

The Impact of Surface Geometry on Vortex Dynamics in Fluid Flows of Different Velocities

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ABSTRACT

This paper will investigate the subject of fluid behavior upon interaction with various geometries. Observations about the different shapes of airplane wings depending on the purpose of the plane caused questioning about the functionality of the wingshape in particular aerial conditions. These questions were further elaborated on and understood by constructing a model wind tunnel used to test numerous variations of objects to determine how air flow is affected by different characteristics of an aerial body, such as the wingtip of an airfoil creating vortices and what implications that may have on the fluid overall, similar to the intent of different cylindrical bodies and how the bluntness of their shape impacts the fluid. A multitude of tests at three different speeds, analyzed by the intensity and frequency of vortices, revealed that airfoils maintain stability with attached flow, while cylindrical and wavy shapes exhibit high drag, early separation, and, in the case of concave surfaces, extreme instability. Surface roughness acts as a velocity-dependent turbulator, reducing displacement at low speeds but catalyzing premature vortex shedding at higher velocities. These results have major implications for aerial and nautical travel in terms of efficiency, safety, and the extent of human travel.

KEYWORDS: vortex, airfoil, turbulence, boundary layer, aerodynamic

INTRODUCTION

Findings regarding the different shapes of airplane wings depending on the purpose of the plane allowed for questions to be asked about the workings of the wingshapes. While the differences between streamlined and blunt bodies are generally recognized, a lack of clarity exists regarding how small modifications to a surface interact with shifting fluid velocities. These questions were elaborated on by recognizing that aerodynamic structures often experience complex boundary layer interactions that standard equations, such as the Navier-Stokes equations, which define fluid movement based on pressure, friction, and momentum, are unable to accurately predict due to the complexity of the equations not allowing for an exact prediction for real-world, unideal bodies. This leaves an absence of understanding in how geometric changes alter structural aerodynamic capability and fluid behavior.

This writing addresses this gap by experimenting on a wide variety of geometric profiles within a controlled testing environment to see how small physical characteristics dictate fluid behavior. By exploring various configurations of airfoils, cylinders, and wavelike shapes, the study explains the particular areas in which solid flow diverges into turbulence. The primary focus of this work is to demonstrate how surface variations cause changes in aerodynamic behavior, such as streamlined airflow or eddying, providing insight into fluid behavior around bodies that can be used to optimize future structural designs.

BACKGROUND INFORMATION

Understanding these fluid interactions requires analysis of the behavior of air when it meets an aerodynamically suboptimal object; it slows down dramatically at the front before splitting around the body [1]. In particular, turbulence is of concern; as the air accelerates along the sides of an object, the pressure drops, and a boundary layer forms on the surface, intensifying as it moves toward the rear until the flow completely separates from the object [2]. This early separation creates a low-pressure, highly turbulent wake behind the object that is

filled with vortices that shed off the body, causing the structure to experience force fluctuations driven by the pressure difference between the front and back [3,4].

Another cause of turbulence is obstructions to airflow as it goes along the object; blockages to the streamlined boundary layer causes the fluid to be pushed off course [1]. These disruptive wake dynamics directly contrast the performance of an airfoil, which produces lift because the air flowing over the top surface moves faster than the air on the bottom, creating lower pressure on top and higher pressure on the bottom [5]. While the flow generally stays attached to the smooth surface at moderate angles to maintain minimal displacement, the wingtips introduce issues in which air travels from the high-pressure bottom to the low-pressure top [6]. This lateral spilling creates a distinct wingtip vortex in the wake that increases overall turbulence and induces drag, though changing the wingtip length or removing it entirely can drastically alter this leakage and solidify the resulting wake [6].

The complex shedding patterns and boundary layer movements build heavily on foundational research regarding fluid mechanics, particularly Theodore von Kármán's work on periodic vortex streets behind blunt objects [2,4]. Modern aerodynamic research expands on Von Kármán's findings by testing how surface alterations can disrupt or manipulate these traditional shedding frequencies to influence structural stability [4]. Introducing surface changes, such as concavities or waviness, disrupts the natural air flow, forcing the fluid into non-linear patterns in which eddies manipulate the expected drag profile of the body [4].

