Two-dimensional stability analysis of the flow in a slat cove

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Abstract

The purpose of the present work is to investigate the eigenmodes of the incompressible flow in a two-dimensional slat cove. A two-dimensional modal computation algorithm relying upon Chebyshev collocation method but suitable for arbitrary curvilinear geometries has been developed and validated. Then it has been applied to the steady mean flow field in the slat cavity, computed by RANS resolution. Amongst the numerous eigenmodes obtained, some of them have been selected which exhibit an interesting structure and their physical properties have been analyzed.

1. Introduction

More and more studies are devoted to aircraft noise, to understand and control the sound generation in order to decrease noise pollution around the airports. Engines are the main cause of noise radiation during the take-off but due to successive improvements, their sound level has been dramatically decreased. During aircraft approach before landing, engines are in idle regime and in-flight sound measurements have shown that airframe noise is now responsible for roughly half noise radiation. The main sources of airframe noise are the landing carriage and the high-lift devices, leading-edge slats and trailing-edge flaps.

Many experimental and numerical studies were devoted to slat noise investigation to describe and compute sound generation mechanisms in slat cavity [1]-[4]. Analytical models based on measurements are very useful for aircraft design but their accuracy is limited. Full numerical simulation is more efficient but it remains very expensive in computation time and therefore it is not suitable for a parametric study. The purpose of the present work is to investigate a third way relying upon modal analysis of the flow in the slat cove. The aim is not to predict the noise created by the slat but rather to understand the unsteady behaviour of this flow, which constitutes the first step towards noise radiation. It is believed that flow eigenmodes and associated frequencies can provide interesting information which complement experimental data and full numerical simulations.

2. Numerical model

As a first step, the fluid is assumed inviscid and incompressible. Hence acoustic phenomena are ignored and only Kelvin-Helmholtz-type inviscid instability can be addressed. Two-dimensional stability analysis consists in searching for the eigenmodes of a small perturbation added to the steady mean flow under the form:

$$\begin{cases} u(x,y,t) = u_0(x,y) + \varepsilon U(x,y)\exp[-i\omega t] \\ v(x,y,t) = v_0(x,y) + \varepsilon V(x,y)\exp[-i\omega t] \\ p(x,y,t) = p_0(x,y) + \varepsilon P(x,y)\exp[-i\omega t] \end{cases}$$

where u_0, v_0 and p_0 are the velocity components and the pressure of the mean flow field, U, V and P are the complex amplitude functions of the perturbations, ω is the angular frequency and ε is a small gauge parameter. The perturbation is thus solution of Linearized Euler Equations. With homogeneous boundary conditions, a differential eigenvalue problem for ω is obtained:

$$\begin{cases} \dfrac{\partial U}{\partial x} + \dfrac{\partial V}{\partial y} = 0 \\ \left(u_0 \dfrac{\partial}{\partial x} + v_0 \dfrac{\partial}{\partial y} + \dfrac{\partial u_0}{\partial x} \right) U + \dfrac{\partial u_0}{\partial y} V + \dfrac{1}{\rho_0} \dfrac{\partial P}{\partial x} = i\omega U \\ \dfrac{\partial v_0}{\partial x} U + \left(u_0 \dfrac{\partial}{\partial x} + v_0 \dfrac{\partial}{\partial y} + \dfrac{\partial v_0}{\partial y} \right) V + \dfrac{1}{\rho_0} \dfrac{\partial P}{\partial y} = i\omega V \end{cases}$$

Classical stability analysis tools have been developed for flows which are invariant or slowly varying in two directions and have only one direction of strong variation. They are well suited for flows like mixing layers, jets or boundary layers, for example. For flows with two directions of strong variation, some new approaches have been developed to perform two-dimensional stability calculations [6]. In this case, the method ends up in large matrix eigenelements computation and the matrix size grows with the mesh size. Therefore the discretization method used to transform the differential problem into an algebraic problem must be as accurate as possible in order to reduce the number of mesh cells. One of the most powerful discretization methods is the collocation method relying on Chebyshev polynomials. This method is widely used for quasi-1D problems but its use for two-dimensional problems was up to now limited to Cartesian geometries.

