CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

Multi-Scale Proper Orthogonal Decomposition for Cavitating Flows: Applications to Isothermal and Thermosensitive Cavitation

Claudia Esposito[1,2]*,Miguel Alfonso Mendez[1], Johan Steelant[3] and Maria Rosaria Vetrano[2]

[1]von Karman Institute for Fluid Dynamics,Waterloosesteenweg 72 , Sint-Genesius-Rode, Belgium
[2] KU Leuven, Celestijnenlaan 300A – postbus 2421, B-3001 Heverlee, Belgium
[3] Aerothermodynamics and Propulsion Analysis Section, ESTEC-ESA, Keplerlaan 1, 2200AG Noordwijk, The Netherlands

Abstract: High-speed imaging and unsteady pressure sensors commonly serve to investigate cavitation dynamics. In this work, we propose the use of the multiscale proper orthogonal decomposition (mPOD) to analyze cavitation instabilities in water and liquid nitrogen. The mPOD is a multiscale variant of the classical POD, which appears extremely advantageous and versatile for analyzing cavitating flows since it provides band-limited modes preserving anyway a good convergence. Cavitation through a cylindrical orifice is investigated in isothermal and thermosensitive environment. As far as isothermal cavitation is concerned, the mPOD analysis has highlighted the presence of two mechanisms, one at low frequencies linked to the jet flow coming from the orifice and one at higher frequencies depending on the cloud shedding. Regarding cryogenic cavitation, the cloud shedding regime did not show multiple characteristic frequencies but a clear peak at $St \approx 0.5$ that propagates undisturbed several diameters both upstream and downstream of the orifice.

Keywords: cavitation dynamics; mPOD; image processing; cloud cavitation

1. Introduction

Flow visualizations are non-intrusive and offer a global view of the cavitating flow. Therefore, they represent an essential tool to understand cavitation mechanisms [1,2] or to identify the cavitating regime [3,4]. Till today, significant effort has been put into improving image processing techniques to extract quantitative information from the image sequences. Recently, Proper Orthogonal Decomposition (POD) has shown a great potentiality to analyze the spatio-temporal structures of cavitating flows and classify the regimes accordingly [4,5]. In this framework, we propose a novel and versatile technique to study cloud cavitation, i.e. the Multi-Scale Proper Orthogonal Decomposition (mPOD) [6,7,8]. Specifically, our work uses the mPOD to analyze the cavitating flow past an orifice both in isothermal (water) and in thermosensitive (LN_2) environment.

