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Stochastic Response of an Airfoil and Its Effects on Limit Cycle Oscillations's Behavior Under Stall Flutter Regime

Dimitrios Ketseas
Engineer
Computational Fluid Mechanics MSc - National Technical University of Athens
Quality Control Department - Hellenic Air Force, Greece
mimisketseas@hotmail.com

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ABSTRACT: In this work, I investigate the effect of noise on a classical two-degree-of-freedom pitch-plunge aeroelastic system. The inlet velocity of the flow is modeled as a stochastically varying parameter by the Ornstein-Uhlenbeck (OU) stochastic process. The system is a 2D airfoil, and the elastic problem is simulated using linear springs. I study the manifestation of Limit Cycle Oscillations (LCO) corresponding to the varying fluid velocity under the dynamic stall regime. The aim to delve into the unexplored facets of the classical pitch-plunge aeroelastic system, seeking a comprehensive understanding of how parametric noise influences the occurrence of LCO and expands the boundaries of its known behavior.

Keywords: Aerodynamics, Aeroelasticity, Computational Fluid Mechanics, Stochastical Processes, Stochasticity, Stall Flutter

1. INTRODUCTION

The exploration of how elastic structures interact with fluid flows stands as a cornerstone in scientific research and engineering. Its implications extend across a diverse array of applications, from the optimization of aeroelastic systems to the innovation of towering skyscrapers and intricate bridge designs [3]. These endeavors necessitate a delicate balance as they hinge upon the complex interplay between three fundamental forces: the inertia, the elasticity of the structure, and the aerodynamic forces at play. This intricate dance of forces may, in certain cases, induce an undesirable outcome known as Limit Cycle Oscillations (LCOs), which can lead to structural fatigue and, in severe instances, catastrophic failure [4]. Much interest has surged in understanding the profound impact of parametric noise in engineering systems [5, 6]. Parametric noise is recognized for its ability to induce transformative changes in the dynamic behavior of complex systems, often taking them into previously uncharted territories. This introduces a novel dimension to the study, enabling us to gain insights into the robustness and adaptability of these structures under real-world conditions, allowing researchers to study how structures behave in less idealized settings. Varying the fluid velocity through such noise enables us to investigate the problem with a more realistic representation of the environmental factors (random vibrations, fluctuations, and disturbances). In this study, I extend the exploration to a dynamic stall regime, where flow detachment occurs, by varying the incoming flow velocity. This approach adds another layer of complexity to the understanding of LCO in aeroelastic systems, as it reflects real-world conditions more accurately. The aim is to delve into the unexplored facets of the classical pitch-plunge aeroelastic system, seeking a comprehensive understanding of how parametric noise influences the occurrence of LCO and expands the boundaries of its known behavior.

2. METHOD

2.1 Aeroelastic Model: The aeroelastic system is modeled according to the experimental setup and measurements of Gkiolas [1]. The airfoil of interest is a NACA 64(3)-418 under a steady flow, undergoing free pitching and plunging 2-degree of freedom oscillation, simulated with linear springs and dumping, under dynamic stall conditions. In later research, Ketseas [2] compared the experimental results of Gkiolas [1] with results from CFD methods. Among others, the regime where stall flutter occurs was captured for certain Reynolds numbers (Re), Angles of Attack (AoA), and spring parameters. The reader can find in [1] and [2] the specific conditions and parameters of the experimental and CFD setup, which are the same used for this research.

2.2 Noise Model: In this study, the incoming flow velocity is not a constant parameter but instead is stochastically modeled using the Ornstein-Uhlenbeck (O-U) process to introduce realistic variations in the computational fluid dynamics simulations. The velocity, denoted as U, is governed by a Stochastic Differential Equation (SDE) represented as follows:

$$dU = k(U_{(mean)}-U)dt + \sigma dW \quad (1)$$

$U_{(mean)}$ represents the deterministic velocity value, serving as the long-term mean around which stochastic properties of the process evolve, and k is a constant parameter that influences the speed of mean reversion, controlling the rate at which the velocity reverts to the long-term mean. The parameter σ is a constant that regulates the noise intensity within the system, while dW refers to the Wiener process, constituting the stochastic component of the SDE. The long-term variance of this stochastic process is given by $\sigma^2/(2k)$. Equation (1) is considered an Itô integral, and I employ the Euler-Maruyama method to solve it according to [7, 8, 9, 10]. This is an approach that enables us to efficiently handle the stochastic nature of the equation and obtain numerical solutions. Figure 1 depicts the noise signal used as fluid velocity input for the CFD simulation produced by the O-U process above. The mean velocity of the simulation is $U(mean)=19.5m/s$, $k=0.9$ and $\sigma=0.03$.