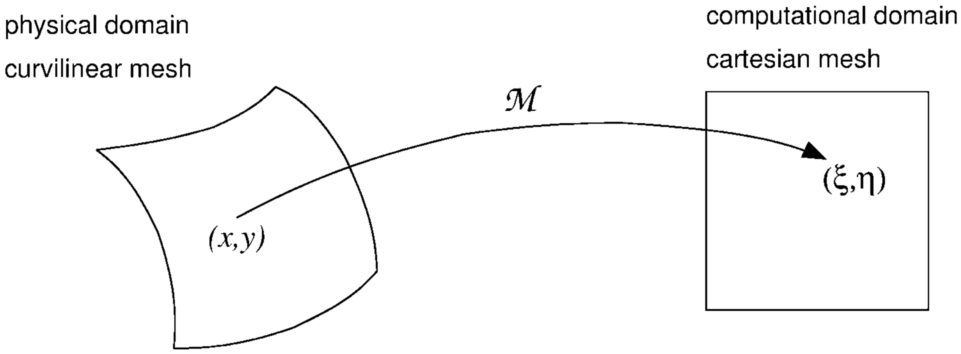

figure 1: mapping from physical domain to computational domain

A numerical algorithm has thus been specially developed to address curvilinear problems [7]. An implicit transformation (*i.e.* without explicit analytic expression) is defined to transform the curvilinear physical domain into a Cartesian computational domain (figure 1), where Chebyshev derivation formulae can be applied in both directions to compute spatial derivatives involved in the eigenvalue problem as well as those stemming from coordinates transformation. This approach was validated on several academic cases [8]. For an eigenvalue problem, all the conditions must be homogeneous. On the walls, the normal velocity is forced to zero. In the slat case, a particular attention must be paid to open boundaries with inflow or outflow non-reflecting conditions. Due to the incompressibility of the fluid, the mean flow convection is the only propagation phenomenon and after systematic trials, an Orlansky condition has been found to give acceptable results. This condition can be written under the general form

$$\frac{\partial \varphi}{\partial t} + c_n \frac{\partial \varphi}{\partial n} = 0$$

where n is the normal to the boundary and c_n is the mean convection velocity along the normal.

3. Modal analysis of the flow in the slat cove

A generic two-dimensional slat geometry is considered here (figure 2). Since the slat geometry is an Airbus property, the exact dimensions and velocities cannot be given but the scale is around 1/10th. The mean flow results from averaged Large Eddy Simulation [5]. One of the structured curvilinear meshes used to compute the eigenmodes is plotted in figure 3. Three different meshes have been used with the same contour but respectively 66x43, 91x50, and 110x50 nodes. The spectrum has been computed globally for the first two meshes using standard QZ algorithm. Partial spectrum computations have also been performed for the three meshes using Arnoldi algorithm. The spectrum of this flow is of course very rich. A part of the global spectra computed with the first two meshes is presented in figure 4. Regularly spaced clusters can be noticed near the axis $\omega_i = 0$. The corresponding partial spectra computed for the finest mesh around the first two clusters can be seen in figure 5. The spectra obtained with the three meshes around cluster #2 are plotted in figure 6. It appears that the eigenvalues are contained inside an horizontal wedge with the vertex on the right side. No convergence can be observed except for the vertex itself. Moreover, the vertex imaginary part is close to zero and it seems difficult to decide whether the mode is damped or amplified. A similar configuration is observed for the other clusters.

The eigenfunctions corresponding to some modes located near the wedge vertex for the first four clusters are presented in figure 8. The coloured iso-contours represent the pressure fluctuation whereas the streamlines are relating to the velocity perturbation. It appears that all the modes located inside a cluster are characterized by a fixed number of vortices with alternate spin directions, looking like a crown. These modes were thus called “crown modes”. The crown radius varies from one mode to one another inside a given cluster. The vortices are more or less centred on a positive or negative pressure extremum. The structure of the crown modes can be compared with that of the eigenmodes obtained in the test case of a circular flow in a disc [7]. The purely tangential mean flow and an eigenmode with six vortices are represented in figure 7. Due to the inflexion point on the tangential velocity profile, a circular Kelvin-Helmholtz instability occurs, producing a similar system of alternate vortices superposed with pressure extrema. Considering the mean flow in the slat cove (figure 2), a tangential velocity shear occurs along the main vortex, playing the same role. Due to periodicity, the frequencies of these modes are discrete, generating the clusters. The frequency gap between two clusters is about 380 Hz, which corresponds to low frequency for the full scale slat.

