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Gust Response of A Porous Wing

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Synopsis

This comprehensive analysis aims to provide an essential review of the aerodynamic disturbances related to the porous wing under a gust using OpenFOAM solver. CFD simulations for higher Reynolds Number (Re) such as 1000, are performed to evaluate the lift and drag forces acting on the wing. A two-dimensional idealized porous wing structure is designed to cut down on computational time and result complexity substantially. The wing designed with a specific porosity pattern is positioned at 45° angle of attack aiming to optimize the airflow characteristics. Assuming unity for factors such as chord length, velocity and density adds up for a simple yet detailed research. Implementation of sinusoidal function assists in simulating gust characteristics. This research includes as a detailed analysis of the airflow through a porous structure, response to the external flow and its resulting lift and drag coefficients. This study also includes the time-dependency of the of the gust providing insights to the attenuation and damping characteristics of the porous wing. The results of this research demonstrates that the porous wing configuration substantially reduces the negative impacts of gusts, which promotes aerodynamic performance and increased stability. Enhanced control and maneuverability are facilitated by the porous structure's capacity to smooth out changes in aerodynamic forces and lower pressure peaks. These results imply that improving the durability and efficiency of aircraft flying in turbulent environments may be achieved by introducing porosity into wing designs. This research's thorough investigation and simulations provide intriguing details on potential applications of porous wings in contemporary aeronautical engineering, providing up the potential enhancements in aircraft development and performance optimization.

1 Introduction

The modern aviation industry constantly searches for novel and innovative approaches to improve the effectiveness, efficiency, and safety of airplanes. The use of porous materials in aircraft wing design is one such development [1]. To preserve flying stability and safety, aircraft wings must respond to gusts and aerodynamic disturbances efficiently. Sudden variations in airflow may be challenging for conventional wing designs to compensate for, which can lead to increased structural stress and inadequate control [2].

The numerous advantages of porous wings, that are highlighted by their permeable development, have the capacity to fundamentally change structural engineering and traditional aerodynamics. Aircraft wings with porosity may significantly reduce weight, increasing operational cost-effectiveness and fuel efficiency. Furthermore, porous materials' unique aerodynamic qualities can maximize lift and reduce drag, improving flying performance [3]. Additionally, these materials have the ability to reduce airflow-related noise, which promotes quieter and greener aircraft [4], by permitting air to flow through the wing structure, it has the ability to reduce the turbulence and pressure variations that cause aerodynamic noise. Furthermore, the noise generated by vortex shedding and other aerodynamic phenomena can be minimized due to the decreased turbulence surrounding the wing's surface [5].

The idea of a porous wing originated by microscopic organisms, whose ability to sustain themselves in the low Reynolds number region has drawn a lot of interest [6]. When it comes to controlled flight, the morphological and kinematic characteristics of natural flyers are very intriguing to the subject of bio-inspired technology. Biological flyers additionally demonstrate impressive maneuverability and propelling performance.

To understand the aerodynamic principles that explain how insects with discontinuous wings can fly in the air, it requires a thorough understanding of the microscopic structure [7]. As the Reynolds number drops, the vorticity in the shear layers that arise from the surface of each hair aggressively diffuses into the surrounding fluid. The highly developed shear layers eventually merge to create virtual fluid barriers in the spaces between the hairs, which enables the hydrodynamic behavior of the spatially distinct hairy structure to resemble that of a paddle. With significant shifts in the vorticity distribution under variations of just one or two orders of magnitude in the Reynolds number, it was discovered that the interaction between the elimination of an existing vortex and the development of a stopping vortex at the same edge was contingent on the number. The clapping and flinging of a pair of wings by small insects like wasps, thrips, and fairyflies is believed to be a usual lift augmentation mechanism utilized by these insects in nature [8].

Although earlier research has associated the morphological characteristics of porous wing to their aerodynamic characteristics, these studies have focused solely at constrained flow scenarios, including a stagnant fluid or an unaltered, uniform, and constant free stream. Insects, however, rarely receive the opportunity to fly in steady conditions or discrete air in the natural world. Rather, they are more likely to experience irregular winds that are diverse and quite unexpected. It is essential to observe that flying insects have remarkable ability to effectively deal with challenging flow circumstances employing active or passive control techniques [9].

As a result, the hairy structure in the low Reynolds number domain can impose fluid-dynamic forces equal to those generated by a structure with a continuous surface, hence lowering the mass required [10]. Rather than considering the bristle diameter and wing chord, the Reynolds number based on gap width has been demonstrated to be the primary dimensionless parameter that characterizes the aerodynamic performance of a two-dimensional (2-D) bristled wing in a constant and homogeneous free stream [11]. For insects having porous wings, the investigation of gusty flows becomes essential since, in contrast to the conventional wings of terrestrial flyers, their smaller body length (<10−3 m) renders them more susceptible to abrupt changes in flow.

2 Governing Equations and Models

2.1 Problem definition

The present study aims to investigate the unsteady aerodynamic forces and the porous wing's gust response. The focus of this research is to determine how the porous structure affects the wing's stability and aerodynamic performance under gust scenarios. Implementing the sinusoidal velocity profile assists in analyzing the flow factors around the wing such as lift and drag characteristics in response to gusts and unstable flow. To capture the intricacies in the early phases of simulation, it is more appealing to compare the results of a porous wing with a flat plate wing. These models are then simulated using different boundary conditions and are compared with their performance metrics respectively.