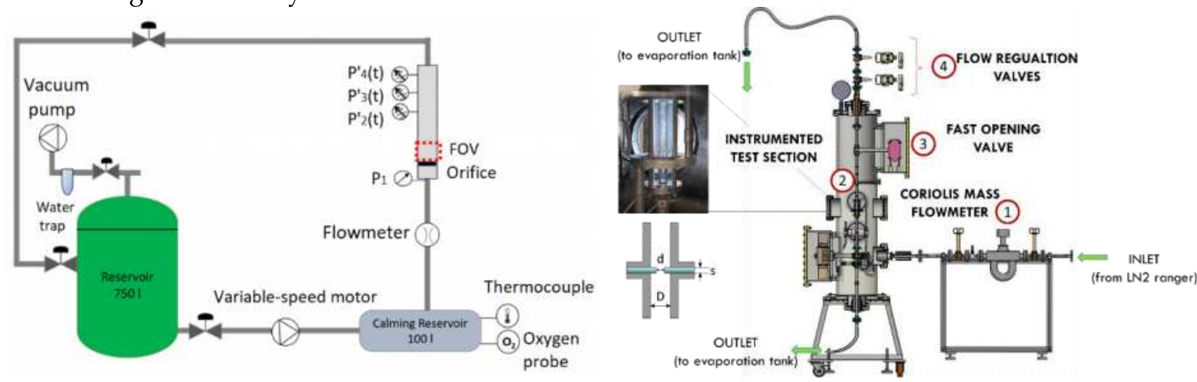
2. Materials and Methods

Cavitation setup

Two different setups, one used with water and one with LN_2, served to perform cavitation experiments and are described in [9] and [10], respectively. In both cases, the test section consists of a cylindrical orifice ($\beta = 0.17$ and $s/d = 1.19$) mounted in between two transparent cylindrical modules, made of acrylic glass for the isothermal cavitation and quartz for the cryogenic cavitation setup. A high-speed camera records images of the cavitating flow through the orifice at a frequency of 12 or 14 kHz. The isothermal cavitation setup is a closed loop where water is stored in a reservoir and put in circulation through a fluid pump. The cryogenic cavitation setup, instead, is an open loop. LN_2 is stored in a ranger and is transferred into the facility at an adjustable and stable pressure. An exhaust line connected downstream of the test section leads the liquid to the evaporating tank outside the laboratory. Besides flow visualizations, measurements consist of flow rate, pressure, and temperature. High-frequency, i.e. at 100 kHz, pressure measurements are

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

performed along the test section, and the recorded fluctuations are coupled with the flow visualizations for characterizing the unsteady behavior of cavitation.



(a) **(b)**

Figure 1 *Schematic of the water closed-loop facility [9]* ***(a)*** *and the cryogenic facility [10]* ***(b).***

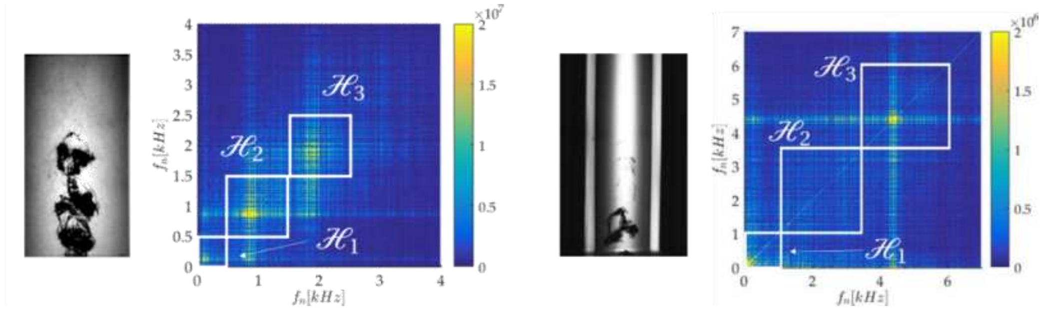
Multi-scale Proper Orthogonal Decomposition

As for any data-driven decomposition, the Multi-scale Proper Orthogonal Decomposition (mPOD) [6,7,8] expands a set of data into a set of modes, each with its own energy $\sigma_{\mathcal{M}k}$, space $\Phi_{\mathcal{M}k}$, and temporal structure $\Psi_{\mathcal{M}k}$. The key idea of the mPOD is to perform the decomposition at different scales, each composed of a different portion of the frequency spectra. The first step consists of computing the temporal structure from the correlation matrix *K*, like for the classical snapshot formulation of the POD [11]. The second step consists in splitting this correlation matrix into m scales via an MRA formulation, i.e. the correlation matrix is filtered with symmetric kernels designed to preserve a symmetric and positive *K* for all the scales. Such operation guarantees the orthogonality of its eigenvectors for all the scales. Then, each contribution K_m is diagonalized, giving a set of eigenbases with non-overlapping frequencies. Since these eigenvectors of all the scales are orthogonal components, these can be reordered by energy contribution and assembled into a final temporal basis $\Psi_{\mathcal{M}}$.

Contrary to the classical formulation of the POD, the mPOD constrains the modes within a certain frequency range, preserving, anyway, a good convergence comparable to the POD. Besides, unlike other hybrid decomposition methods as the spectral Proper Orthogonal Decomposition [12], it does not require the hypothesis of statistically stationary or periodic data. The possibility to have band-limited modes appears extremely advantageous for analyzing cavitating flows. Fig.2 shows two examples of the spectrum of the correlation matrix for isothermal cloud cavitation at $\sigma = 1.30$ (Fig.2.a) and cryogenic cavitation at $\sigma = 1.05$ (Fig.2.b). Here σ is the cavitation number defined as the dimensionless pressure drop through the orifice, i.e. $(P_{up} - P_{min})/(P_{up} - P_{dw})$. Within this work, we consider only σ to quantify cavitation, even if other parameters, e.g. the downstream pressure ratio in water [9] or the superheat level in LN_2 [10], have proven to impact cavitation occurrence and intensity. Concerning isothermal cavitation, multiple frequencies characterize the flow past an orifice. Thanks to the mPOD, phenomena occurring at different frequencies are distinguished. As for cryogenic cavitation, apart from some lower energy regions, spread in the range of low frequencies up to ~500 Hz, the dominant energy content is visible at f~4 kHz. Since we are mainly interested in considering this last frequency, after having separated the full spectrum in ranges ([0-1000, 1000-3500, 3500-6000]Hz), the mPOD analysis is only applied to the one containing the dominant peak. In practice, the mPOD is performed on n_t images from the recorded grayscale video I[x,y,t] recorded immediately downstream of the orifice. The number of images (n_t) is chosen to ensure the convergence of the results, and the spatial dimension of our dataset is much larger than the temporal domain, i.e. $n_s >> n_t$. Fig. 3 shows the evolution of the energy contribution of the first three dominant modes as a function of