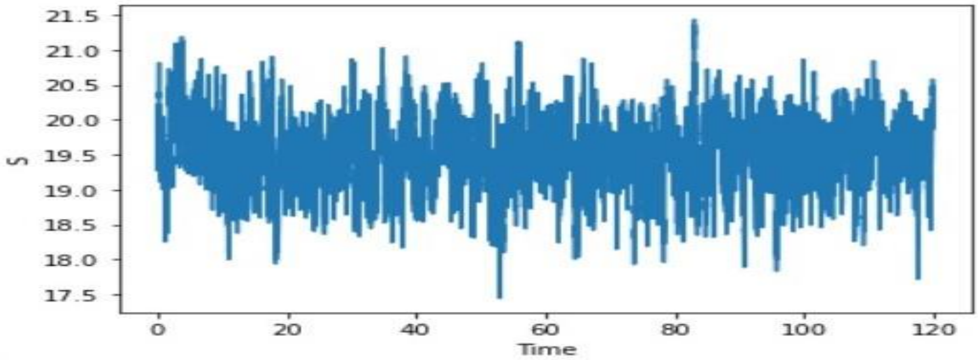

Figure 1. Noise signal used for fluid inlet velocity

3. RESULTS AND DISCUSSION (10 PT)

In earlier research, it was determined that, under the specific conditions detailed in Ketseas [2], the airfoil exhibits a critical threshold at an initial Angle of Attack (AoA) of 16.65 degrees. Beyond this point, any random perturbation induces Limit Cycle Oscillations (LCO) in the airfoil. Consequently, the graphs depicting the Lift Coefficient (CL) as a function of AoA, the Pitch, and Plunge by the chord length over time converge to a distinct pattern owing to the Lock-In phenomenon (see Figure 2, Figure 3, and Figure 4). Our observations reveal that the amplitude of both the pitching and plunging oscillation remains relatively constant over an extended duration (on the long scale), and the lift coefficient is confined to a stable loop. This phenomenon is underscored by the overlapping trajectories of each oscillation at the LCO boundary, resulting in a more pronounced graphical representation (bold blue outer loop at Fig.4). For initial angles of attack lower than this critical value, disturbances are effectively damped, leading to an overall attenuation of the airfoil's oscillatory behavior.

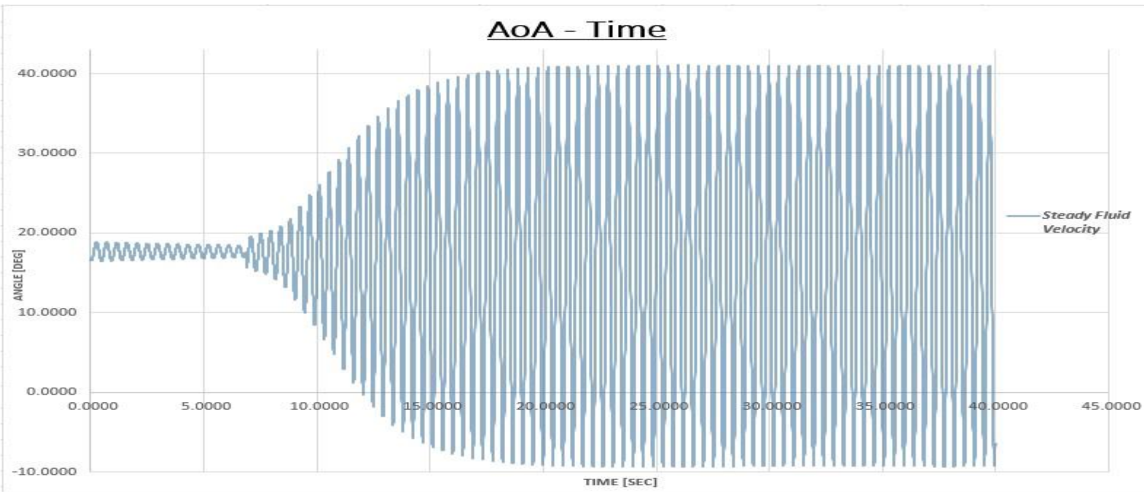

Figure 2. Time history for Pitching Motion (Angle of Attack) when exhibiting an LCO

