



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**EXPERIMENTAL MEASUREMENT
OF THE PHASE-SENSITIVITY FUNCTION
FOR A CIRCULAR CYLINDER FOR USE
IN PREDICTING WAKE LOCK-IN**

by

Jacob M. Barberio

June 2023

Thesis Advisor:
Co-Advisor:

Joseph T. Klamo
Kunihiko Taira (UCLA)

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2023	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE EXPERIMENTAL MEASUREMENT OF THE PHASE-SENSITIVITY FUNCTION FOR A CIRCULAR CYLINDER FOR USE IN PREDICTING WAKE LOCK-IN			5. FUNDING NUMBERS RSKYH	
6. AUTHOR(S) Jacob M. Barberio				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Science Foundation, Alexandria, VA 22314			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) The goal of this research is to evaluate the feasibility of determining phase information from experimentally measured wake velocity data for use in phase-reduction analysis. The study is part of a combined effort with the University of California-Los Angeles to assess the validity of phase-reduction analysis on realistic fluid flows. The outcome from this effort is the validation of a general method to predict wake-synchronization conditions. Experimental data collection took place in the recirculating water tunnel at the Naval Postgraduate School, utilizing a custom-built testing fixture capable translational and rotational motion. Collected experimental data includes recorded time histories of wake velocity behind a circular cylinder before and after a small impulse that was introduced into the flow by perturbing a circular cylinder. Analysis of the data includes a curve-fit and Hilbert transform method in an attempt to accurately quantify the phase offset difference between the signals before and after impulse. The analysis showed some success in producing localized phase offset measurements, but still faces challenges due to variability in shedding frequency and the presence of irregular regions in the flow at Reynolds number 300. Alternate Reynolds numbers that were also explored show potentially more suitable conditions at lower Reynolds number flows with a lower shedding frequency.				
14. SUBJECT TERMS wake synchronization, vortex shedding, vortex-induced vibrations, phase-reduction analysis, experimentation			15. NUMBER OF PAGES 79	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

**EXPERIMENTAL MEASUREMENT OF THE PHASE-SENSITIVITY
FUNCTION FOR A CIRCULAR CYLINDER FOR USE IN PREDICTING WAKE
LOCK-IN**

Jacob M. Barberio
Ensign, United States Navy
BS, United States Naval Academy, 2022

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
June 2023**

Approved by: Joseph T. Klamo
Advisor

Kunihiko Taira
Co-Advisor

Oleg A. Yakimenko
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The goal of this research is to evaluate the feasibility of determining phase information from experimentally measured wake velocity data for use in phase-reduction analysis. The study is part of a combined effort with the University of California-Los Angeles to assess the validity of phase-reduction analysis on realistic fluid flows. The outcome from this effort is the validation of a general method to predict wake-synchronization conditions. Experimental data collection took place in the recirculating water tunnel at the Naval Postgraduate School, utilizing a custom-built testing fixture capable translational and rotational motion. Collected experimental data includes recorded time histories of wake velocity behind a circular cylinder before and after a small impulse that was introduced into the flow by perturbing a circular cylinder. Analysis of the data includes a curve-fit and Hilbert transform method in an attempt to accurately quantify the phase offset difference between the signals before and after impulse. The analysis showed some success in producing localized phase offset measurements, but still faces challenges due to variability in shedding frequency and the presence of irregular regions in the flow at Reynolds number 300. Alternate Reynolds numbers that were also explored show potentially more suitable conditions at lower Reynolds number flows with a lower shedding frequency.