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

the number of images for the cryogenic case. Their trend demonstrates that 1000 images are sufficient to reach convergence for this case.



(a) Water **(b) Liquid Nitrogen**

Figure 2 *Color plot of the spectrum of the correlation matrix: (a) Water at* $\sigma = 1.30$ *with highlighted three scales* $\mathcal{H}$ *[0–500, 500–1500,1500–2500]; (b) Liquid Nitrogen at* $\sigma = 1.05$ *with highlighted three scales* $\mathcal{H}$ *([0-1000, 1000-3500, 3500-6000]).*

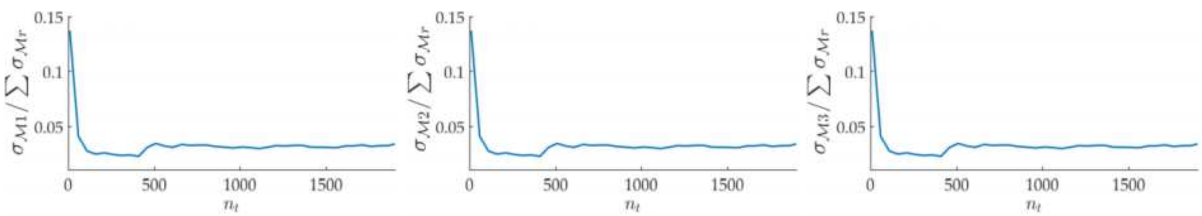


Figure 3 *Energy contribution of the first three dominant modes for the cryogenic cavitation case at σ=0.89.*

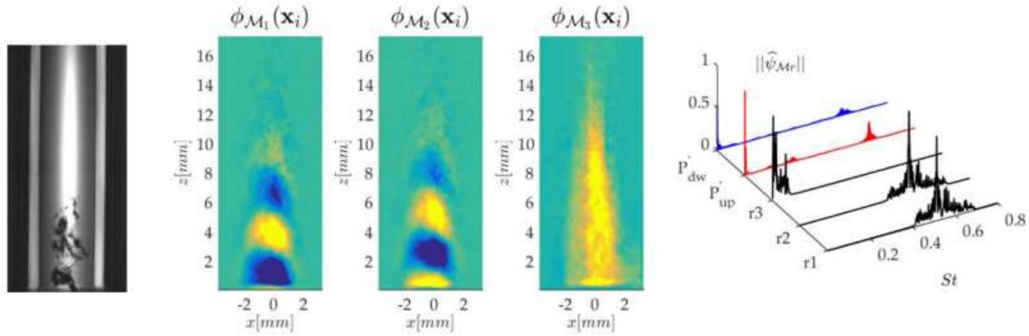
3. Results

As far as isothermal cavitation is concerned, the correlation matrix in Fig.2.a has highlighted that multiple characteristic frequencies mark the cavitating flow past the orifice. If the spectral analysis of the pressure signals already showed their presence [9], it is only the mPOD analysis of the video sequences which revealed the nature of these characteristic frequencies. Specifically, this modal analysis helped us understanding that two different mechanisms drive cavitation dynamics past an orifice. The first mechanism is observed at the lowest range of frequencies and is linked to the jet flow coming from the orifice. The second mechanism characterizes the highest range of frequencies and is linked to the regular shedding of large clusters of bubbles in the cloud cavitation regime. As cavitation develops, the increase in both size and lifetime of the vapor clusters lowers these characteristic frequencies.

