Walking in the Wake: Exploring the Dynamics of Vortical Structures

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Abstract

This interdisciplinary research project investigates the methods and processes of visualizing a natural phenomenon, Vortex-Induced Vibration, a subfield in Fluid Dynamics, through a collaboration among fluid dynamicists and architects. Over the course of two years, a body of drawings, models, videos and installations were created to capture the variety of ways in which a phenomenon can be visualized. Furthermore, the project made relevant representations for different fields as well as the general public. Starting with a series of architectural drawings and models that aimed at depicting the experiments conducted at a Fluid Dynamics lab, the project evolved into an augmented investigation that shed light on the scientific finding, while also proliferating to offer formal and spatial possibilities for architecture.

Figure 1: *An image of the exhibition.*

Introduction

The study of natural phenomena in scientific disciplines employs mathematical, computational, and experimental methodologies to understand the world around us. In design disciplines, such studies serve a different purpose—that of inspiration. Both fields share the ambition for new and altered forms of simulation, emulation, and imitation of natural phenomena, where science often gears towards solving focused problems, while design, and in particular architecture, aspire to transform environments. Corralling these different forms of exactitude, and their respective representational methods, this project undertakes the study of such a natural phenomenon (Vortex-Induced Vibration – VIV) and engages in a careful investigation to understand it. By

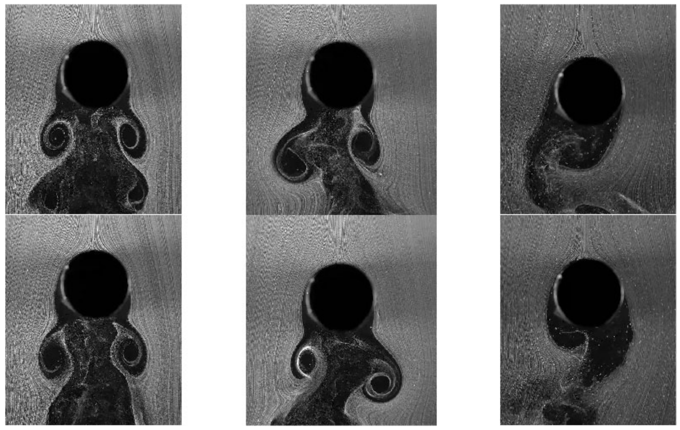


Figure 2: *Snapshots of the experiments' videos: symmetric (left column), alternating symmetric (middle column), and asymmetric shedding (right column).*

discovering the arcs of analytical, visual, and spatial narratives, our team made a series of observations, in drawings and models of varied sizes (from small to installation size), to abstract, reinterpret, and interpolate the phenomenon we studied over time. Believing firmly that representation is never neutral, and accuracy is often a construct around a constellation of rules, circumstances, and conventions, we have attempted, in this interdisciplinary endeavor, to finetune methods for visualizing a phenomenon. We started this process from a series of bubble visualizations that were conducted for scientific research on VIV, with the goal of coming up with novel methods of visualizing this phenomenon. In the process of this research. we came up with different methods of visualisations and it was through this process that the idea of designing and building an installation emerged. Our work culminated in a multi-media exhibition that included drawings, models, and videos capturing the variety of ways in which a phenomenon can be visualized (Figure 1).

Context and Background

From the 1500s onward, individuals with scientific proclivities created "Curiosity Cabinets" to inspect the world by collecting objects of naturalia and artificialia. The significance of these collections was as much dependent on their assembly as it was on the objects themselves. While many different forms of curiosity cabinets proliferated, some dominated by aesthetic concerns, whole others were ruled by scientific inquiries. They shared a deep desire to understand the world in a systematic, organized manner. The intention to "see" the world and its underlying orders in "systems" and "hierarchies" is not new nor is it the domain of a specific discipline. Yet the cabinets of curiosities manifested qualities that correlated to the domain of architecture. The attributes that resonated and became the underlying principles of the present study were the combination of a curiosity-driven act of observation and collection, therefore open-ended and not targeting a particular objective, and the desire to document a phenomenon, as accurately and with as much multiplicity as possible.