A different kind of eigenmodes has been found for higher frequency. One of them is presented in figure 9. In this case, no crown is present in the slat cove but a continuous vortex street goes around the main vortex and escapes on the wing upper side. These modes are also generated by the Kelvin-Helmholtz instability along the shear layer between the slat and the wing but they do not loop in the slat cove. They have been called “street modes”.

4. Conclusion

This first attempt to capture the eigenmodes of the inviscid flow in the slat cove produced encouraging results. Thanks to the implicit mapping method, the eigenvalue problem could be discretized using Chebyshev collocation method, allowing a nearly correct representation of the flow with a moderate number of grid points. The clusters of crown modes were brought into evidence, likely associated with a Kelvin-Helmholtz instability around the slat cove main vortex. These low-frequency modes could be involved in the broadband noise radiated by the slat. The higher frequency street modes have also been pointed out. However, numerous important questions remain:

– no convergence has been observed for cluster modes except for the wedge vertex: are these modes spurious ? do they belong to a continuous branch ?
– do these modes correspond to a physical reality ?
– what is the interplay of acoustics and hydrodynamic instability ?
– what are the mechanisms of noise radiation and frequency selection ?
– what about three-dimensional effects ?

Answering all these questions will certainly not be a small matter.

References

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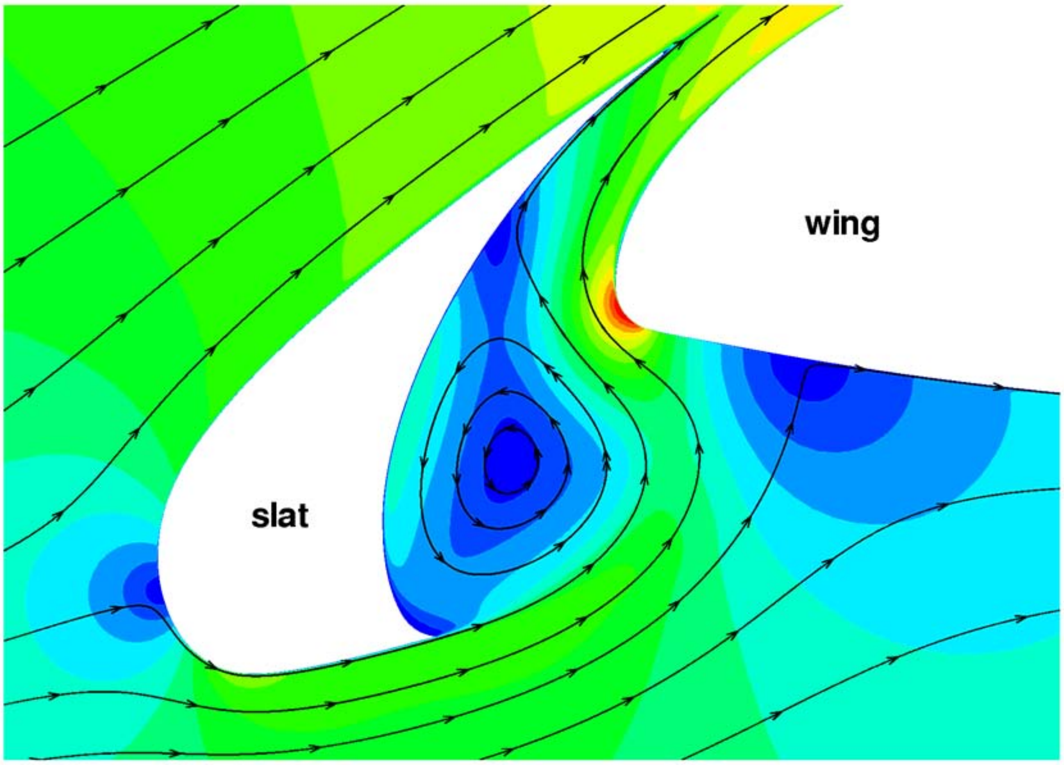

figure 2: slat geometry and mean flow (ONERA DAAP [5])

