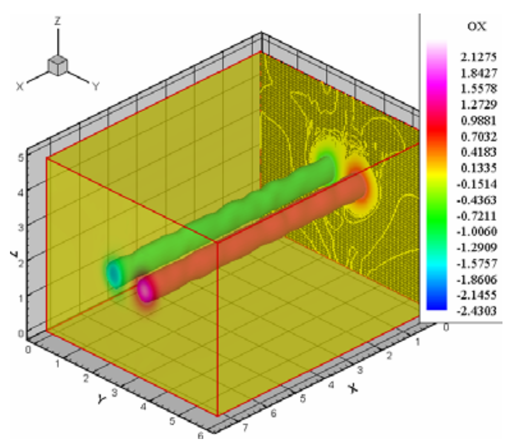

Fig. 14 Iso ω_x surface in noise effect at t=100

On figure 11 it can be deduced that preferentially a high wave number mode exhibiting features of elliptical instability is developed at long time (t=100). It is deduced that such a fully random short time and length correlation does produce high wave number instability the evolution low wave numbers are observed and this corresponds to the local maximum in enstrophy and to the plateau in energy in the decrease curves of figure 12.

C. External turbulence

In the case of the synthetic turbulence forcing the situation is quite different.

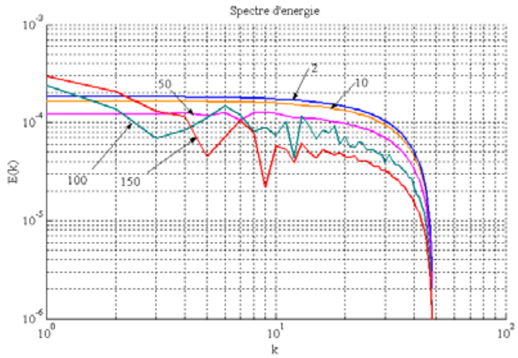

Fig. 15 Spectrum evolution of energy in external turbulence effect

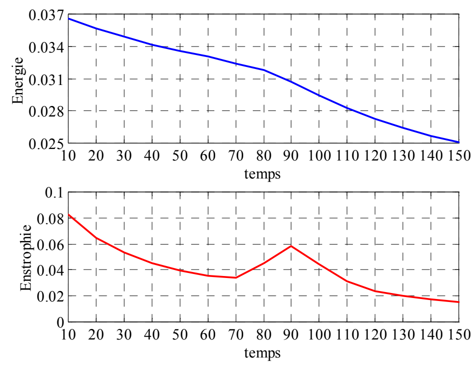

Fig. 16 Energy and enstrophy time evolution in external turbulence effect

The time evolution of overall energy and enstrophy has similar shapes but on shorter time scales (50 rather than 100) and the low number spectrum content is more marked. The difference is even more obvious on the pressure fields that clearly show that a Crow perturbation is excited and the turbulent flow is structured by this energy curves as it is known to be faster than elliptical instability.

One of the questions that arise from this simulation is the influence of the periodic boundary conditions in the longitudinal direction. In this case the large scale perturbation is forced to return to the initial values. The box effect can be the reason for maintaining a periodic structure in the flow provoking a global instability when convective instability could prevail. This is one of the motivations for conducting the same kind of simulations in a spatial evolution context which is well inside the capacities of the numerical code used.

VII. Conclusions

The numerical study shows that a pair of longitudinal counter-rotating vortices is receptive to both large and small wavelength disturbances. If the large scale periodic Crow instability is imposed it implies a clear development of regular vortex oscillation leading to vortex ring that behave separately.

In the case of a white noise high wave number elliptical like instabilities are observed. Although transient low wave number components appear during the evolution the destruction process of the vortex is mainly controlled by short wave lengths and the unsteadiness is excited after a relative long time. The decrease of energy and enstrophy exhibits two different slopes. This shape is attributed to the effect of these large scale components at intermediate stages and the dominance of small scale ones at long time.

Forced by external turbulence a pair of longitudinal vortices presents a large wavelength unsteadiness that develops at the beginning in the same way as crow instability. It is also destructed in the final stage by associated with the type of simulation conducted. Discussing this particularity opens the way to spatially evolving simulation that should provide picture of the phenomenon.

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