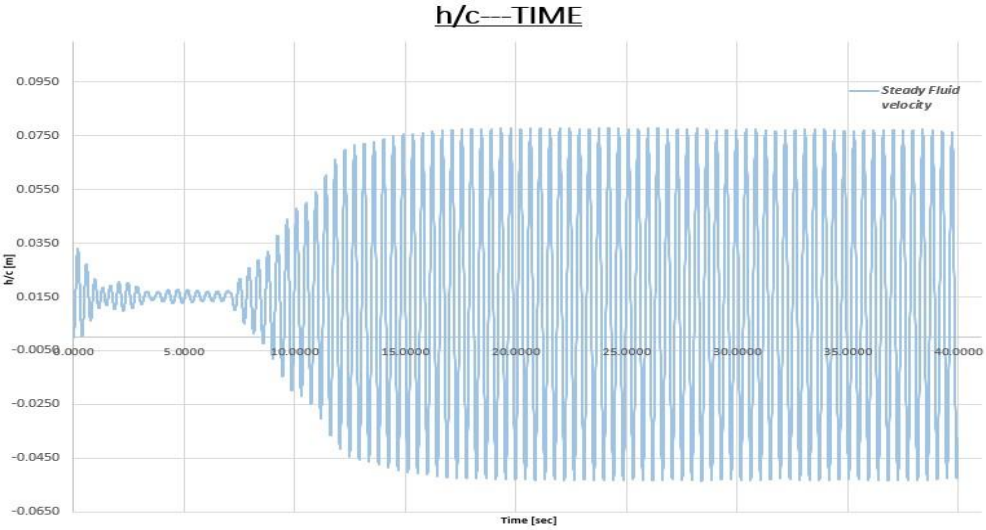

Figure 3. Time history for Plunging Motion (Heaving distance/Chord) when exhibiting an LCO

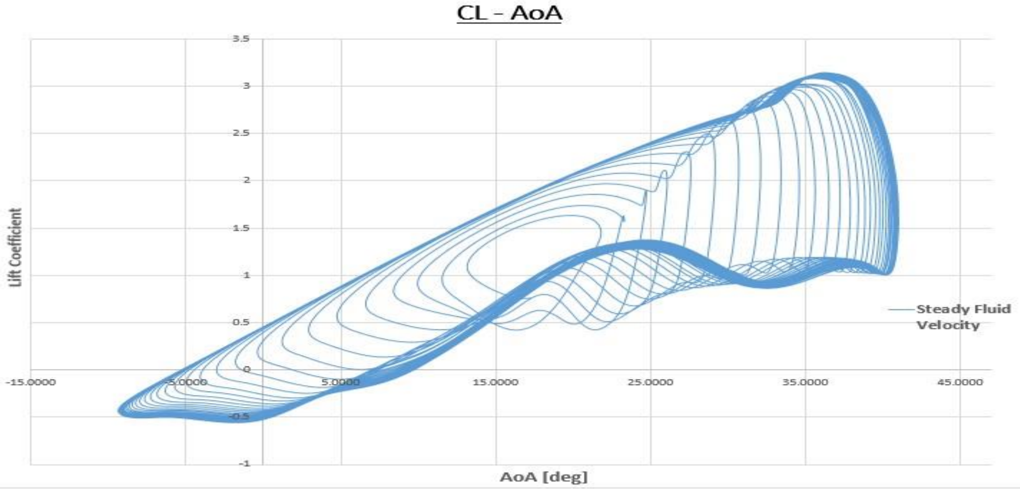

Figure 4. Lift Coefficient over time when exhibiting an LCO at 16.65 deg of initial airfoil angle

Next, I introduce a stochastic component to the previously deterministic fluid velocity by incorporating a stochastic signal generated by the Ornstein-Uhlenbeck (O-U) process, as depicted in Figure 1. This introduces notable qualitative alterations in the Limit Cycle Oscillation (LCO) regime, as evident in the following graphical representations (see Figure 5, Figure 6, and Figure 7).