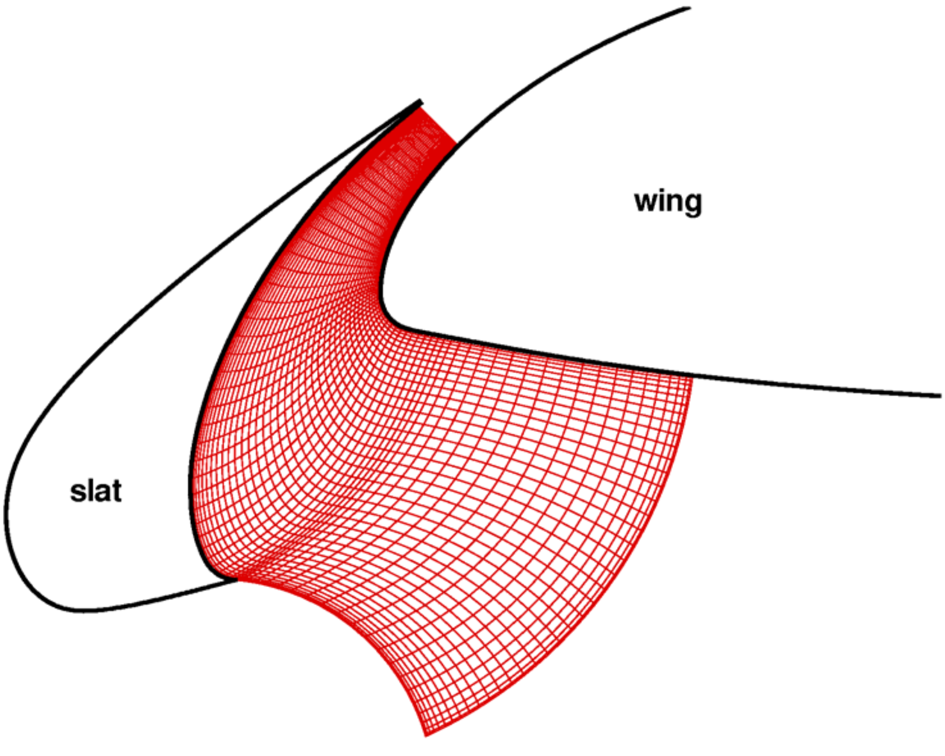

figure 3: slat cavity curvilinear mesh 91x50 nodes

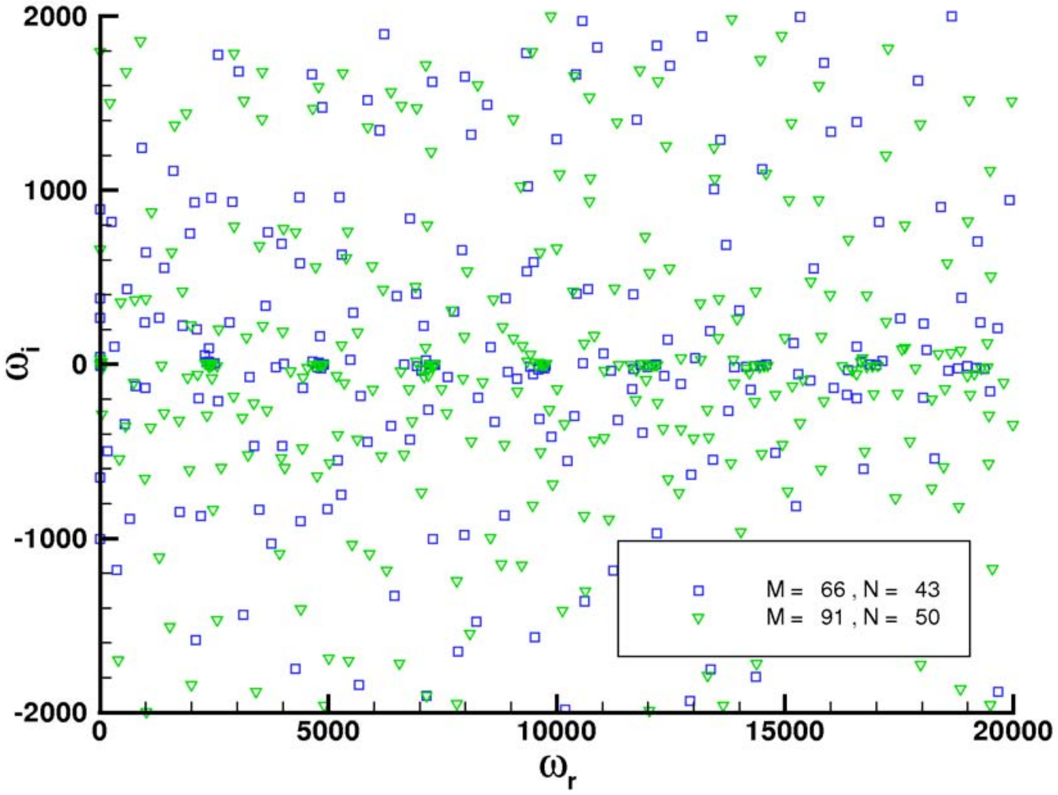

figure 4: complete QZ spectra