Regarding cryogenic cavitation, the strong dependence of the cavitation behavior on the thermodynamic state of the fluid [10] hinders the identification of the resulting cavitation regime. In this context, flow visualizations appear essential to identify the flow regime and the mPOD provides us with quantitative information about the dynamics of the vapor clouds downstream of the orifice. As an example, Fig.4 presents the case at σ=0.89 where the resulting two-phase flow has a high level of superheat, i.e. downstream flow conditions are far from the saturation conditions at the upstream temperature. The cloud shedding observed downstream of the orifice is described by the spatial structures of the first two modes $\Phi_{\mathcal{M}1}$ and $\Phi_{\mathcal{M}2}$ with a spatial wavelength λ~4.5 mm and a clear peak at St~0.5. The Strouhal number is here defined as $St = (fd)/(\sqrt{\Delta P}/\rho_l)$ where d is the orifice diameter, $\sqrt{\Delta P}/\rho_l$ is the reference velocity with $\Delta P = P_{up} - P_{dw}$ the square root of the pressure drop through the orifice and ρ_l is the density of LN_2 upstream of the orifice. The frequency *f* is extracted from the image analysis. The observed vapor cloud shedding travels at the same velocity of the flow, i.e. ~16 m/s. The mode *r*=3, instead, belongs to the largest scale corresponding to the mean flow traveling downstream along the pipe. Finally, as shown in Fig.4.c, the cloud shedding propagates unperturbed for several diameters farther from the orifice. However, the way

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

the intensity of these disturbances propagate upstream and downstream of the orifice depends on the level of subcooling of the fluid.



(a) **(b)** **(c)**

Figure 4. *Cryogenic test case (σ= 0.89): (a) Instantaneous image of the cavitating flow; (b) Spatial structures from the first three dominant mPOD modes; (c) Corresponding dimensionless spectra of the first three dominant mPOD modes together with the dimensionless spectra of the pressures upstream and downstream of the orifice.*

Acknowledgments: This work was supported by the ESA's Networking/Partnering Initiative (NPI) grant 4000117725/16/NL/MH/GM.

References

1. S. Jahangir, et al. Dynamics of partial cavitation in an axisymmetric converging-diverging nozzle, *Int. Journal of Multiphase Flow* 106 (2018) 34–45.
2. M. Callenaere, et al. The cavitation instability induced by the development of a reentrant jet, *J. of Fluid Mechanics* 444.
3. C. Stanley, et al. Periodic cavitation shedding in a cylindrical orifice, *Experiments in Fluids* 51 (5) (2011) 1189–1200.
4. Danlos, et al. Cavitation regime detection through proper orthogonal decomposition: Dynamics analysis of the sheet cavity on a grooved convergent–divergent nozzle, *Int. Journal of Heat and Fluid Flow* 47 (2014) 9–20.
5. M. D. Giorgi, et al. Characterization of cavitating flow regimes in an internal sharp-edged orifice by means of proper orthogonal decomposition, *Exp. Thermal and Fluid Science* 93 (2018) 242–256.
6. M. A. Mendez, et al. Multi-scale proper orthogonal decomposition of complex fluid flows, *J. of Fluid Mechanics* 870 (2019) 988–1036.
7. M. Mendez, et al. Multiscale modal analysis of an oscillating impinging gas jet, *Exp. Thermal and Fluid Science* 91 (2018) 256–276.
8. D. Ninni, M.A.Mendez MODULO: A software for Multiscale Proper Orthogonal Decomposition of data. *SoftwareX* 12 (2020) 100622
9. C. Esposito, et al. Spectral and modal analysis of a cavitating flow through an orifice. *Exp. Ther. and Fluid Science*, 121, 110251.
10. C. Esposito, et al. On the influence of thermal phenomena during cavitation through an orifice. *Int. J. of Heat and Mass Transfer*, 164, 120481.
11. L. Sirovich, Turbulence and the dynamics of coherent structures. I. coherent structures, *Quarterly of applied mathematics* 45 (3) (1987) 561–571.
12. M. Sieber, et al. Spectral proper orthogonal decomposition, *J. of Fluid Mechanics* 792 (2016) 798–828.

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com