2.2 Governing equations

The OpenFOAM software is utilized to numerically solve the 2D in-compressible laminar flow, which serves as the governing equation in the current study. Given that the pimpleFOAM can handle complicated simulations, using it as a steady-state solver seems a plausible approach to conduct the research. The Navier-Stokes equations, which characterize the motion of viscous fluid substances, serve as the foundation for the governing equations for fluid flow when employing the laminar model. These equations are the momentum equations and the continuity equation for incompressible flow. Mass conservation is guaranteed by the continuity equation, which can be written as $\Delta.u = 0$ where u is the velocity vector. The momentum equations, derived from Newton's second law, are given by

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \mathbf{f} \tag{1}$$

where ρ is the fluid density, p is the pressure, µ is the dynamic viscosity, and f represents body forces such as gravity. These equations account for the viscous effects that are significant in laminar flow regimes, where the fluid flow is smooth and orderly. Solving these equations provides detailed insights into the velocity and pressure fields within the fluid, allowing for accurate modeling of laminar flow behavior around various geometries.

2.3 Geometry and Mesh

To study on gust response of porous wing, we model a 2D porous wing model that is simplified yet adequately depicts the 2D characteristics of a biological porous wing. The flat plate wing model represents a traditional wing.

The model consists of five cylinders, each of which depicts a porous wing's bristles with an equal diameter of D. The chord length (L) of the porous model is taken as unity. For the computational domain, every bristle D has a diameter of 0.1. There is a straight alignment between these cylinders. Both the models are kept at a fixed angle of attack (α) of 45°. The distance between the centers of the two neighboring bristles is represented by the gap width (G). Similarly, the flat plate wing has a thickness of D, and the chord length as unity. Numerous previous investigations on bio-inspired

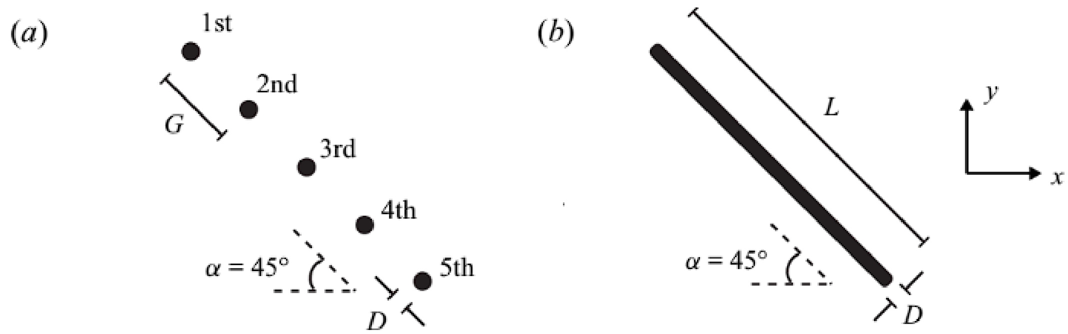

Figure 1: Schematic diagrams of (a) a simplified 2D porous wing and (b) a corresponding flat plate wing [8]

aerodynamics have taken consideration of the high angle of attack range of around 45°, and it may be regarded as a typical angle of attack during the unstable flying of insects [8].

A rectangular domain of dimensions 15x1x10 is considered as the control volume for the porous and flat plate wing. The blockMesh utility in the OpenFOAM was used to model the geometries. The mesh was refined using the same utility.