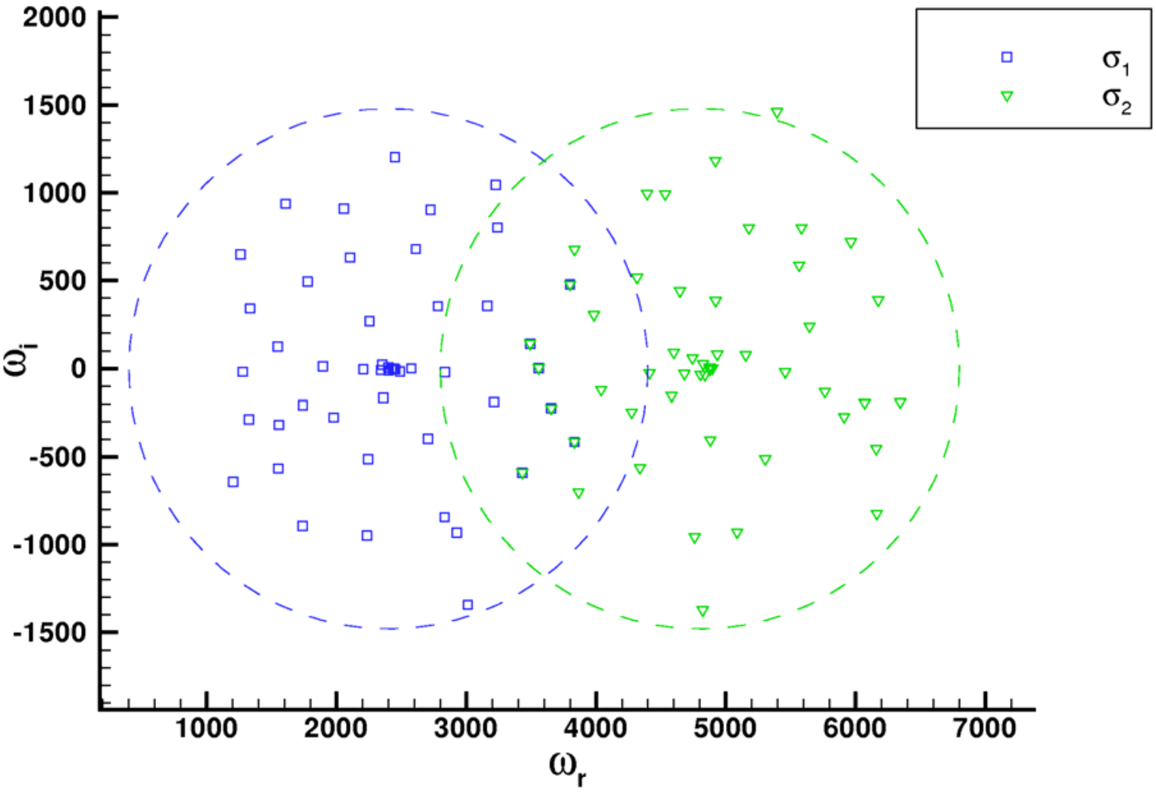

figure 5: partial Arnoldi spectra, mesh 110x50

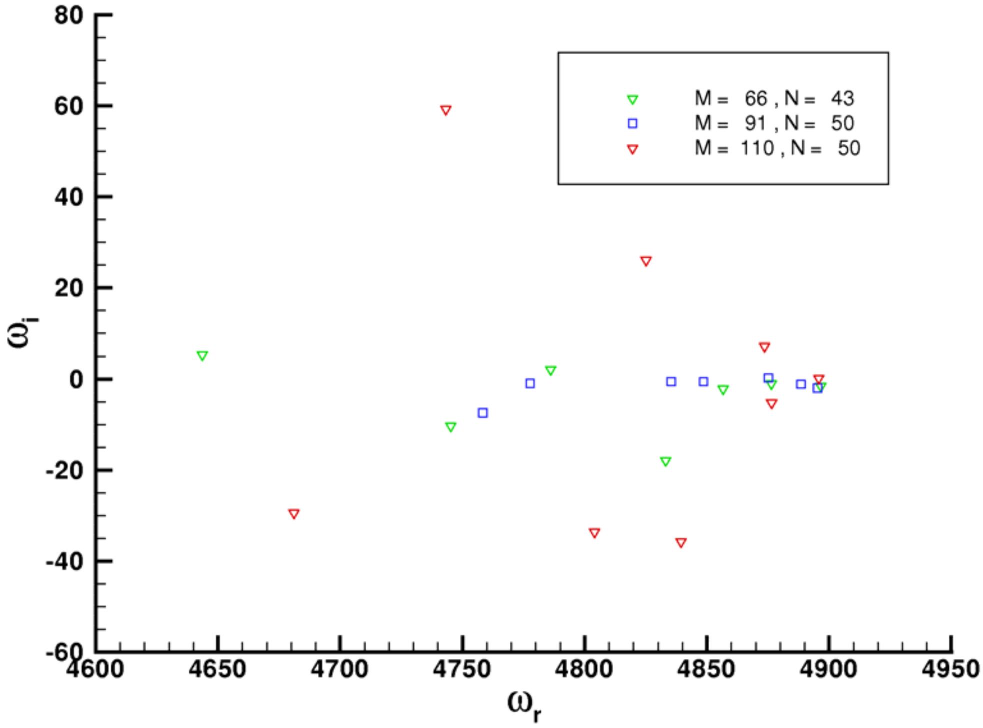