To do so, we formed a team, comprised of architects and fluid dynamicists to focus on novel visualization methods for a model problem in fluid-structure interactions, called Vortex-Induced Vibration (VIV). VIV is widely observed in the world that surrounds us and manifests itself in both extremely large (offshore structures) and infinitely small (laboratory size experiments) settings [7]. In VIV, a cylinder, i.e., a beam with a circular cross-section, is placed in fluid flow and is free to oscillate. In the case that we consider here, the cylinder can oscillate in the direction of the incoming flow, i.e., inline (IL) with the incoming flow (IL VIV) [5]. This problem can be modeled by coupling the Navier-Stokes equations that represent the flow around the cylinder with the equation of motion of a one-degree-of-freedom oscillatory system. When a cylinder is placed in flow, vortices are formed in the wake of the cylinder. The first documented observation of vortices in the wake of a cylinder are Leonardo da Vinci's drawings in his notebooks [6]. Several studies exist on the observation of vortices in the wake of a fixed cylinder. According to these studies (e.g., [10]) as the flow velocity is increased, the frequency at which these vortices are shed increases and when this shedding frequency matches the natural frequency of a flexibly-mounted cylinder (i.e., a cylinder supported by springs) oscillations are observed. These oscillations are called VIV. VIV is observed for cases when the cylinder is free to oscillate in a direction perpendicular to the incoming flow (crossflow direction, CF VIV) [12, 8], free to oscillate in the IL direction (the case considered here, IL VIV) or free to oscillate in both directions (2 degree-of-freedom (DOF) VIV) [3, 4]. A flexibly-mounted cylinder is a simplified version of a long flexible cylinder that is placed in flow (modeled by a partial differential equation), such as a riser that brings oil from seabed to the surface or mooring lines that hold a floating offshore wind turbine in place. VIV has been extensively observed and studied in such cases as well [2, 9]. Studies on the fundamental problem of VIV of a flexibly-mounted cylinder are essential for gaining a better understanding of the VIV responses of these much more complicated offshore structures.

In the specific case that we consider here, i.e., IL VIV, oscillations are observed in two ranges of a dimensionless flow velocity called the *reduced velocity*, defined as $U^* = U/f_nD$, in which U is the incoming flow velocity, f_n is the natural frequency of the flexibly-mounted cylinder, and D is the cylinder's diameter. Within these two ranges of oscillations, three types of vortex shedding are observed: at lower reduced velocities, two vortices are shed simultaneously from the two sides of the cylinder in every cycle of oscillations resulting in a symmetric pair of vortices in the wake (symmetric shedding) (Figure 2, left column). At slightly higher reduced velocities, while again two vortices are shed simultaneously from the two sides of the cylinder, their sizes alternate in each cycle of oscillations: in one cycle a larger vortex is shed from one side (side 1) of the cylinder and a slightly smaller one from the other side (side 2), and in the following cycle, the smaller of the two vortices is shed from side 1 and the larger one from side 2, resulting in an alternating symmetric shedding in the wake (Figure 2, middle column). Both symmetric and alternating symmetric patterns are observed within the first range of oscillations. At higher reduced velocities, during each cycle of oscillations two vortices are shed from the two sides of the cylinder one after the other, forming an asymmetric shedding in the wake (Figure 2, right column).

Methods and Processes

We considered the three types of vortex shedding that are observed in the IL VIV (symmetric, alternating symmetric and asymmetric) for our in-depth study and visualization explorations. These wakes had been visualized using hydrogen bubbles in a series of experiments conducted before [5]. Samples of those visualizations are shown in Figure 2. We used the videos of these bubble visualizations as the inputs to our work here. In the paragraphs that follow, a chronological account of different processes we set up is given and a selection of images accompany them to shed light on this extended exploration. A range of software and hardware were used to achieve the results.

Installation

The culmination of our project was in the form of a multi-media installation that included drawings, models, and a spatial rendition of the project for the public. For this installation, we first created a model in which we followed the progression of the alternating symmetric case through time. To accomplish this, every 20th frame was taken from the video, with a total of 10 frames being used to show a full cycle of oscillations. The frames were overlayed to create a base which would allow all 10 frames to be shown at once over its span. Each frame was then used to make a series of points which would be used to represent the movement of a vortex pair over the duration of the cycle. Once these point drawings were made, they were layered and evenly spaced to create a height of 6 feet. We used transparent acrylic rods, which were etched to the length of 4 inches to track the movement of the vortices across time and space, where each rod is placed at an xy coordinate that corresponds to a coordinate in the wake. As visitors walk through the structure, they experience a vortex, further accentuated by LED lights that illuminate the rods from a concealed base. The immersive experience of the light, the forms, the transparencies of the tubes and background turns into a multi-sensory experience that does not describe but augments the phenomenon and its unfolding across time and space (Figure 3). The bright parts represent the bubbles in the wake. The vertical direction represents time—as time passes taller rods are needed and the bright points move higher in the rod. As one walks through the installation, they experience being inside the wake. Toward the end, bright points are only at the tip of the rod. Anything below is for the time that the flow had not reached that point of the wake. Initially, we experience the near wake, and several bright points down low. We experience the different sizes of the vortices, and we experience the vortices that are shed before—they are at a higher level—the time passed has no bright spots. They are dissipating.