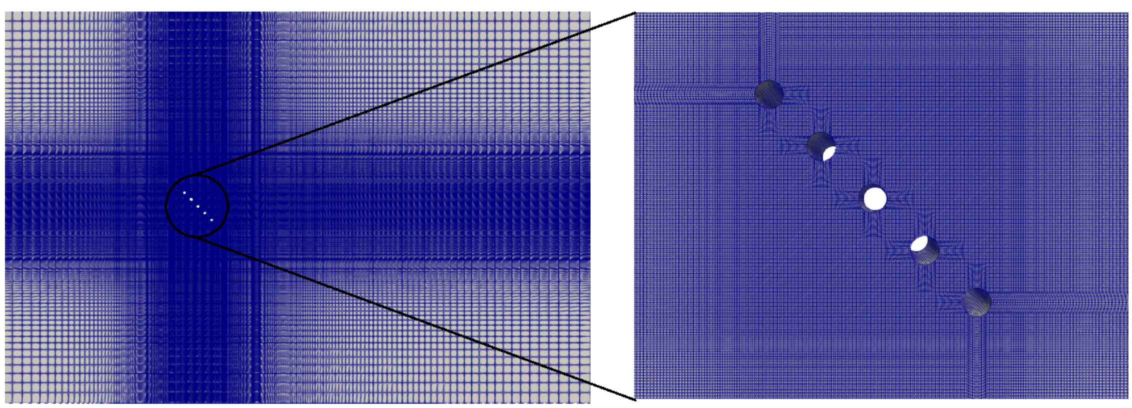

Figure 2: Computational Domain of Porous wing

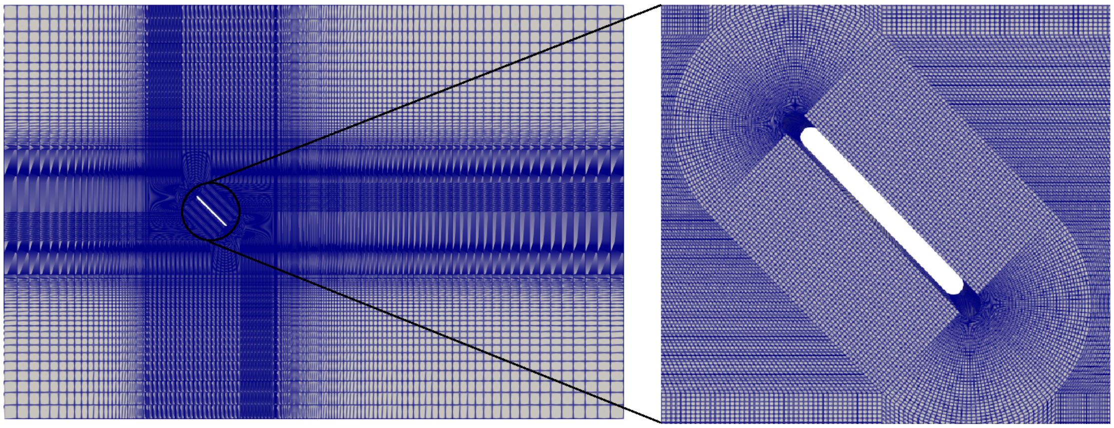

Figure 3: Computational Domain of Flat plate wing

2.4 Solver setup

2.4.0.1 Fluid Properties

The kinematic viscosity (ν) of an in-compressible, laminar flow of a Newtonian fluid with unity velocity ($U = 1$) and unity density ($\rho = 1$) is given as $0.001 m^2$/s. The velocity inside the computational domain is considered to be as free stream. In light of these circumstances, the Reynolds number (R_e) which is defined as $Re = \frac{UL}{\nu}$ is computed to be 1000, in agreement with the values provided. With the substituted values, these characteristics describe the fluid as having a laminar flow regime, characterized by a smooth, steady flow regime with no turbulence and a dominance of viscous forces over inertial forces. The Newtonian transport model represents the fluid's transport properties to ensure consistent behavior. A sinusoidal velocity profile is introduced to the free stream assuming that the gust is uniform in the x - direction. The gust velocity profile in the x - direction is set to be

$$\mathrm{F(x)} = \mathrm{A} \sin\left(\frac{2\pi}{T}x + \Phi\right) + D \tag{2}$$

where A is the amplitude of the sinusoidal function, T is the time period, ϕ is the phase shift, and D is the vertical shift. Porous wings naturally experiences a high reynolds number ranging from $10 - 10^3$.

2.4.0.2 Initial and Boundary conditions

This research employs two distinct strategies to arrive at the desired outcome. The boundary conditions employed in each of these simulations make them fundamentally different from one another. One of the approaches is implementing uniformFixedValue boundary condition, whereas codedFixedValue boundary condition were used in the other approach. In order to simulate a gust response to the porous and flat plate wing, these conditions were individually applied at the inlet to create a sinusoidal velocity profile. The following tables describe the initial and boundary conditions.

	inlet	outlet	topAndBottom	frontAndBack	wall
U	uniformFixedValue	zeroGradient	slip	empty	noSlip
P	zeroGradient	fixedValue	slip	empty	zeroGradient

Table 1: Boundary Conditions For uniformFixedValue approach

	inlet	outlet	topAndBottom	frontAndBack	wall
U	codedFixedValue	zeroGradient	slip	empty	noSlip
P	zeroGradient	fixedValue	slip	empty	zeroGradient

Table 2: Boundary Conditions For codedFixedValue approach

2.4.0.3 Solution Method and Control

The simulations are carried out using the pimpleFoam solver in OpenFOAM, which is a combination of Pressure-Implicit with Splitting of Operators (PISO) and Semi-Implicit Method For Pressure Linked Equations (SIMPLE) algorithms. The pimpleFoam solver ensures the stability and accuracy of the solution approach. It is a transient solver for incompressible, turbulent flow. Larger time steps can be treated effectively using this hybrid solver. All the control parameters of the simulation are composed in the controlDict file. A time step ($\Delta t = 10e^{-}4$) was selected for the stability of the solution and to resolve transient phenomena. The endTime was selected as 50 secs to eliminate the compromise for the computational time and accuracy of the final results. The maxCo was set to be 1 for the promising accuracy and stability of the mesh. Other parameters such as nCorrectors = 2 and nNonOrthogonalCorrectors = 0 were set in the fvSolution file which employs the finite volume method. The Euler method was implemented to approximate the time derivatives while spatial discretization employed the Gauss linear schemes for gradient calculations.

3 Results and Discussions

3.1 Preliminary Test

To ensure that the test simulation setup was error-free, preliminary testing was carried out by setting up the simulation under two different Reynolds Number such as Re = 30 and 1000 respectively for each wing models. In addition to the preliminary testing, the unstructured meshing was performed, to reduce the computational time of simulation. It is crucial to have appropriate boundary conditions to presuppose the test run such as specifying the porous structure as a wall, defining the far-field conditions, and setting the inflow conditions. The pimpleFoam solver within the OpenFOAM framework was used to evaluate the performance and accuracy of the simulation. In addition, key parameters such as C_l and C_d were analyzed. The results revealed that pimpleFoam operated low and intermediate Reynolds number flows effectively, laying the foundation for more intricate and thorough simulations in later phases of the study.