figure 6: detail of cluster number 2

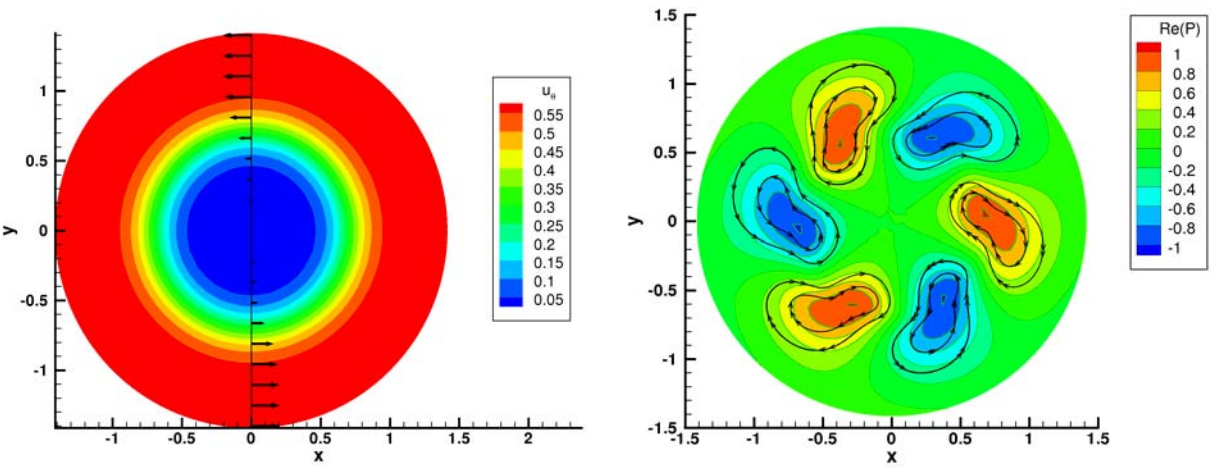

figure 7: disc test case [7]

Tangential mean velocity (left) and n = 3 eigenmode (right)