Figure 3: *More images of the Installation.*

Negative Space Flow Model (Shroud Model)

To make this first model, we captured a single frame from the experiment's videos at the highest point of the cylinder's oscillations for each wake condition (symmetric, alternating symmetric, and asymmetric). In their planimetric configuration, we traced the voids created by the bubbles as they moved around the cylinder in each condition. By doing so, we were able to visualize the negative space left by the bubbles in each case and how they compared with each other. Each of the three conditions was then layered along the z-axis, with the lowest reduced velocity at the bottom and the highest at the top. We then connected these different models and tweaked the transitions so that the shell-like structure depicts this augmentation of the reduced velocity and the metamorphosis of the volume as it twists and turns with increasing reduced velocity (Figure 4).

Datascape Model

To translate and visualize the phenomena into architectural software thoroughly and accurately, we worked on what we called the Datascape Model. In this case, we first conducted a Particle Imaging Velocimetry (PIV) analysis on the bubble videos using an open-source Matlab software, PIVLab [11], and found the flow

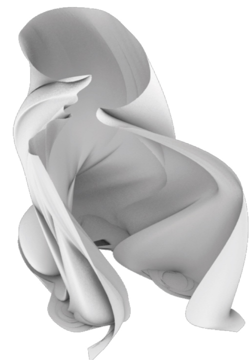


Figure 4: *The shroud model.*

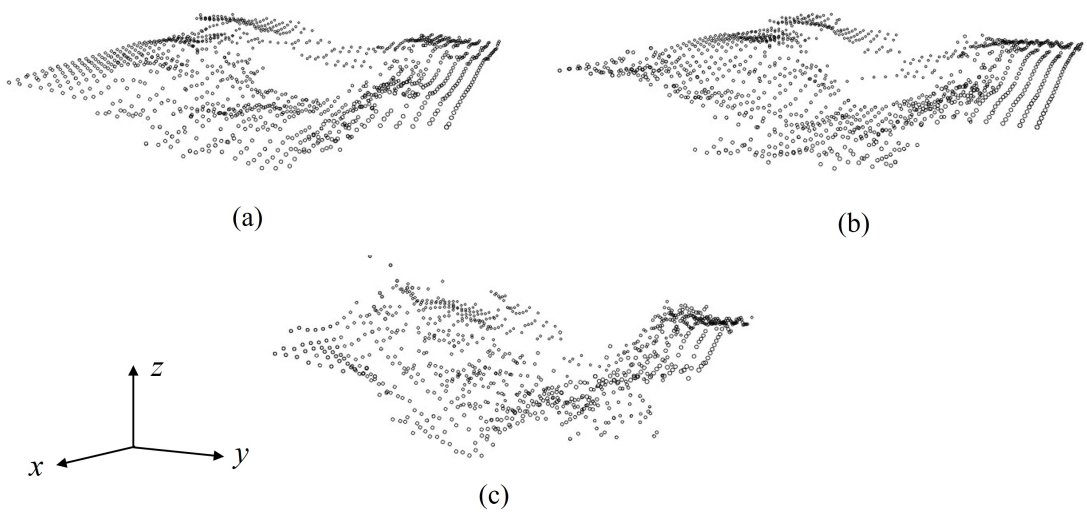
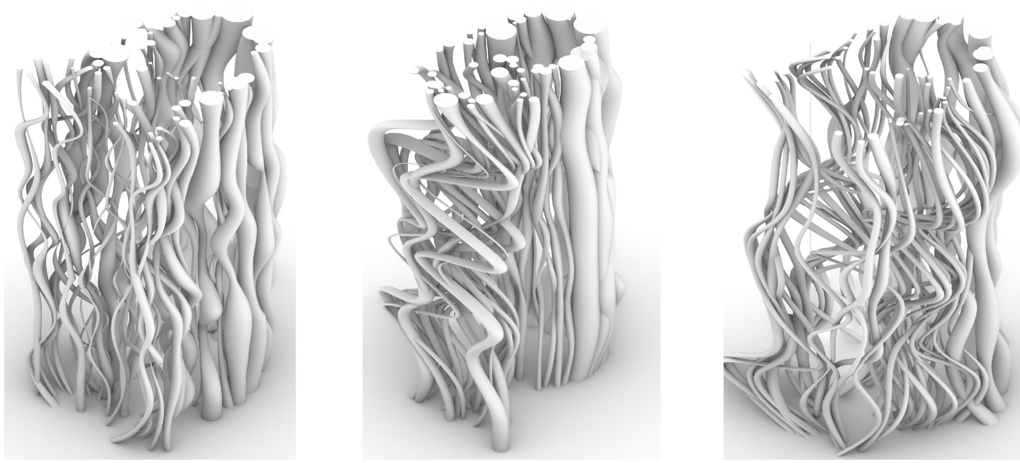