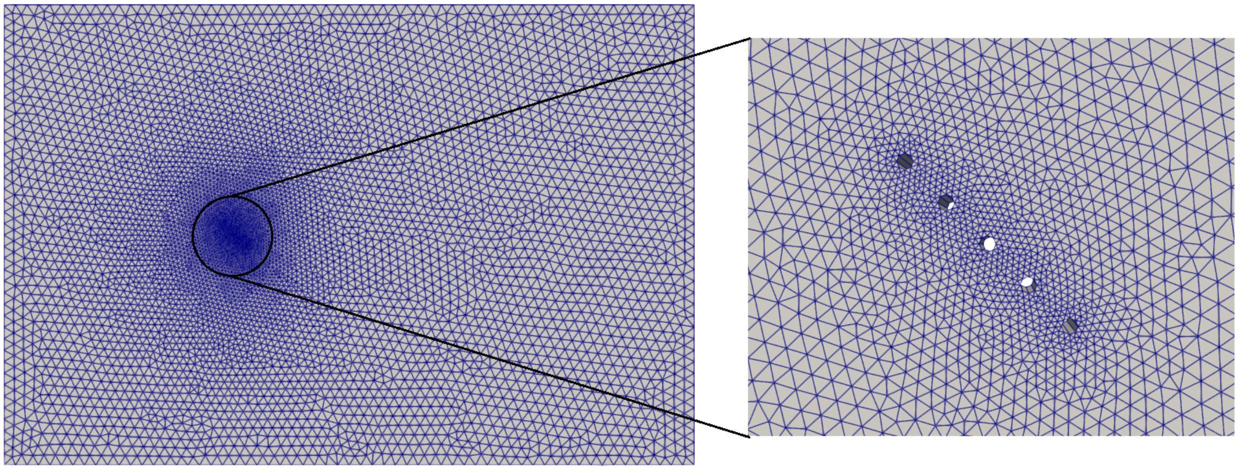

Figure 4: Computational Unstructured Domain of Porous Wing

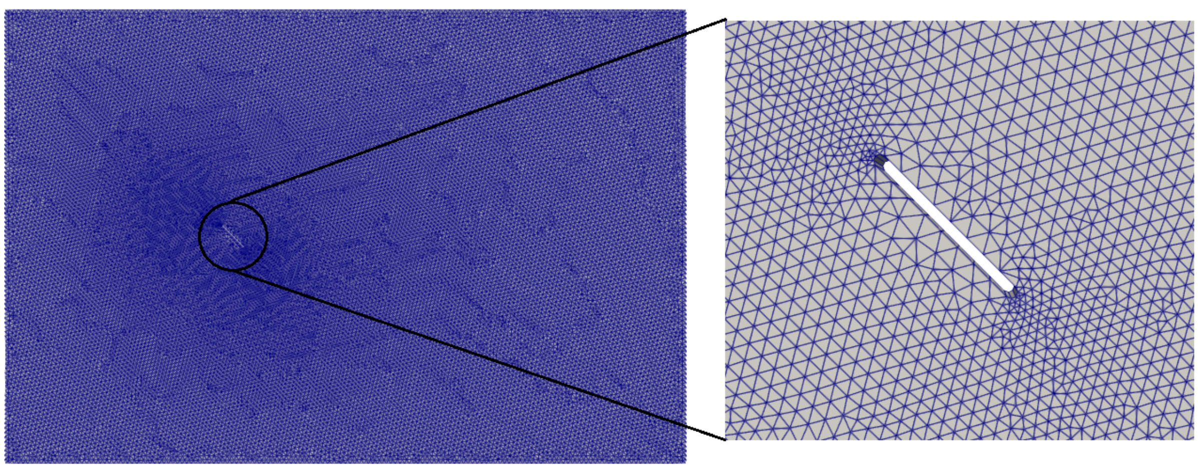

Figure 5: Computational Unstructured Domain of Flat Plate Wing

3.2 Convergence Tests

3.2.0.1 Grid Size Convergence Test

In this study, a comprehensive mesh convergence test was conducted using Richardson's extrapolation, to ensure the accuracy and reliability of the numerical simulations performed. This method allows for determining the solution's grid independence study by estimating discretization errors. The test was performed at Re=1000 which is a moderate flow regime. The initial computational mesh of the porous wing comprises 35629 cells which provides a baseline for comparison. Subsequently, the mesh was systematically refined to produce two finer meshes with 73705 and 145564 cells respectively, whereas the initial computational mesh of the flat plate wing comprises 22145 cells and was refined to produce two finer meshes with 43608 and 86740 cells respectively. To capture the flow properties more accurately, every mesh refinement aimed to lower the cell size across the domain consistently with a factor of $\sqrt{2}$. The purpose of each mesh refinement was to capture the flow characteristics more accurately by equally reducing the cell size across the domain. Crucial flow parameters, such as C_d and C_l, have been monitored carefully throughout the simulations to evaluate the convergence behavior. To evaluate the relative changes in these parameters, results from each of the mesh levels were compared. By assuming a polynomial connection between the mesh size and the solution error, the Richardson extrapolation approach was employed. The numerical scheme's apparent order of accuracy was measured by comparing the solutions derived from the various meshes. This procedure entailed determining the discretization error for every mesh level and computing the extrapolated solution on an indefinitely fine mesh.

