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Spatio-temporal description of the cavitating flow behavior around NACA 2412 hydrofoil

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Abstract. Spatio-temporal description of the cavitating flow around hydrofoil with 8 degrees incidence using proper orthogonal decomposition (POD) is presented. POD is a suitable tool, which provides information not only about the flow dynamics, but also about relevance of different flow structures. POD also enables to track energy transport within the domain and energy transfer among the eigenmodes of the flow field. Analysis documents change of the flow structure for decreasing cavitation number, which can be most likely attributed to sheet/cloud cavitation transition.

1. Introduction

Two regimes of cavitating flow around hydrofoils are usually distinguished: sheet and cloud cavitation. Sheet grows from the hydrofoil (blade) leading edge and at some distance transition to cloud occurs. It is known that collapse of the cavitating clouds is responsible for the most severe cavitation erosion [1, 3, 12]. Strong cavitating swirling structures in form of U-shaped (horseshoe) vortices within the cloud are believed to cause the highest pressure pulses during their collapse [1]. Large pressure pulses generated by cloud cavitation are associated with shock waves, which are propagating inwards [8, 12].

Development of the cloud is connected with existence of the re-entrant jet, which is cutting off the sheet and is responsible for cloud separation. Thorough investigation of this process, its Reynolds number dependence and definition of the critical Reynolds number for transition from the sheet to cloud cavitation was carried out by Keil et al [5]. It was also pointed out by Pelz et al [7] and by Avellan et al [1] that development of the cavitation around the hydrofoil is connected with strong energy transfer from mean flow to the shedding vortices in the region of the cavity closure. Energy is stored in the sheet until the cloud is separated. It makes the cloud cavitation the most harmful cavitation regime [7]. Above described, rather complicated, cavitating flow around hydrofoil can be roughly summarized into following sentence:

Development of the unstable cavitating flow around the blade is governed by energy transfer from the mean flow into strong swirling structures. Therefore it is inevitable to understand the process of energy transport within the flow, its temporal and spatial behavior.



2. Experiment

An experimental visualization of the cavitating flow around NACA2412 hydrofoil was done in cavitation tunnel of Center of Hydraulic Research [11]. Hydrofoil has chord length 120 mm, test section has 150x150 mm, incidence angle is 8 degrees. Flow rate was measured with magnetic-inductive flowmeter, pressures upstream and downstream of the test section were recorded with tensometric pressure transducers. Other details of the experimental set up are in [11]. High speed camera with 3000 fps and two halogen lamps were used to visualize the cavitating flow from the top view. 21 different regimes corresponding to three different Reynolds numbers (864000; 1173600; 1557600) and a range of cavitation numbers from 5.2 to 1.4 were investigated. Both Reynolds number and cavitation number are based on inlet velocity, chord length and upstream pressure.

3. Proper orthogonal decomposition

Since cavitating flow is highly unstable and shedding of the clouds and vortices is observed, different methods were previously applied to study the temporal evolution of the flow. Usually normal FFT analysis in individual points of the flow was applied. Kjeldsen et al [6] employed joint time-frequency analysis to investigate sheet/cloud transition. Present authors successfully applied in their previous research POD for identification of the flow structures, which carry most of the energy [9, 10] for turbine draft tubes with highly swirling flows. POD modes generally characterize the dominant unsteady flow structures, i.e. coherent structures of the flow. It can be stated that the POD modes concentrate maximum of the fluctuation power in the lowest modes, which are most energetic. Description of the method can be found in [2], its recent application on study of cavitation clouds on the side view of the cavitating hydrofoil was done by Danlos et al [4]. POD offers complete spatio-temporal description of the flow providing detection of the most energetic flow structures in whole domain and information about their spatial shape and associated frequencies. Mathematically speaking, an approximation of a function $\mathbf{u}(\mathbf{x}; \mathbf{t})$ (e.g. velocity, pressure or vapor volume fraction) is searched by decomposition into set of time-dependent eigen functions \mathbf{a}_i (temporal POD modes) and time-independent eigen functions $\boldsymbol{\phi}_i$ (spatial POD modes). Eigen functions are identified by searching for eigenvectors and eigenvalues of the temporal correlation matrix, which is built from snapshots of the flow field acquired with given sampling frequency.