Figure 5: *The datascape models for (a) symmetric, (b) alternating symmetric, and (c) asymmetric shedding.*

velocity distribution in the wake in terms of the velocity in the x (IL) direction, V_x, and the velocity in the y (CF) direction, V_y. This is the information that we need to represent the behavior of the wake in different ways. To create the datascape model, we found the magnitude of the total velocity at each point (the square root of the summation of the squares of velocities in the x and y directions) as the value in the z-direction. These data were then used as input for a Grasshopper script which served both as a starting point data and a motion data script (Figure 5). While this model's development represents the results of the PIV software, it was a crucial step in recreating the phenomenon in 3D accurately.

Positive Space Tube Models

Figure 6 shows three 3D models corresponding to the three different conditions. In these models, we reversed the parameters of the Negative Space Flow Model to build Positive Space Tube Models for each of the three cases, thereby representing the core of the vortex by solid objects. To create these models, we used snapshots of the videos from the experiments in five-second intervals, input them into the Grasshopper Image Sampler, and created a Rhino model that represented the size and orientation of the bubbles at each time instant. Then we stacked these 2D curves along the z-axis to represent the time, by giving the intervals of 5 mm between each two snapshots (such that 5 mm space represents 5 seconds in time), and then we lofted the curves. As



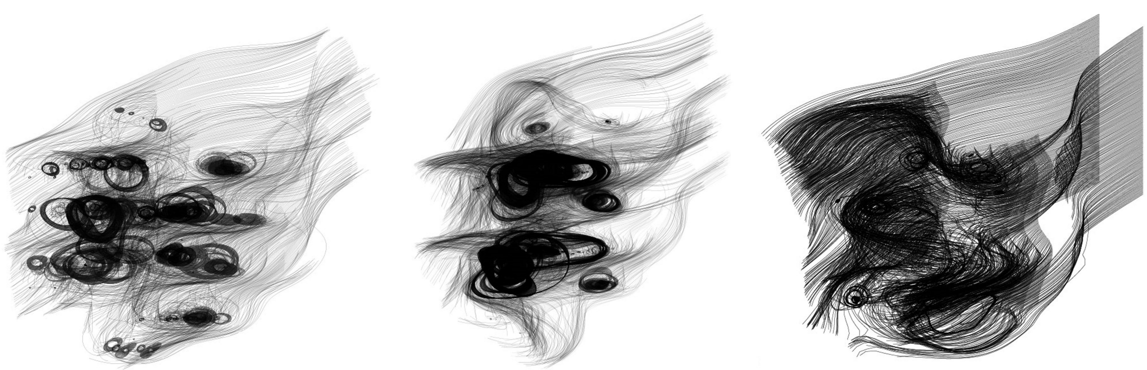
(a) (b) (c)

Figure 6: *Computer-generated images of the positive space tube models (a) symmetric, (b) alternating symmetric, and (c) asymmetric shedding.*

visible in the images, the size of the circles is different and correlates with the density of the bubbles. These models, which are highly spatial, already interpret the passage of time and turn it into an active component that determines the form. The images of Figure 6 were presented in the exhibitions in the form of 3D printed sculptures.