Mesh	**Number of Cells**		**Coefficient Of Lift (Cl)**		**Coefficient Of Drag (Cd)**	
	Porous	**Flat plate**	**Porous**	**Flat Plate**	**Porous**	**Flat Plate**
Coarse	35629	22145	2.31150	2.03549	1.20953	2.38089
Medium	73705	43608	2.46090	2.12909	1.21329	2.52099
Fine	145564	86740	2.51634	2.28537	1.21411	2.57103
Rich. Extra.			2.54905	2.30353	1.21433	2.59892

Table 3: Grid Convergence Test Data Table

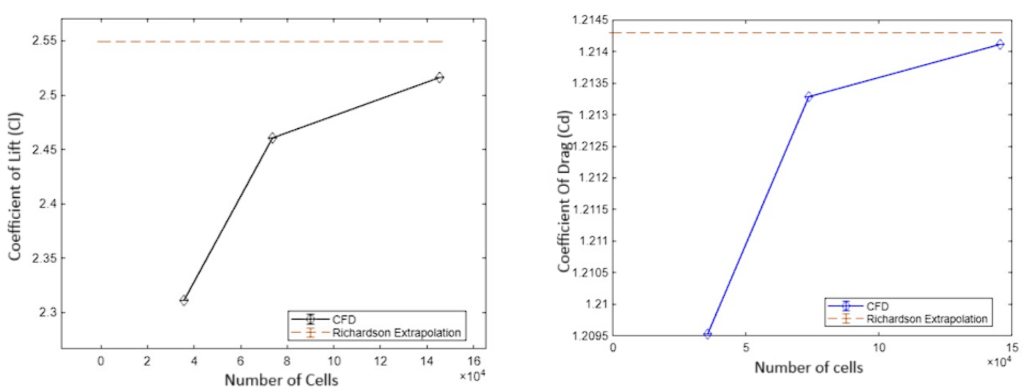

Figure 6: Grid Convergence Test of Porous wing (a) Coefficient of Lift (Cl)-Left (b) Coefficient of Drag (Cd)-Right

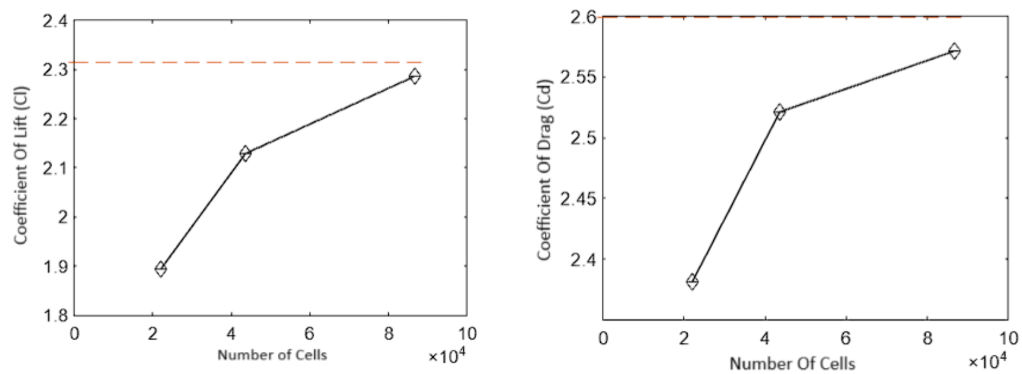

Figure 7: Grid Convergence Test of Flat Plate wing (a) Coefficient of Lift (Cl)-Left (b) Coefficient of Drag (Cd)-Right

3.3 Results

3.3.0.1 No gust Condition

In this section, we present the two different types of wings' various aerodynamic reactions to gusty flows. Firstly, by comparing the wings in a non-gusty environment and by applying the appropriate boundary conditions at Re = 1000 in the pimpleFoam solver setup, the differences in the aerodynamic forces can be visualized in the following figures.

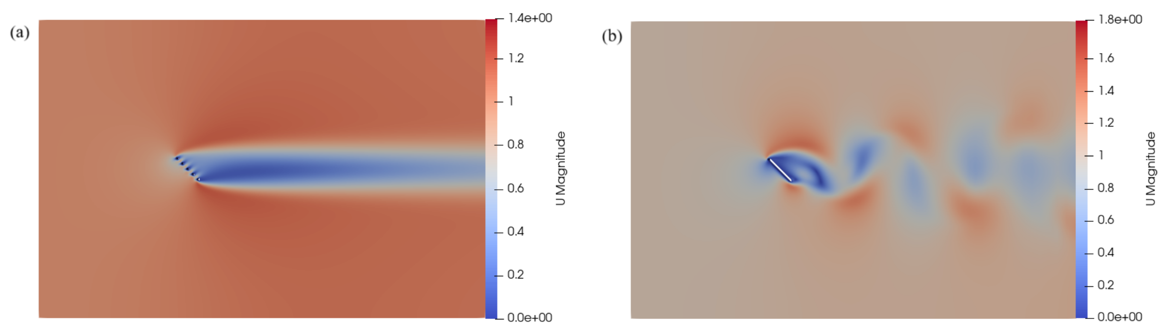

Figure 8: Velocity Contours: No gust condition for (a) Porous wing and (b) Flat plate wing

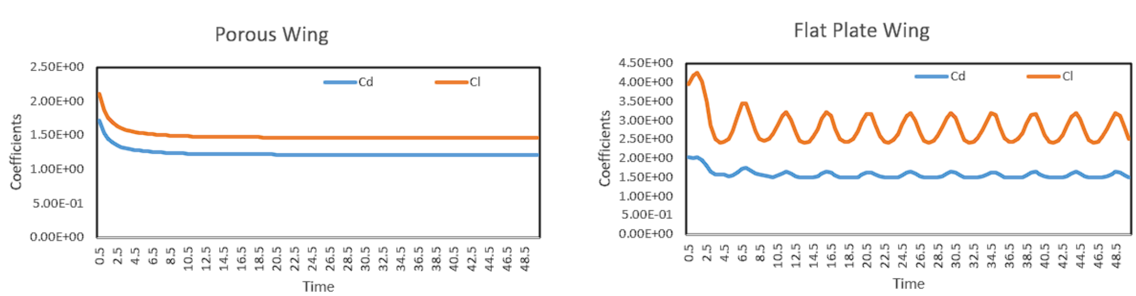

Figure 9: Aerodynamic Forces of (a) Porous wing-Left and (b) Flat plate wing-Right

As shown in figure 8, vortex shedding can be visualized in the flat plate wing due to its natural property of exhibiting higher oscillations and less effective damping when compared to the porous wing. The vortex shedding in the flat plate wing can also be referred to as the Von Karman Vortex Formation where the surrounding flow experiences oscillations and turbulence.