$$C_{ij} = \frac{1}{\text{vol}\Omega} \int_{\Omega} \mathbf{u}(\mathbf{x}; t_i) \mathbf{u}(\mathbf{x}; t_j) d\mathbf{x} \quad (1)$$

Eigenvalues of matrix C_{ij} are then directly connected with spatial eigenmodes $\boldsymbol{\phi}_i(\mathbf{x})$ of the flow and magnitude of the eigenvalues corresponds to energy content of the eigenmodes. Temporal coefficients \mathbf{a}_i are then obtained by projecting the data functions $\mathbf{u}(\mathbf{x}; \mathbf{t})$ on the eigen functions $\boldsymbol{\phi}_i(\mathbf{x})$.

$$a_i(t) = \sum_{i=0}^N \mathbf{u}(\mathbf{x}; t) \boldsymbol{\phi}_i(\mathbf{x}) \text{ for } i = 0, \dots, N \quad (2)$$

4. Results

POD analysis is based on snapshots of cavitating flow around the hydrofoil taken from the top view. Uneven lighting did not allow to process whole suction side of the hydrofoil. Rather narrow stripe along the hydrofoil axis of symmetry had to be used (evaluated domain was shrunk from 1900x1000 pixels to 500x100 pixels. Shrunk domain contains hydrofoil leading edge and extends further downstream, but does not capture whole region of cloud cavitation. Values from 0 to 255 were assigned to every pixel according to its grey level (pure vapour = white color).

Output of the POD analysis is set of figures depicting the spatial form of the eigenmodes and also frequencies associated with these eigenmodes. Example for one operating point is illustrated in figure 2. This figure depicts the most dominant modes, which can be associated with erosive process.

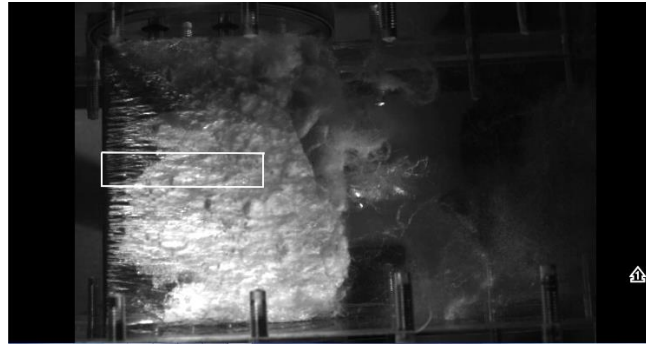


Figure 1. Whole visualized domain and the part used for POD evaluation ($Re = 1173600$, $\sigma = 2.75$)