EXPERIMENT CONDITIONS

To investigate how the geometry of objects impact airflow, thorough experimentation needed to be done in a way that could be both visually and quantitatively interpreted. The most logical course of action for this investigation was to construct a model wind tunnel used to test

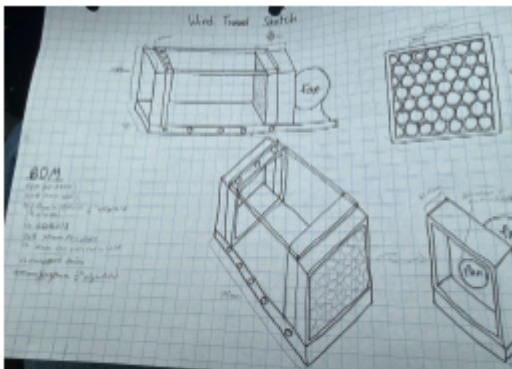


Fig 1: drawn diagram of wind tunnel

numerous variations of objects to determine how properties of the air are affected by different characteristics of an aerial body. The design, as seen in *Fig 1* was a rectangular, twenty-inch wooden wind tunnel with a large test section, utilizing plywood for the base and frame. It was constructed with polycarbonate viewing walls and flow straighteners made with sixty-three PVC pipes. A cardboard frame holds the fan and an entry for a smoke machine, while adjustable wooden strips support test objects. After gathering materials, a bandsaw and hot glue were primarily used for manufacturing. When the smoke machine failed to work properly, the methodology was adapted to use light strings to visualize the airflow without altering its properties.

The physical models were built to represent a spectrum of aerodynamic designs that ranged from typical cylinders and modified cylinders to airfoils with varying wingtips to wave shapes. The primary independent variable throughout the trials was the air speed, while the dependent variables emphasized tracking air velocity in inches and vortex shedding frequencies. These specific metrics allowed for quantitative comparison of the success of each shape in allowing the fluid to maintain stability under changing aerodynamic velocities.

DATA COLLECTION METHODS

Data was collected through a combination of both visual tracking and physical measurement to record the movement of the air. Lightweight air tracking strings were attached to the models to visually trace where the flow was attached and where it broke away into a wake, with photos and videos recording the intensity and frequency of the vortices. Structural displacement was measured using markers that provided a clear dataset that revealed how flow separation translated to physical instability.

RESULTS & DISCUSSION

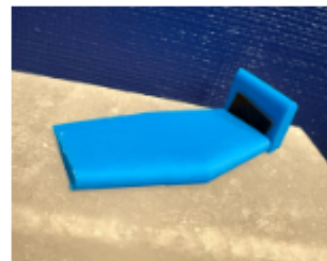
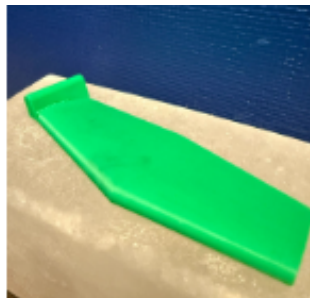
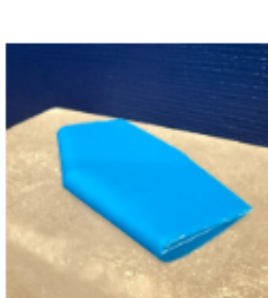


Fig 2: standard airfoil

Fig 3: airfoil with wingtip

Fig 4: airfoil with smaller wingtip

Fig 5: airfoil with larger wingtip

Displayed above in Fig 2-5 are the airfoil, wingtip, modified smaller wingtip, and modified larger wingtip models, respectively. Observations concerning the physical reactions of the string and the corresponding frequency of generated vortices across three speeds displayed aerodynamic relationships governing wingtip geometry modifications.