3.3.0.2 uniformFixedValue Approach

This research section investigates the gust response of the porous wing with the implementation of uniformFixedValue boundary condition at the inlet patch. OpenFOAM makes extensive use of the uniformFixedValue boundary condition due to its simplicity and effective methodology to define consistent values across a border. This boundary condition is ideal for rudimentary simulations and initial testing as it is especially helpful in situations where a constant and uniform inflow or outflow is needed. The uniformFixedValue condition assists in establishing a baseline behavior of the wing under steady, regulated conditions in the context of gust response simulations, facilitating an easy comparison of performance metrics including C_l and C_d. Its simplicity of use and obvious physical interpretation guarantee accurate and repeatable simulation findings, offering a solid basis for more intricate research. Gust response was simulated by setting up the case in the pimpleFoam solver, with Re at 100 and 1000, covering the laminar and turbulent flow regimes. A sinusoidal velocity profile is introduced to provide a realistic dynamic flow environment. In this approach, the following parameters were set such as the amplitude (A) as 1, time (T) as 5, and phase shift (ϕ) as 0, a gust response throughout the domain is observed. This approach allows an accurate representation of the actual nature of turbulence and its impact on the aerodynamic performance of the wing. To evaluate the wing's response, key performance indicators such as lift and drag coefficients are analyzed to improve efficiency.

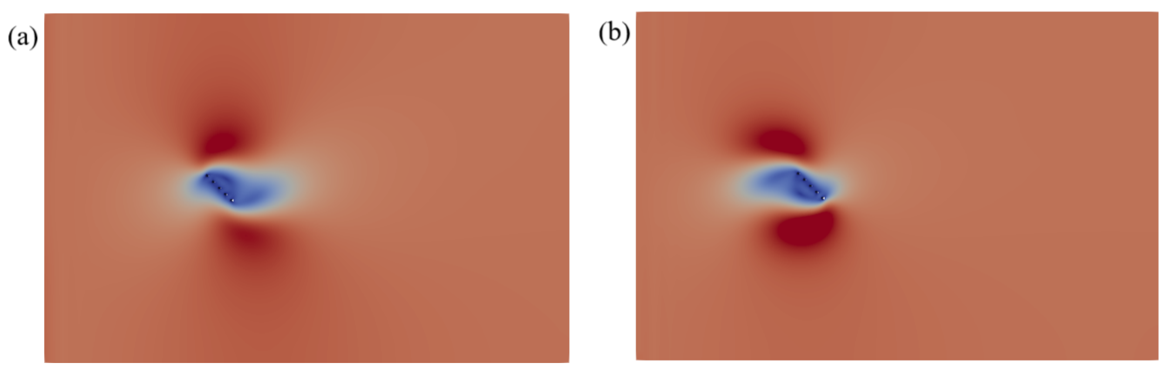

Figure 10: Velocity Contours of Porous wing at Re = 30 where (a) positive flow and (b) negative flow

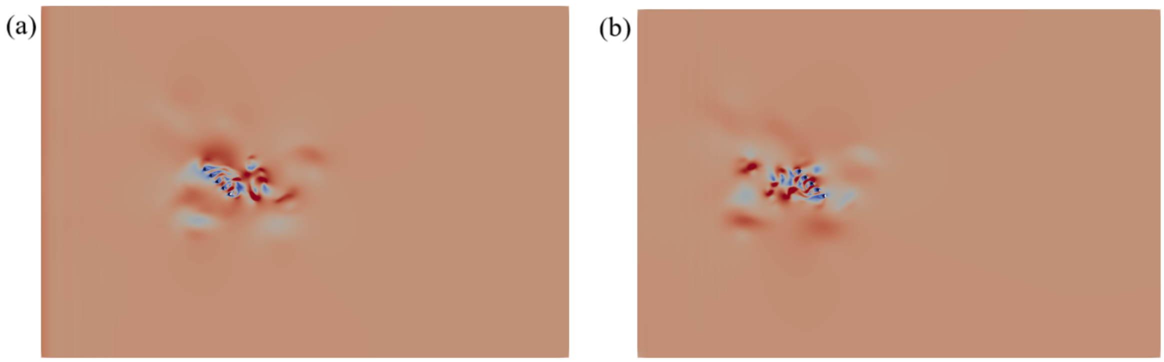

Figure 11: Velocity Contours of Porous wing at Re = 1000 where (a) positive flow and (b) negative flow