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

1	Introduction	1
1.1	Motivation	1
1.2	Research Background	3
1.3	Definition of Key Terms	4
2	Hardware and Facilities	9
2.1	Recirculating Water Tunnel	9
2.2	Ultrasonic Flow Meter	10
2.3	Constant Temperature Anemometry System.	10
2.4	Cylinder and Mounting Apparatus	11
2.5	Data Acquisition System	13
3	Equipment Validation	15
3.1	Purpose and Procedure	15
3.2	Translation Validation	16
3.3	Rotation Validation	19
4	Data Collection	23
4.1	Probe Location	23
4.2	Data Description	26
4.3	Testing Procedure	26
4.4	Testing Matrix	27
5	Data Reduction and Analysis Techniques	29
5.1	Overall Process	29
5.2	Curve-Fit Approach	31
5.3	Hilbert Transform Method.	35

6	Results and Discussion	37
6.1	Curve-Fit Results	37
6.2	Hilbert Transform Results	40
6.3	Alternate Reynolds Numbers Exploration.	45
7	Concluding Remarks	51
7.1	Fundamental Challenges	51
7.2	Conclusions	51
7.3	Future Work	52
	List of References	55
	Initial Distribution List	57

List of Figures

Figure 1.1	Overhead view of flow visualization.	1
Figure 1.2	Side view of flow visualization for Reynolds numbers 200 and 525.	2
Figure 1.3	Strouhal/Reynolds numbers relationship.	5
Figure 1.4	Expected signal response from perturbation.	7
Figure 1.5	Example of phase-sensitivity functions.	8
Figure 2.1	Image of Eidetics water tunnel.	9
Figure 2.2	CTA hot film probe and module.	11
Figure 2.3	Testing apparatus configuration.	12
Figure 4.1	Probe location coordinates depiction.	24
Figure 4.2	Frequency content of $(X_p/d, Y_p/d) = (4.5, 0.5)$ for Reynolds number 500.	24
Figure 4.3	Frequency content of $(X_p/d, Y_p/d) = (6.0, 1.5)$ for Reynolds number 2000.	25
Figure 4.4	Frequency content of $(X_p/d, Y_p/d) = (3.0, 1.5)$ for Reynolds number 2000.	25
Figure 5.1	Constructed theoretical window for perturbation.	30
Figure 5.2	Demonstration of irregular regions in Reynolds number 300 pre-perturbation signal.	31
Figure 5.3	Reynolds number 300 post-perturbation signal with expected peak intervals.	32
Figure 5.4	Reynolds number 300 post-perturbation signal with multiple curve fits.	34

Figure 6.1	Reynolds number 300 frequency by cycle comparison.	38
Figure 6.2	Reynolds number 300 phase offset by cycle comparison.	39
Figure 6.3	Reynolds number 300 phase offset by Hilbert method comparison.	41
Figure 6.4	Reynolds number 300 $g(\theta, t)$ function comparison.	43
Figure 6.5	Reynolds number 300 phase-sensitivity function for translational motion.	44
Figure 6.6	Reynolds number 300 phase-sensitivity function for rotational motion.	45
Figure 6.7	Reynolds number 200 pre-perturbation signal.	46
Figure 6.8	Reynolds number 1000 pre-perturbation signal.	46
Figure 6.9	Reynolds numbers 200 and 1000 frequency by cycle comparison.	47
Figure 6.10	Reynolds number 200 and 1000 curve fit phase offset by cycle.	48
Figure 6.11	Reynolds number 200 and 1000 $g^*(\theta, t)$ functions.	50

List of Tables

Table 3.1	Translation validation: encoder pulses.	17
Table 3.2	Translation validation: time.	17
Table 3.3	Translation validation: distance.	18
Table 3.4	Rotation validation: encoder pulses.	19
Table 3.5	Rotation validation: time.	20
Table 4.1	Translation testing matrix.	27
Table 4.2	Rotation testing matrix.	28

THIS PAGE INTENTIONALLY LEFT BLANK

List of Acronyms and Abbreviations

CTA	constant temperature anemometer
FFT	fast Fourier transform
NPS	Naval Postgraduate School
PIP	phase at instant of perturbation
UCLA	University of California-Los Angeles
VIV	vortex-induced vibration