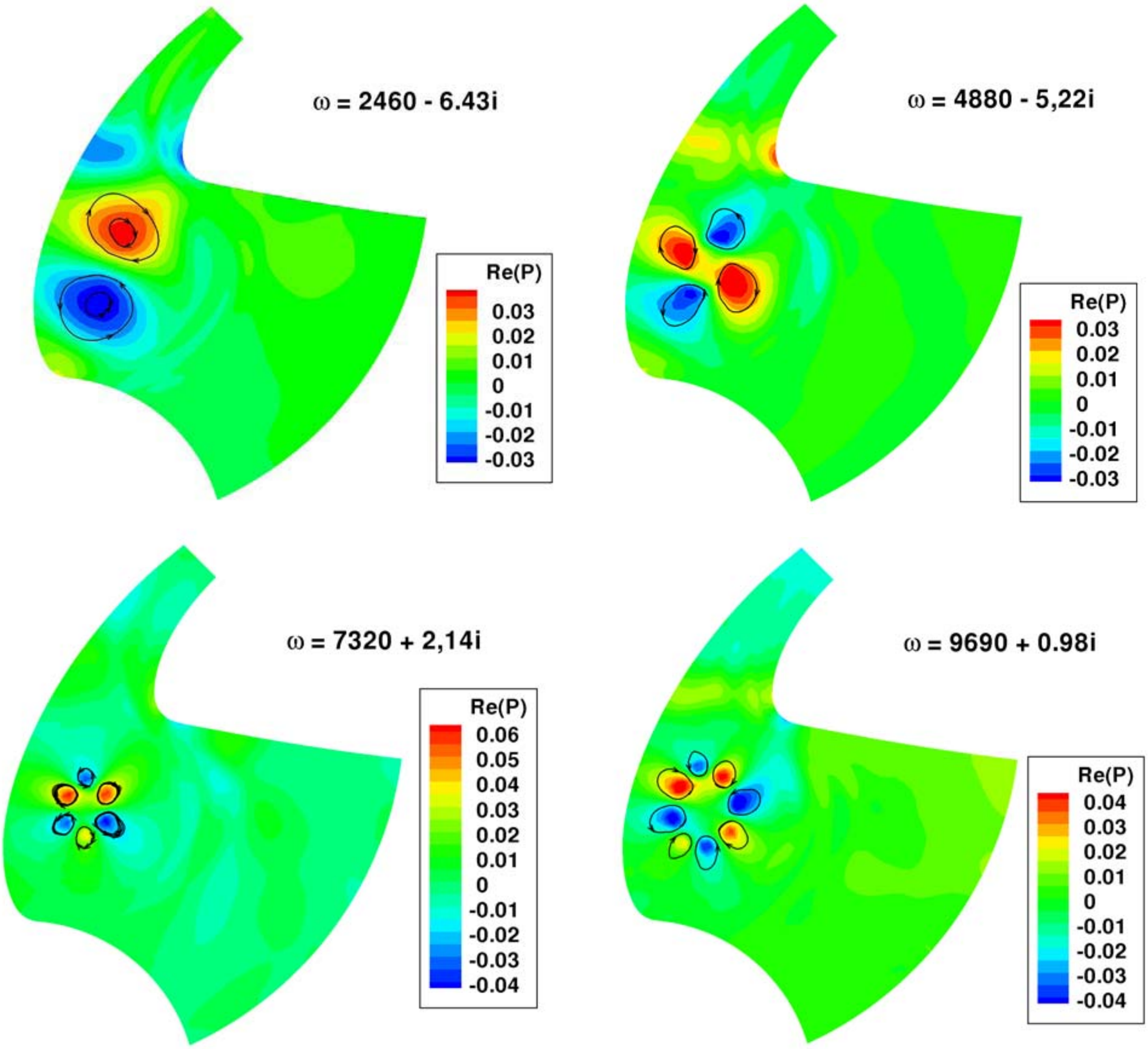

figure 8: crown modes in the slat cavity, n = 1, 2, 3 and 4

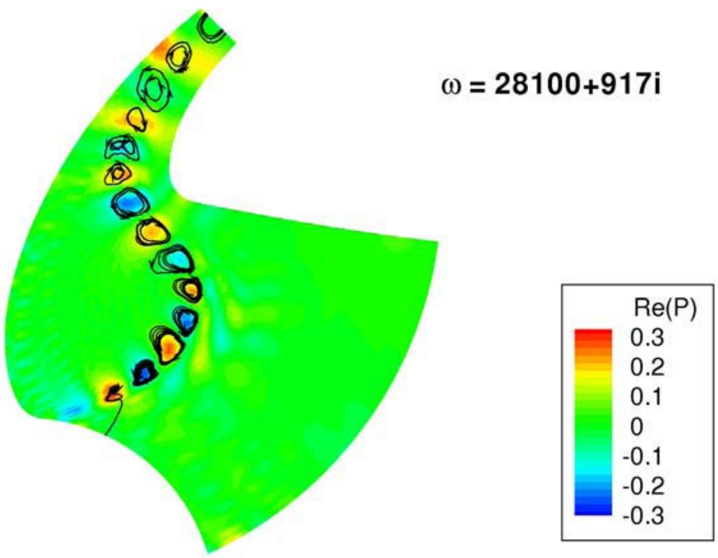

figure 9: vortex street mode