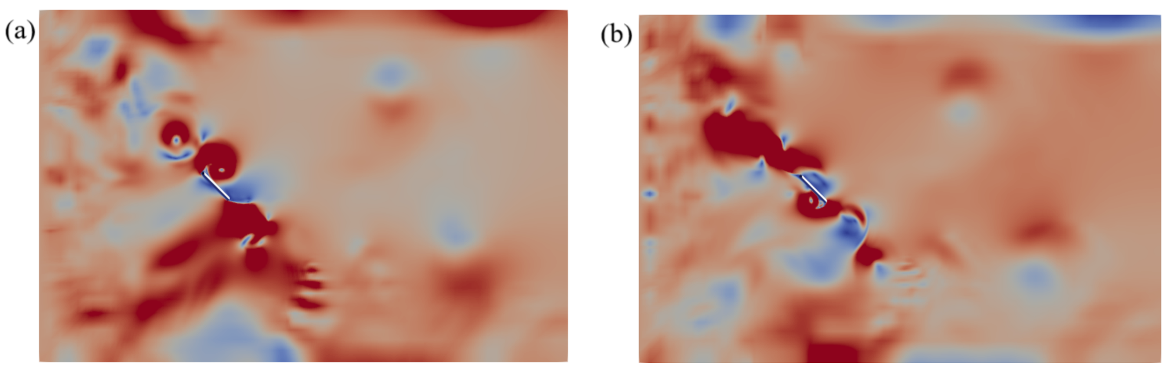

Figure 12: Velocity Contours of Flat Wing at Re = 1000 where (a) positive flow and (b) negative flow

Simulations show that the porous wing maintains a more stable and controlled aerodynamic profile in gust conditions. A smoother and more stable response to gusts was established by the porous wing, which exhibited enhanced damping qualities under the sinusoidal velocity profile. This impact was evident at the higher Reynolds number of 1000 when turbulence plays a more substantial part. Porous wings demonstrated smaller oscillation amplitudes and a quicker return to equilibrium than flat plate wing. In contrast, the flat plate wing demonstrated a more prominent gust response and higher oscillations, indicating increased instability and less efficient damping.

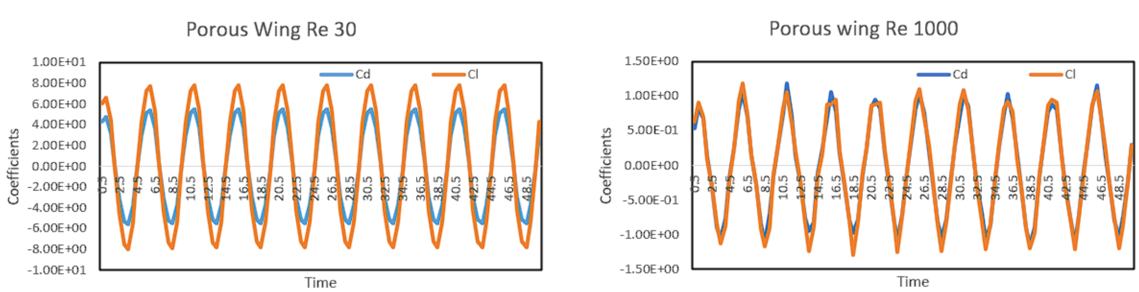

Figure 13: Force Coefficients of Porous wing under Re 100 and 1000

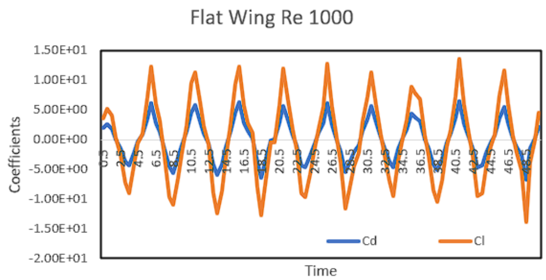

Figure 14: Force Coefficients of Flat Plate Wing under Re 1000

There were significant variations in the two wing types' lift and drag coefficients, two important performance metrics. Lower peak lift and drag forces on the porous wing indicated that it could significantly reduce gust impacts. The porous wing proved its potential benefits for applications where gust response is crucial by maintaining a stable aerodynamic profile under dynamic gust circumstances. The comparison study demonstrated how effectively porous materials work in wing design to increase aerodynamic efficiency and stability, particularly under challenging flow circumstances brought on by a sinusoidal velocity profile.

3.3.0.3 codedFixedValue Approach

In this section of the research, the gust is simulated with the codedFixedValue boundary condition at the inlet patch of the domain. More flexibility and customization in boundary value specification are provided by the codedFixedValue boundary condition, which makes it a great resource for simulating intricate and dynamic flow scenarios. With the use of custom code, users may set boundary values for this boundary condition, which makes it possible to develop time-dependent and spatially variable profiles—for example, a sinusoidal velocity profile to imitate gusts. The codedFixedValue condition is essential for effectively representing the transient and non-uniform character of gusts in gust response simulations, resulting in a more realistic and thorough examination of the aerodynamic behavior of the wing. For advanced research, where exact control over boundary conditions may greatly affect the quality and applicability of the simulation results, this customization feature is crucial. The two wing types are simulated with Re = 1000 and their performance metrics are later compared. Similar parameters have been used to implement the sinusoidal velocity profile.

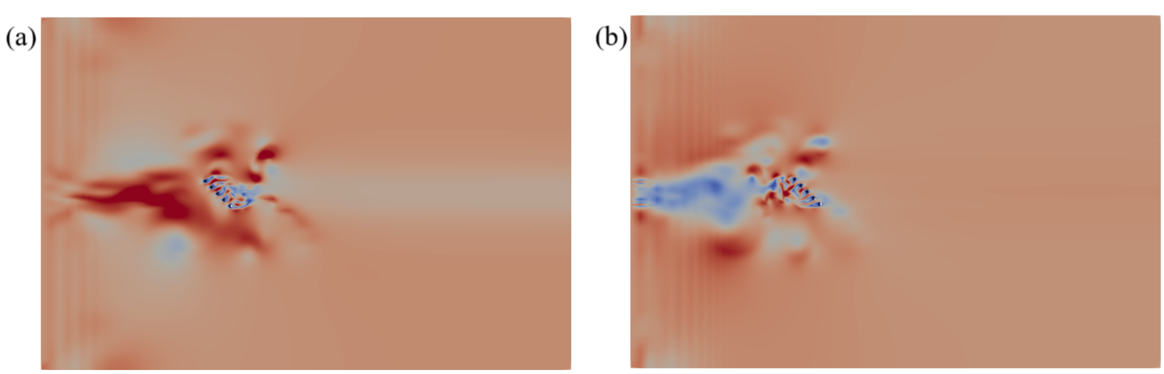

Figure 15: Velocity Contours of Porous wing at Re = 1000 where (a) positive flow and (b) negative flow