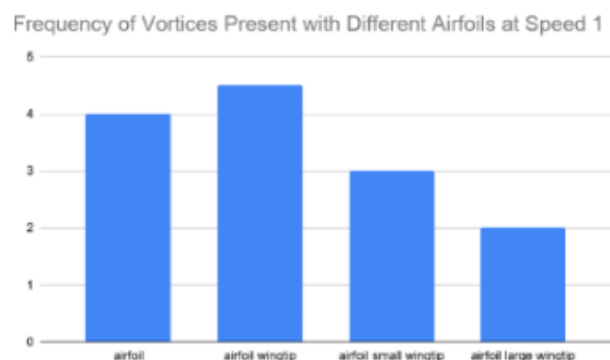
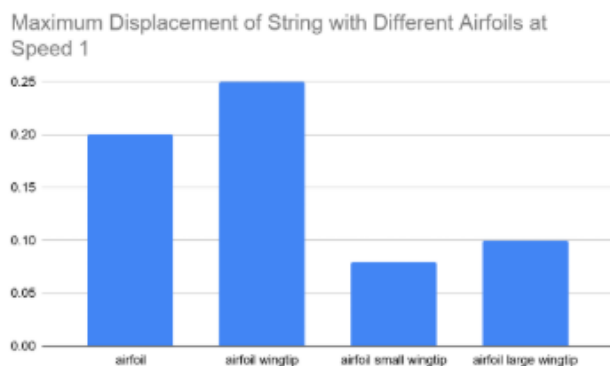


Fig 6: bar graph of data for flow tracking by maximum displacement for airfoils at speed 1 (top) and bar graph of data for vortex frequency for different airfoils at speed 1 (bottom)

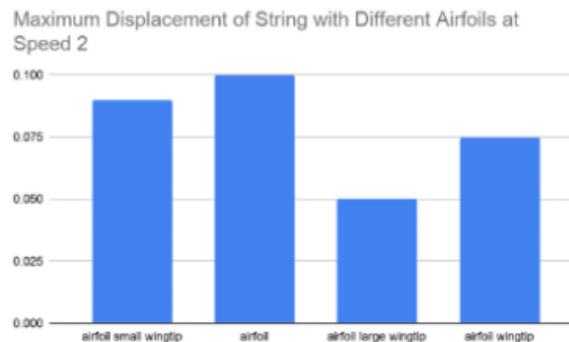
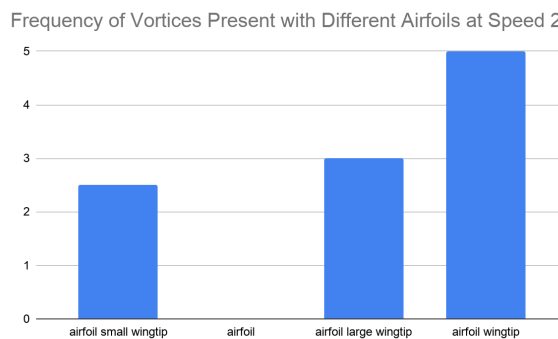


Fig 7: bar graph of data for vortex frequency for different airfoils at speed 2 (top) and bar graph of data for flow tracking by maximum displacement for different airfoils at speed 2 (bottom)

During initial testing at lower velocities, designated as Speed 1—speed level was defined by the fan setting because direct velocity measurements were unavailable—the standard airfoil configuration and the basic airfoil wingtip exhibited substantial fluid disruption, as seen in *Fig 6*, characterized by higher vortex frequencies of 4.0 and 4.5 cycles per second, which induced reactions from the objects, as shown by maximum string displacements—which were a visual proxy for vortex activity rather than a direct measurement of vortex shedding frequency—reaching peak values between 0.20 and 0.24 inches. Conversely, the implementation of small and large wingtips at this lower velocity threshold successfully mitigated the formation of wingtip vortices, suppressing their frequencies down to 3.0 and 2.0 cycles per second, respectively, while simultaneously stabilizing the surrounding air to restrict physical displacement below 0.10 inches. As the air velocity was raised to Speed 2, as seen in *Fig 7*, there was a major change wherein although visible vortex activity was minimized to a frequency of zero cycles per second, the string still showed measurable displacement of approximately 0.100 inches, suggesting steady flow deflection or drag effects rather than periodic shedding.