THIS PAGE INTENTIONALLY LEFT BLANK

Executive Summary

When a non-streamlined object is immersed in a fluid flow, alternating vortices are shed from opposite sides of the body and into the wake. This shedding occurs at a non-dimensional frequency, known as the Strouhal frequency, which is only dependent on the Reynolds number of the flow. Under certain conditions, the shedding frequency breaks away from the Strouhal frequency and instead matches the oscillation frequency of the body. The term wake synchronization has been used to describe this behavior, which can cause unwanted oscillations in a system and can even cause structural degradation to the point of failure. Currently, the only way to predict the occurrence of wake synchronization is to laboriously test all combinations of body oscillation amplitude and frequency for a given fluid velocity to see if wake synchronization occurs. This thesis studies the feasibility of predicting wake synchronization using phase-reduction analysis as part of a collaborative effort with University of California-Los Angeles (UCLA). The focus of this thesis is the collection and analysis of Reynolds number 300 wake velocity data to create an experimental phase-sensitivity function and document the challenges to determining phase information from physical fluid wake data.

To facilitate experimental data collection, a testing apparatus was designed and constructed with the ability to move a cylinder with both one and two degrees of freedom. The system was designed in such a way to accurately enable extremely small, fast motions of the cylinder to create small perturbations in the flow. This system was positioned on top of the open test section of the recirculating water tunnel located at the Naval Postgraduate School to perform the experiments. Separate software programs to control the motion of the testing apparatus and to collect data were written and used to conduct experimentation over a variety of testing parameters.

Prior to collecting the experimental data, the motion capabilities of the constructed system were validated to ensure that the system was performing the desired motions as expected. Encoders attached to the motors were used to evaluate the magnitude of translational or rotational motion and the time taken to complete the motion. Successful validation of the requested motions provided confidence in the system's ability to perform as needed during the experimental testing that followed.

The location of the fluid velocity measurement probe relative to the cylinder was determined by evaluating signal responses at different locations. The selected location was the one that produced a signal that contained the largest amount of energy around the vortex shedding frequency. During testing, for each experimental run, the data collection process involved collecting a total of four continuous minutes of wake velocity data, with a cylinder driven perturbation occurring at approximately two minutes. The test matrix included three cases each for translational and rotational perturbations. Each case varied the distance or angle of movement of the cylinder as well as the time over which the motion was completed. Since phase-reduction analysis evaluates the phase offset difference as the magnitude of the impulse goes to zero, impulse distance was kept under 1% of the cylinder diameter or full rotation, and the time was kept under 10% of the expected shedding period.

The data analysis process began with the parsing of the collected wake velocity time history signal into pre-perturbation and post-perturbation portions. Because a relatively low sampling rate was used during testing, only a small number of the actual encoder pulses are detected. A theoretical time window was constructed for when the perturbation must have occurred based on the measured encoder pulses, and then it was shifted in time to approximately the same instant when the fluid velocity probe registers the effects of the perturbation in the wake. The initial analysis approach was to fit a single sine wave to the entire pre- and post-perturbation data portions. However, it became clear that there were irregular regions throughout the time-history signal that disrupted the normal shedding behavior, creating the need for a cycle-by-cycle curve fit approach with an emphasis around the time of perturbation. This individual cycle method has a variable frequency sinusoidal fit to each cycle to assign an average phase offset over each cycle prior to a perturbation. An alternative method, using the Hilbert transform, was also used. This Hilbert transform method was ultimately used to determine the phase difference between the pre- and post-perturbation portions of the wake velocity signal. The Hilbert transform was applied to each signal, and the instantaneous phases were compared to a baseline pure sine wave in order to determine their phase offset over time. The phase offsets for each signal were subtracted to determine the phase difference caused by the cylinder perturbation. To assign a single phase difference for each run, the phase differences over time were averaged using the most consistent region around the time of perturbation for that run. The assignment of a phase difference along with identifying when the perturbation occurred during the shedding cycle

for each run creates a phase-sensitivity function. This function, along with its uncertainty, is shown for translational and rotational cases at Reynolds number 300.

The amount of uncertainty assigned to the phase-sensitivity function was dependent on the stability of the wake velocity signal around the time of the perturbation. The main challenges to gathering phase information from the given wake velocity signals are the disruptive, irregular regions in the wake as well as the slight variation of shedding frequency from cycle to cycle. These challenges appear to be driven by higher shedding frequencies and Reynolds numbers. Exploration of alternate Reynolds numbers and shedding frequencies showed that testing at a lower Reynolds number and shedding frequency may produce more consistent signals that can enable a phase difference calculation with less uncertainty or at least provide more success than the Reynolds number 300 cases tested in this work.