Streamline Models

We used the velocity vectors that were calculated in the PIV analysis to calculate the streamlines, by finding the curves that remain tangent to the local velocity vectors. These streamlines were created for each frame of the original videos and imported to grasshopper. Then the time was translated to the z-axis of the streamline model, showing how the streamlines move over the course of the experiments. The streamline models (Figure 7) exhibited intriguing spatial qualities while also presenting the dynamics of the vortex in the wake of the cylinder in three-dimensional configurations. These models allowed for a more visually tangible comparison among the three distinct types of shedding while creating a sense of motion and change in each 3D rendition. We presented these drawings in our exhibition.



(a) (b) (c)

Figure 7: *Streamline models for the (a) symmetric, (b) alternating symmetric, and (c) asymmetric shedding.*

Vortex Boundaries Models

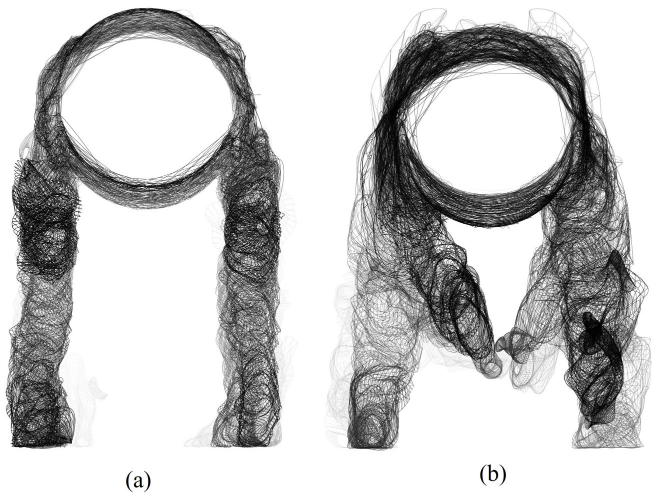


Figure 8: *Drawings of the vortex boundaries models for (a) symmetric, and (b) alternating symmetric.*

By reverting to the quintessential 2D representation, a set of drawings in Figure 8 shows planimetric figurations of the boundary of the vortices, and how they move and interact with each other over the duration of the experiment. The vorticity in the wake of the cylinder is calculated through the PIV software, which provides high level information on the location of the vorticies in the wake. The boundary of each vortex is determined by establishing a minimum vorticty threshold, and assuming that the vorticity below that threshold is negligible. This results in an outline of the vortex from which information on the formation and dissemination of vortices over time can be obtained. We then produced a series of points that made up the outline of each vortex, which were then fed into grasshopper where each vortex could be turned into a closed curve and layered to show the progression of time in the z-axis. This representation revealed the details of how the small and large vortices that are shed in the alternating symmetric case interact in the wake and how the larger vortex moves faster in the wake and forces the smaller vortex toward the center of the wake—properties of the wake dynamics that were not observed previously. It was the gradual progression of these plans, where each layer manifests the unfolding of a vortex in time, that made the observation possible. The drawings of Figure 8 were presented in our exhibitions. They were also used to extract new scientific understanding on the VIV phenomenon [1].

Summary and Conclusions

This project serves as a pilot for a cross-disciplinary approach to think, draw, and make by combining and alternating architectural and scientific methods of visualizations to investigate a phenomenon. By documenting vortices that form in the wake of a structure, a widely observed and highly three-dimensional phenomenon in fluid mechanics, we created a body of evidence which would otherwise not be observable, or accessible to a wide audience. We hosted several visitors during the opening night of the gallery, and we held gallery talks for several classes—from art to engineering. During these events, we answered questions related to fluid dynamics asked by students and researchers from arts, architecture, political science, and music. And from the general public. During this investigation, we have produced drawings, videos, and models of the original fluid mechanics phenomenon. The formal, logical, and imaginative possibilities we gathered hint at the possibility of developing new methods for creative thinking and design methods for architecture by annexing new disciplines not currently used in the field. Architecture has a deep history in investing in new modes of operation to advance its own creative facet. This project demonstrates a more open-ended and versatile method for integrating, translating, and interpreting scientific data into the creative and imaginative process of ideation for the architect. This process will continue for our research group as we plan to calibrate and deploy our joint arsenal of understanding and abilities, as well as our modes of operations to real-world problems, fully activating the shared spheres between our disciplines. If the present project is an indication, the time and effort invested in making the process productive and the challenges to see beyond one's discipline are real and numerous. However, there is also an incredible reward in the hybridity that we have inhabited. This process has been an exercise in understanding and augmenting one's discipline all along, while exploring the boundaries, or lack thereof, of a multi-disciplinary approach.

Acknowledgements

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