Further analysis of these interactions across increasing speeds reveals a significant

Frequency of Vortices Present with Different Airfoils at Speed 3

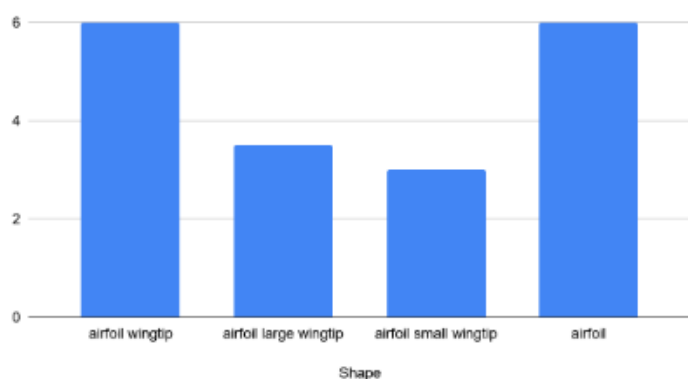


Fig 8: bar graph of data for vortex frequency for airfoils at speed 3

difference when transitioning to the highest speed, Speed 3, shown by *Fig 8*. At this velocity, the standard airfoil and basic wingtip structures had dramatic spikes in vortex frequency, meaning they experienced major flow separation, causing their vortex frequencies to increase dramatically to approximately 6.1 and 6.0 cycles per second, which underscores a failure to maintain streamlined aerodynamic profiles under higher flow speed. While the small and large wingtip modifications kept airflow consistent at Speed 3, maintaining lower vortex frequencies of roughly 3.1 and 3.6 cycles per second, the physical displacement metrics, depicted in *Fig 9*, displayed that the

large wingtip model was insufficient at this speed, as the string displacement rose to 0.19 inches. This major shift demonstrates that while geometric alterations effectively suppress

vortex shedding under low to moderate air speeds, they are ultimately unhelpful and suboptimal at higher speeds, at which they generate severe drag and aerodynamic instability. A culmination of these results show that the airfoil with the shorter wingtip performed consistently well, with low displacement and vortices across all speeds, yet the standard airfoil was consistently better than or

Maximum Displacement of String with Different Airfoils at Speed 3

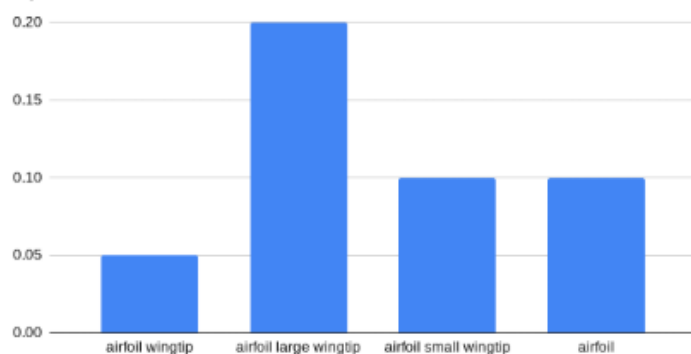


Fig 9: bar graph of data for flow tracking by maximum displacement for airfoils at speed 3

similar to the base wingtip design, which went against the predicted results.