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgments

I would like to acknowledge and thank the following people for their efforts in enabling this thesis: Jonathan Lussier for the design and assembly of the testing fixture along with writing the motion control software, Christopher Clay and John Mobley for the machining of the testing fixture components, Matthew Stegmeir for assistance in troubleshooting the CTA hardware, and the UCLA group that includes Dr. Taira and his graduate students Joungjae Kim and Vidasri Gadavarthi for their assistance and collaboration with data analysis techniques. Finally, I'd like to thank my advisor, Dr. Klamo, for countless hours of effort and guidance.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 1:

Introduction

1.1 Motivation

In 1878, Vincent Strouhal was the first to document the characteristics of oscillatory vortex shedding in fluid flow past a bluff body [1]. This was the beginning of more than a century of investigations into the nature and effects of vortex shedding, which still continues today. For a fixed bluff body, vortices shed at a natural frequency (defined in Section 1.3) associated with the flow's Reynolds number. The natural, periodic shedding of vortices behind a bluff body form a pattern that is known as the von Kármán vortex street [2]. Figure 1.1 is an overhead view of this pattern from a flow visualization experiment using a low Reynolds number flow around a cylinder. It demonstrates the behavior in which the fluid travels in a circular manner around the center of each vortex as they travel downstream with the overall flow. The measurement of the fluid velocity within the wake has therefore been a standard method to analyze the shedding behavior for a given setup [3].



Figure 1.1. Example of low Reynolds number (approx. 200) wake visualization from an overhead view. Source: [4].

The Reynolds number not only governs the frequency of shedding, but it also affects the overall structure of the wake. As Reynolds number increases, the flow experiences more complex motion in three dimensions. Figure 1.2 shows the side view of the same

flow visualization experiment that demonstrates the increase in three-dimensionality and complexity of the flow structure for increasing Reynolds numbers. Figure 1.2 (a) shows a Reynolds number of 200 and the vortices are mostly contained in two dimensions. On the other hand, Fig. 1.2 (b) is for a Reynolds number of 525. For the higher Reynolds number, the vortices show more complex movement in three dimensions. This is an important factor in experimentation, as the more complex motion can affect the velocity measurement within the wake. The effects of this behavior on performing phase-reduction analysis are considered within the analysis of the present study, which documents the impact of three-dimensionality on the determination of phase information from wake velocity measurements.

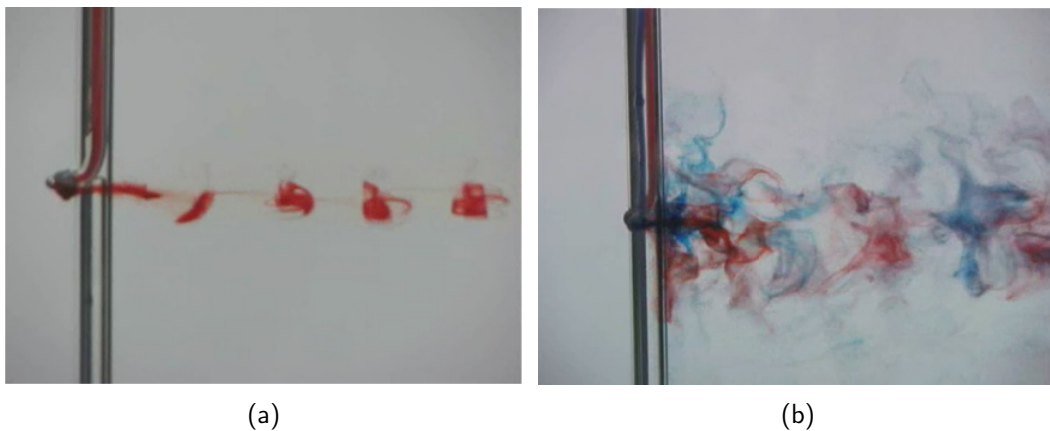


Figure 1.2. Side view of flow visualization for (a) Reynolds number 200 and (b) 525, demonstrating the increase in three-dimensionality of the flow. Source: [4].