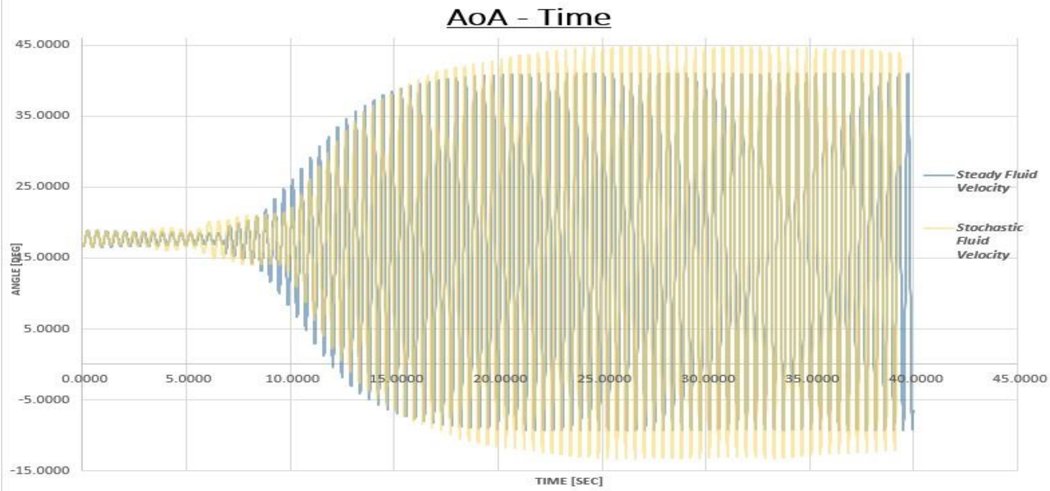

Figure 5. Time history for Pitching Motion (Angle of Attack) when exhibiting an LCO for deterministic and stochastic oscillator

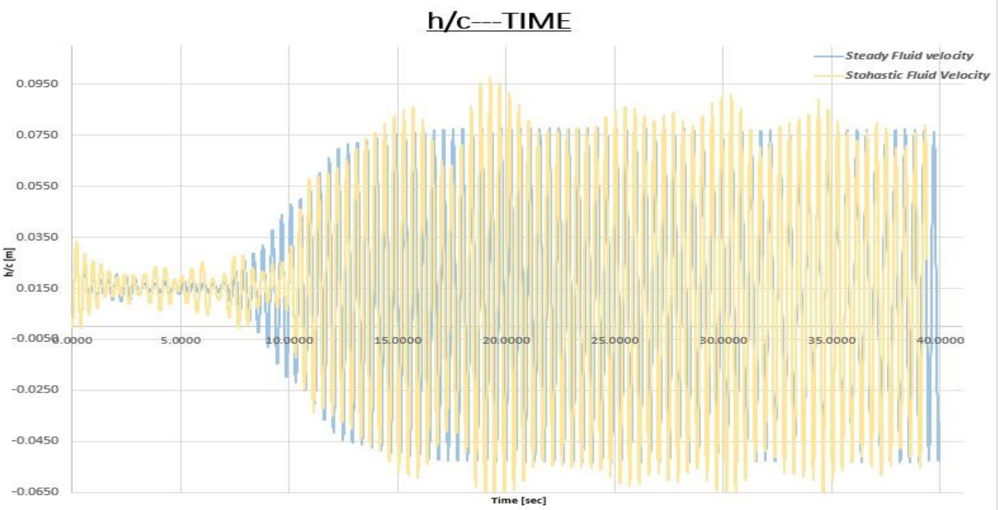

Figure 6. Time history for Plunging Motion (Heaving distance/Chord) when exhibiting an LCO for deterministic and stochastic oscillator