Fig 10: large cylinder

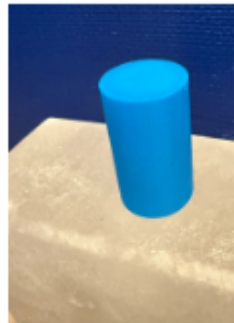


Fig 11: small cylinder

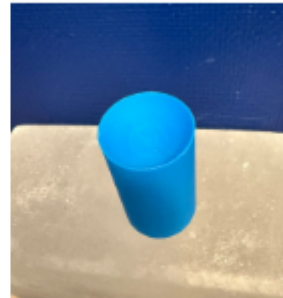


Fig 12: small concave cylinder

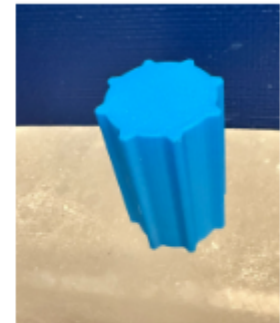


Fig 13: small ridged cylinder

Another object investigated was the cylinder, which was chosen for its initially blunt front but smooth, curved sides; it provided a dichotomy in the way the fluid could behave. The above model types, shown by Fig 10-13, are the large cylinder, the small cylinder, the small cylinder with a concave face, and the ridged small cylinder, all tested individually. The testing method consisted of placing the cylinders vertically within the wind tunnel, as depicted in Fig 14, and measuring the distance which the string moved from its original position to calculate maximum displacement, as well as recording the number of times the strings completed a full revolution every second to measure vortex occurrence. There were disparities in the vortex frequencies of the different cylinder geometries that allowed for predictions to be made regarding the capabilities of each geometry and what characteristics changed their ability to be aerodynamically successful. These predictions were made by analyzing the frequency data from the model wind tunnel tests through tables of measurements of the recorded vortex frequencies based on

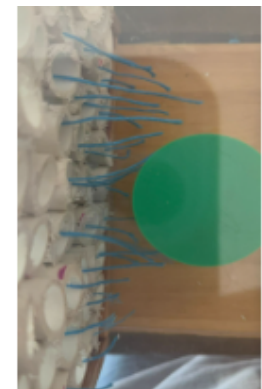


Fig 14: large cylinder being tested

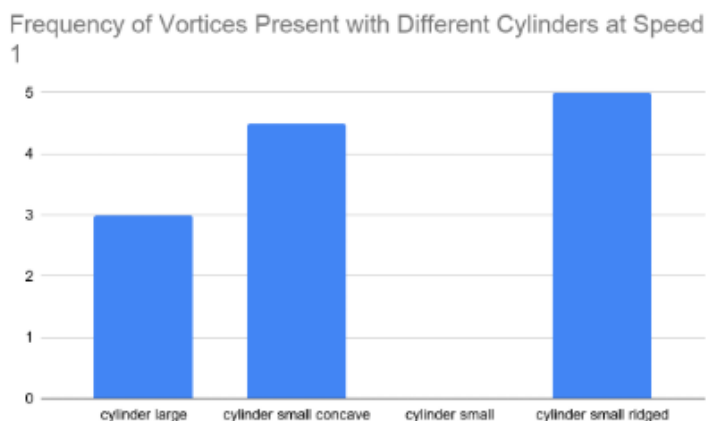


Fig 15: bar graph of data for vortex frequency for different cylinders at speed 1

string displacement, which revealed that at the lowest velocity threshold of Speed 1, shown by Fig 15, the baseline small cylinder maintained entirely attached flow with a vortex frequency of zero cycles per second, while the large cylinder, small concave cylinder, and small ridged cylinder generated distinct periodic disturbances, registering frequencies of 3.0, 4.5, and 5.0 cycles per second, respectively. A moderate acceleration to Speed 2 (Fig 16) demonstrated a change in

aerodynamic behavior where the large cylinder and baseline small cylinder successfully suppressed vortex shedding to reach frequencies of zero cycles per second, though the small ridged cylinder surged to a peak frequency of 6.0 cycles per second, and the small concave variant established about 4.0 cycles per second. A final escalation to the maximum velocity threshold of Speed 3, as seen in *Fig 17*, revealed the small cylinder to have strong flow separation and increased unsteady wake activity as its frequency rose to 6.0 cycles per second, closely followed by the small concave cylinder at 5.5 cycles per second and the small ridged cylinder at 5.0 cycles per second, while the large cylinder maintained a vortex frequency of zero cycles per second across both higher speeds, shifting fluid interaction away from periodic shedding toward a low-pressure separation zone. A summary of this shows that the large cylinder produced less visible periodic shedding at higher speeds, although this does not necessarily mean it produced less total drag or wake disturbance, while the cylinders with alterations to their surfaces caused the most violent disturbances to the fluid.