As these vortices are shed, perpendicular forces act transversely on the cylinder in a periodic manner. These forces can be problematic, motivating many later studies that examine the behavior of a moving cylinder in fluid flow, both forced and freely vibrating [5]–[7]. The oscillatory movement of a cylinder can create a behavior in which the vortex shedding breaks from its natural shedding frequency, controlled by the Reynolds number, and instead sheds at the frequency of the cylinder oscillation. Various studies have documented this phenomenon as “lock in” or wake synchronization and described the impacts that it can have [8]–[14]. Since structures tend to oscillate at their natural system frequency, the occurrence of lock-in creates a resonance type response, leading to increasing amplitudes of oscillation and potential structural failure of the system. Although initially believed to occur over only a

small range of oscillation amplitudes and frequencies, it has subsequently been found that this behavior can occur over a much wider region, known as the synchronization region [15].

Wake synchronization can occur in both forced oscillations and free oscillations of a bluff body. Forced oscillations are the intentional prescribed movement of the body in a controlled manner by an external force other than the fluid force. Free oscillations are the uncontrolled motions of the body that occur naturally due to the periodic fluid forcing acting on the body. In this situation, the amplitude of the motion will depend on the mass, damping, and stiffness of the system. The free oscillation of a bluff body under the conditions of wake synchronization is known as vortex-induced vibration (VIV). VIV can be extremely dangerous to engineered systems, as it can play a large role in the degradation and potential failure of structures [4]. VIV is of interest to the fields of fluid mechanics and dynamics, as it has applications to bridges, offshore structures, cables, heat exchangers, and many other engineered systems [16]. However, there are currently no methods to predict wake synchronization regions. Rather, they must be experimentally mapped through forced oscillation experiments using a parametric sweep of cylinder amplitudes and frequencies at a given flow speed, using a cylinder setup of interest. This method is extensive in time and effort, and it must be repeated for every new Reynolds number and system geometry of interest. Therefore, this current research effort is focused on the feasibility of using phase-reduction analysis to provide a systematic way to predict wake synchronization with only a limited amount of experiments or numerical simulations that examine the vortex shedding response to a small perturbation in the flow at the cylinder [15]. This research will contribute to advancing the application of phase-reduction analysis in an effort to better understand and predict wake-synchronization, therefore enabling the avoidance of VIV and its destructive consequences.

1.2 Research Background

This thesis is part of a collaborative research effort between the Naval Postgraduate School (NPS) and the University of California-Los Angeles (UCLA) with funding support from the National Science Foundation. The project contains two parts: a theoretical and numerical portion performed by UCLA and an experimental portion by NPS. Together, the combined goal of the study is to examine the validity of phase-reduction analysis in realistic three-

dimensional fluid flows and enable a future systematic prediction of wake synchronization that is not currently available.

The focus of this thesis was the collection and analysis of experimental wake velocity data to facilitate the UCLA effort in the validation process of their numerical portion, while simultaneously assessing the feasibility of performing phase-reduction analysis on experimentally collected wake velocity data. The experimental data collected includes a time history of the measured wake velocity behind a circular cylinder in a free stream, before and after a small perturbation in order to quantify the vortex shedding response behavior. Analysis of numerous test runs over a variety of impulses at various stages of the shedding process allows for the development of phase-sensitivity functions, which are also being numerically developed by the UCLA team through simulation.

1.3 Definition of Key Terms

This study is concerned with the wake that forms behind a cylinder immersed in fluid flow, specifically documenting the effects on the vortex shedding process of extremely small, forced movements of the cylinder, henceforth referred to as perturbations. The physical mechanics of the wake and vortex shedding are governed by two main non-dimensional parameters. The first parameter is the Reynolds number, Re , which is defined as

$$Re = \frac{\rho U D}{\mu} \quad (1.1)$$

where ρ is the fluid density, U is the incoming free stream fluid velocity, D is the cylinder diameter, and μ is the dynamic viscosity of the fluid. The Reynolds number is a dimensionless quantity that captures the ratio of inertial forces to viscous forces [17], [18]. It shows the relative importance of inertial effects to viscous effects, which contribute to the behavior of vortex shedding. By varying cylinder diameter and flow speed, a variety of Reynolds numbers can be selected for testing.