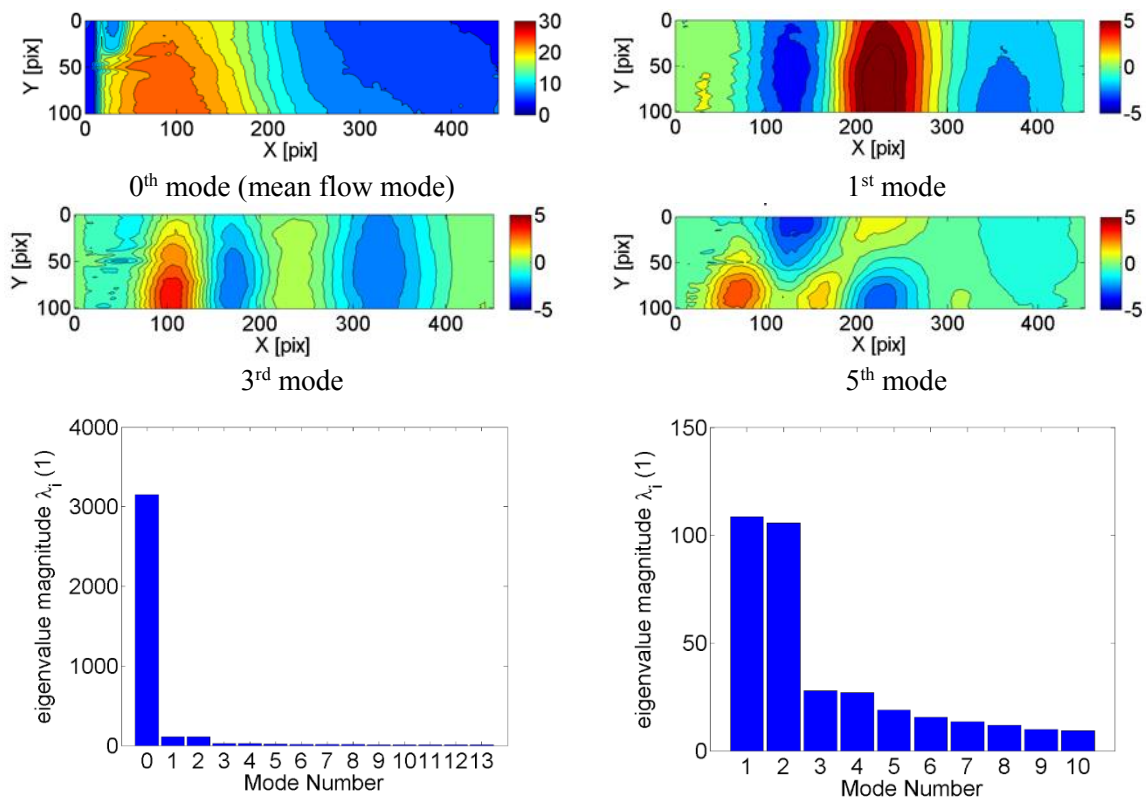


Figure 2. POD analysis of operating point $Re = 1173600$, $\sigma = 3,82$

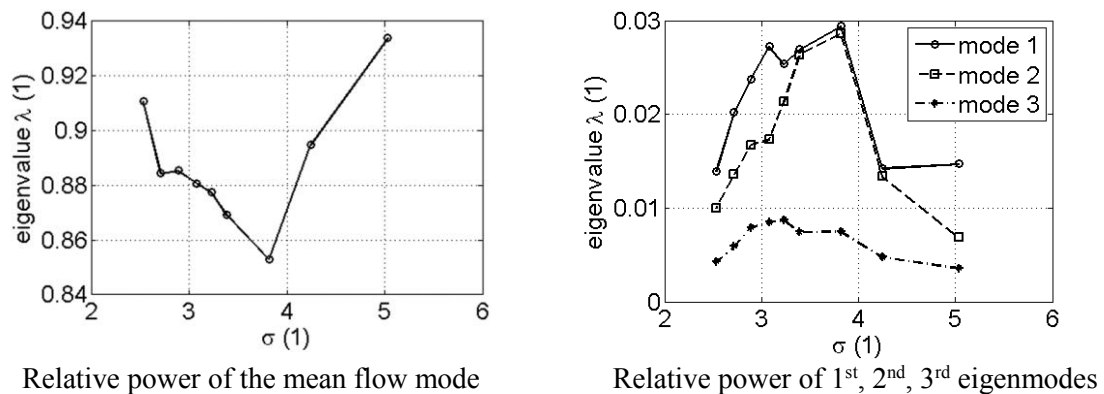


Figure 3. Relative power of eigenmodes for $Re = 1173600$

While figure 2 presents absolute magnitude of the eigenvalues, it is more interesting to look at relative magnitudes within each operating point characterized by unique cavitation number, see figure 3. Sudden drop of the eigenvalue of the mean flow for σ close to 4 is observed. Simultaneously redistribution of the energy towards higher modes occurs. Enrichment of the dynamic modes (tracked up to 20th mode) is quite likely connected with sheet/cloud transition. Similar process was documented in [6] for pressure rms values.

5. Conclusion

Proper orthogonal decomposition proves to be efficient tool for study of the cavitating flow dynamics and energy transfers within the flow field. Decomposing into the very basic corner stones of the flow enables to identify the relevant modes, their frequencies and behaviour with decreasing cavitation number. Further investigation will focus on confirmation of the sheet/cloud transition characterized by energy transfer from mean flow to dynamic modes by rules presented in [5].

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