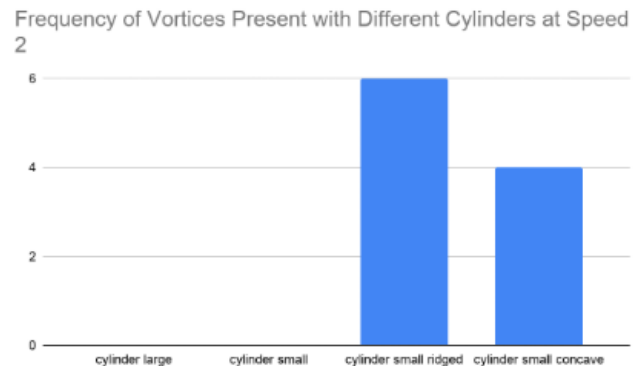


Fig 16: bar graph of data for vortex frequency for different cylinders at speed 2

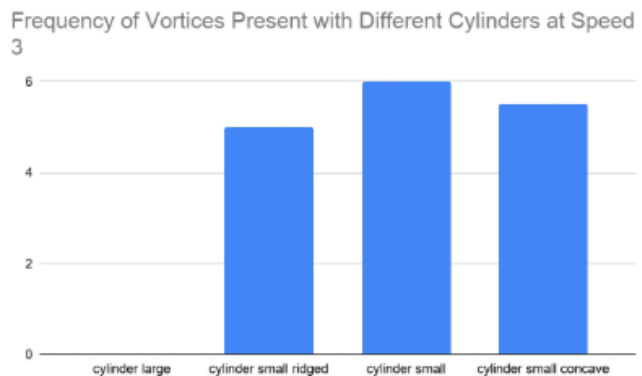


Fig 17: bar graph of data for vortex frequency for different cylinders at speed 3

The physical displacement of the tracking string raised queries about how these specific vortex shedding frequencies translate directly into physical structural instability across changing aerodynamic forces. They were remedied by measuring the maximum string displacement in

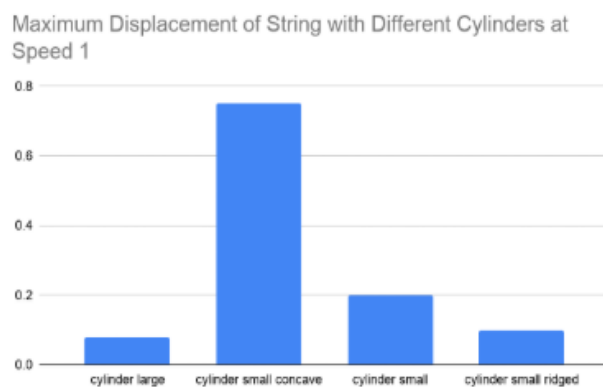


Fig 18: bar graph of data for flow tracking by maximum displacement for different cylinders at speed 1

inches, which revealed that under initial Speed 1 conditions, as displayed in *Fig 18*, the small concave cylinder experienced extreme aerodynamic vulnerability, exhibiting a massive displacement of 0.75 inches that heavily eclipsed the small baseline cylinder at 0.20 inches, the small ridged cylinder at 0.10 inches, and the large cylinder at 0.08 inches. A multitude of tests at Speed 2 (*Fig 19*) revealed that the small concave cylinder continued to lead structural deformation at 0.40 inches, while the small baseline cylinder and small ridged cylinder demonstrated superior boundary layer control with minimal displacements of 0.08 and