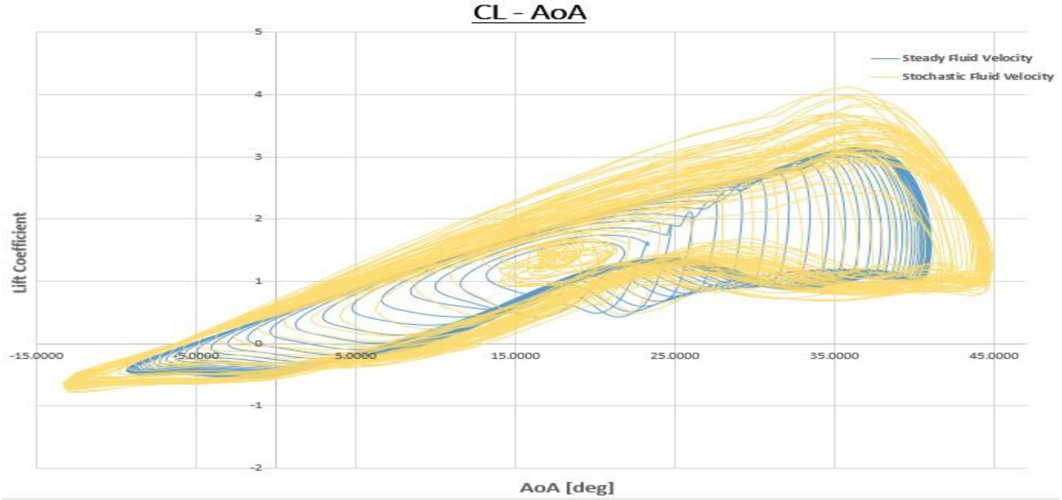

Figure 7. Time history for Angle of Attack when exhibiting an LCO for deterministic and stochastic oscillator

While the amplitude of the pitching oscillation (Figure 5) exhibits a degree of stability over a long time scale, it displays small inherent variability due to fluctuations in the fluid velocity. These fluctuations are very well depicted in the heaving motion of the airfoil (Figure 6), following the yellow nonstable curve. This variability is also especially mirrored in the fluctuating limit values on the Lift Coefficient plot (Figure 7). Consequently, as the fluid velocity varies, so does, albeit to a small extent, the maximum and minimum angles of attack within each oscillation, resulting in different trajectories for each loop. This variation accounts for the absence of a prominent LCO limit curve, as seen in the yellow curve of Figure 7, where multiple, slightly distinct curves correspond to consecutive oscillations. Furthermore, our observations reveal that the overarching trend of the phenomenon is captured, as the paths appear to follow a 'mean' trajectory with fluctuations occurring in each cycle. This 'mean' trajectory is the previous deterministic blue curve produced by the steady fluid velocity.

4. CONCLUSION

This study investigated the impact of noise on a two-degree-of-freedom pitch-plunge aeroelastic system, utilizing the Ornstein-Uhlenbeck (O-U) stochastic process to model variations in inlet flow velocity. Unlike conventional methods, the O-U model demonstrates a reverting tendency to the mean of varying parameters, rendering it particularly suitable for engineering problems, especially in the aeroelastic domain. This contribution signifies an important advancement in the arsenal of stochastic processes tailored to address the intricacies of aeroelastic systems. I focused on a 2D airfoil with aeroelastic properties simulated through linear springs, providing insights into Limit Cycle Oscillations (LCOs) under dynamic stall conditions.

Our research aimed to uncover how parametric noise alters the behavior of engineering systems, introducing unpredictability and complexity. The substantial contribution of this study is the revelation of inherent volatility within Limit Cycle Oscillations (LCO) under realistic conditions. By adding noise to vary fluid velocity, I achieved a more realistic representation of environmental factors, including random vibrations and disturbances. The introduction of stochastic noise led to qualitative changes in the LCO regime. The research showcases the nuanced boundaries of these oscillations. Contrary to the deterministic view of LCO, the study demonstrates that, in practical scenarios, there exists a certain volatility around the primary path. Inherent variability due to fluid velocity fluctuations resulted in fluctuating LCO limit values on the Lift Coefficient (CL) plot, producing distinct trajectories. This leads us to the conclusion that the LCO regime adheres to the stochastic nature of the fluid velocity, which fluctuates around a mean value and reverts to it whenever the amplitude of oscillation tends to deviate from the anticipated. This result highlights the influence of the LCO behavior due to the stochastic nature of fluid velocity. This revelation is pivotal in understanding the true limits of Limit Cycle Oscillations, providing a more accurate representation of their behavior in real-world aeroelastic environments. It contributes to a deeper understanding of aeroelastic systems and their adaptability under real-world conditions, paving the way for future research and engineering applications.

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Conflict of interest: The authors declare no conflicts of interest.

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