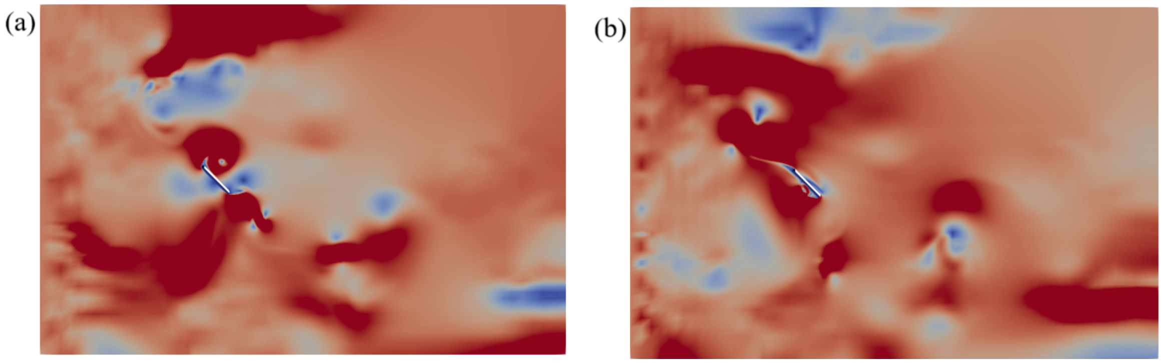

Figure 16: Velocity Contours of Flat Plate wing at Re = 1000 where (a) positive flow and (b) negative flow

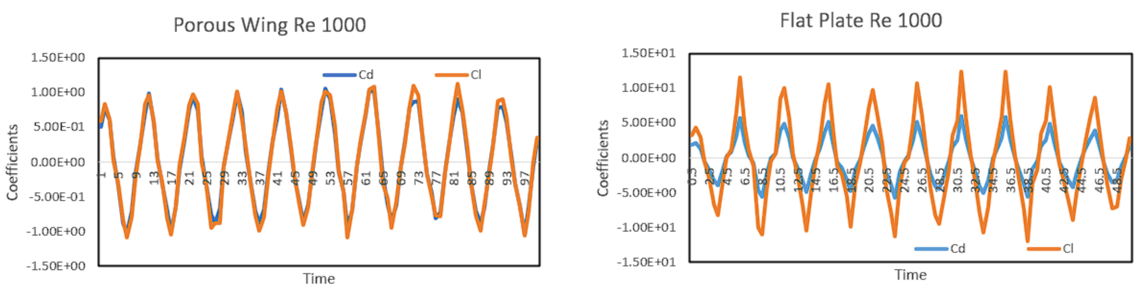

Figure 17: Force Coefficients of (a) Porous Wing-Left and (b) Flat Plate wing-Right

A similar response for the various wings' type is noticed in this approach. The ability of the porous wing out stands of that of the flat plate wing. The dampening and return to equilibrium properties of the porous wing is analyzed to be dominant. Determining these deficiencies required the codedFixedValue border condition to effectively imitate dynamic flow conditions. This boundary condition allows for a detailed examination of the lift and drag coefficients by offering a realistic depiction of the gusty environment. The results demonstrated the usefulness of porous materials in obtaining improved aerodynamic performance and stability by confirming that the porous wing maintained a more stable aerodynamic profile during dynamic gust environments.

4 Conclusions

The gust response of the porous wing is thoroughly analyzed in this work, and it is analyzed that the porous wing is better suited to turbulent and transitional regimes. Using OpenFOAM's pimpleFoam solver, we conducted extensive simulations to evaluate the aerodynamic performance of porous and flat plate wings in a range of flow conditions. A smoother and more stable response to gusts was produced by the porous wing's improved damping properties, especially at higher Reynolds numbers when the flow changes from laminar to turbulent. The precise representation of sinusoidal velocity profiles was made possible by the uniformFixedValue and codedFixedValue boundary conditions, which allowed for the exact modeling of dynamic gust environments. Systematic analysis of the flow mechanics for each configuration indicated significant variations in performance. In contrast to the flat plate wing, the porous wing demonstrated a smaller oscillation amplitude and a faster return to equilibrium, underscoring its higher resistance to gust disturbances. An analysis of critical performance measures, including the lift and drag coefficients, and other factors, further supported the porous wing hypothesis. These measures showed that the porous wing maintained a more consistent and stable aerodynamic profile in addition to handling gust effects more effectively. The flat plate wing, on the other hand, showed more oscillations and a more noticeable gust response, suggesting less efficient damping and increased instability. Unfavorable aerodynamic phenomena including flow separation and vortex shedding were not as prevalent on the porous wing due to the homogeneous pressure distribution over it, compared to the flat plate wing. Overall, the study finds that the porous wing is a better option for applications needing stability and performance in dynamic flow circumstances because it operates more efficiently, particularly in transition and turbulent regimes.

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