0.10 inches, respectively. Surface roughness on the ridged profile acts as a velocity-dependent turbulator, successfully constraining physical displacement at low and moderate speeds, but catalyzing vortex shedding at Speed 3 to yield a displacement of 0.65 inches, displayed in *Fig 20*, trailing only the small concave cylinder at its

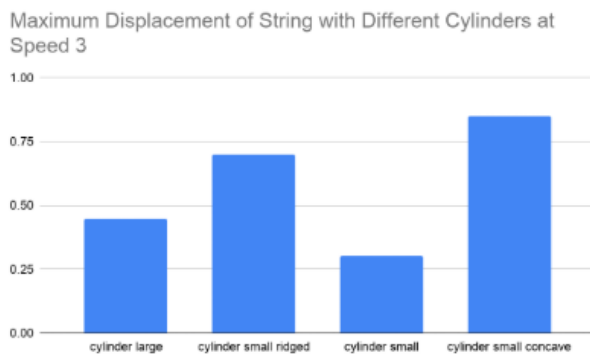


Fig 20: bar graph of data for flow tracking by maximum displacement for different cylinders at speed 3

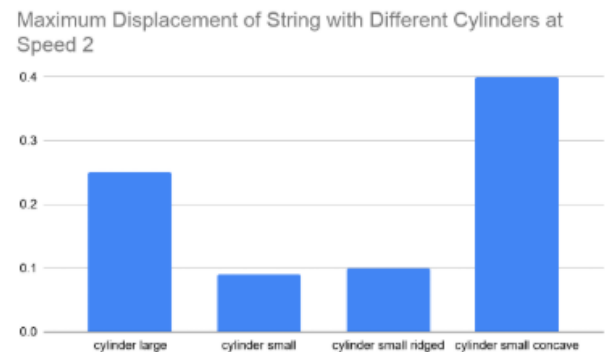


Fig 19: bar graph of data for flow tracking by maximum displacement for different cylinders at speed 2

peak instability of 0.85 inches, the large cylinder at 0.43 inches, and the baseline small cylinder at 0.30 inches. These quantitative results confirm that geometric cavities consistently trap fluid masses to induce wake turbulence, which has major implications for the efficiency, safety, and structural design of high-velocity transit bodies.

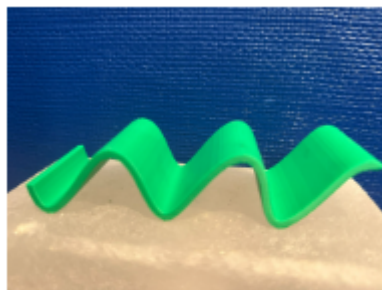


Fig 21: wave model

Fig 21 depicts the final model upon which tests were conducted, which was the sine-like curve, tested for its unique properties and violent changes in the overall direction of the shape. Analyzing the quantitative string displacement metrics derived from the model wind tunnel trials revealed that at the lowest velocity threshold of Speed 1, shown in *Fig 22*, the wavy profile introduced substantial disruption into the fluid stream, yielding a high maximum tracking string displacement of approximately 0.60 inches. Further testing at Speed 2, as seen in the chart, demonstrated heightened aerial disruption in which the wave model suffered its most severe aerodynamic degradation, driving the maximum physical displacement of the

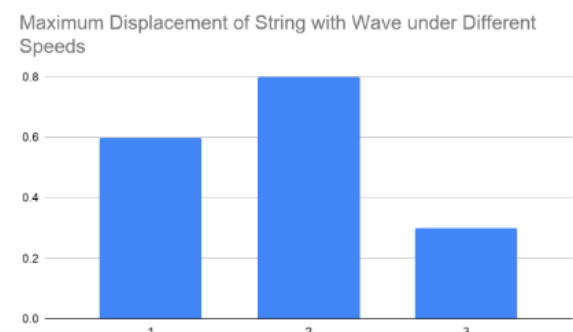


Fig 22: bar graph of data for flow tracking by maximum displacement of wave model at all speeds

tracking string to approximately 0.80 inches. At the highest setting, Speed 3, there was a significant shift in the displacement of the string as it declined substantially to a value of approximately 0.30 inches, demonstrating that there is a large disparity in the way the wave model interacts with the air at high-speed boundary layers versus low speed.

While the direction of airflow was diverted due to the pressure differences caused by the changes in the body, vortices were also initiated by blockage and pressure changes due to the wave model. Wind tunnel trials measuring the frequency of vortices revealed that at Speed 1, seen in *Fig 23*, the wavy profile generated a vortex frequency of approximately 2.5 cycles per second. However, increasing the speed to Speed 2 (*Fig 23*) caused a correlative increase in turbulence, with the frequency of generated vortices rising to approximately 3.0 cycles per second. There was a further rise in aerodynamic disruption at Speed 3 (*Fig 23*), as the frequency of vortices culminated to approximately 4.0 cycles per second. Physical observation

Frequency of Vortices Present with Wave under Different Speeds

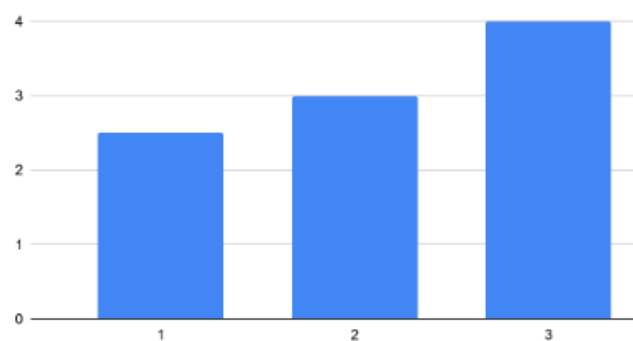


Fig 23: bar graph of data for vortex frequency for wave model at all speeds

of the model confirms that the curves of the object are substantial obstructions to consistent airflow across all testing phases. As air velocity increases, the increased kinetic energy traveling over the undulations in the wave shape continuously amplifies boundary-layer separation rather than suppressing it, forcing the air into reactive, nonlinear shedding patterns in the form of Von Kármán vortices. Ultimately, these quantitative increases in displacement and vortex frequency demonstrate that pressure differences from the changing directional path of the shape disrupt traditional synchronized airflow, which initiates a correlative progressive increase in the presence of vortices as the

speed of the air rises, which has critical design implications for the safety and efficiency of aerodynamic structures.

ACKNOWLEDGEMENTS

As a comprehensive summary, wind tunnel testing demonstrated that structural aerodynamics are extremely dependent on specific geometric profiles, and their implications on the surrounding fluid depend on the velocity at which the fluid is moving. Backed by empirical string-displacement metrics and vortex frequency tracking, the research confirmed that while streamlined airfoils maintain stability through attached flow, modifications like extended wingtips only suppress disruptive vortices at low speeds, while generating drag and aerodynamic instability at higher velocities. In the case of cylindrical shapes, the bluntness of the overall geometry causes major eddying and turbulence as the fluid surrounds and passes the object. This disruption is also present in wavy objects due to the major drops and rises in the shape that cause pressure differences that force the air into cavities that cause it to hit blockages, which create further turbulence. At a greater scale, these findings suggest that geometric profiles should be designed around the expected range of operating speeds, since a shape that performs well at one speed may become less stable at another, as conditions are unpredictable



and will naturally vary. For future experiments, the logical next steps would be to retest with a successful and more advanced wind tunnel to more accurately observe the behavior of the air. The methods used to record data could also be ameliorated in terms of quality and accuracy, as more advanced and precise technology or computational methods could be used for collecting data. Furthermore, expanding the testing matrix to include active flow control mechanisms and a wider range of Reynolds numbers would provide a more definitive aerodynamic dataset. Yet, the data collected in this experiment can be used for research in the optimization of the design of machines interacting with fluids in the area around them, such as aircraft wings, nautical hulls, and wind turbine blades, to maximize fuel efficiency and operational stability.



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