The second parameter is the Strouhal number, St , which is defined as

$$St = \frac{f D}{U} \quad (1.2)$$

where f is the vortex shedding frequency. It is a function of the Reynolds number, with the relationship shown in Figure 1.3. The figure shows calculated Strouhal numbers plotted against Reynolds numbers and covers a range of different cylinder diameters. For Reynolds numbers below 300, the Strouhal number changes rapidly as Reynolds number changes. However, for Reynolds numbers above 500, the Strouhal number changes very slowly as Reynolds number changes.

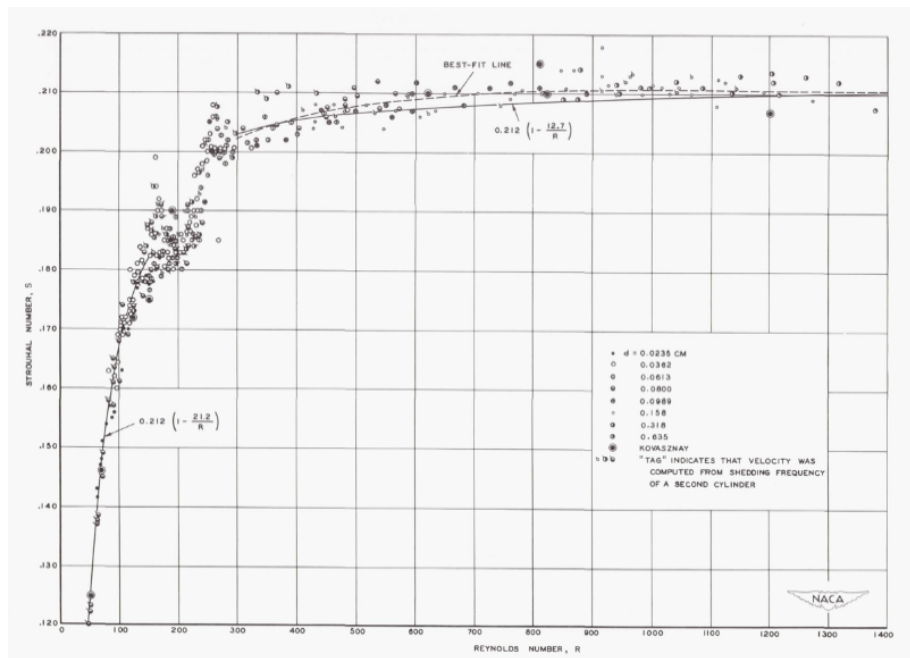


Figure 1.3. Strouhal number dependence on Reynolds number for a fixed circular cylinder of various diameters. Source: [3, Figure 4].

For a given Reynolds number, the Strouhal number can be estimated from the curve in Figure 1.3. Since the diameter and free stream velocity are controllable parameters, Equation 1.2 can be used to solve for the shedding frequency. This calculation provides a theoretical frequency at which the given flow is expected to shed vortices. It is henceforth referred to as the expected shedding frequency.

For any single point in the wake, the velocity should fluctuate periodically at the shedding frequency as vortices pass by the point. Therefore, time history of the measured velocity at a point within the wake is expected to behave periodically. This velocity signal over time, $v(t)$, will be represented by $v(t) = A \sin(\omega t + \phi) + B$ where A is the amplitude of the signal,

ω is the frequency, ϕ is the phase offset, and B is the signal offset.

The representation of the velocity in this way is important, as the change in ϕ due to a perturbation is the main parameter of interest in phase-reduction analysis. In theory, the signal before and after a perturbation is expected to have the same amplitude, frequency, and signal offset, but a slightly different phase offset due to the time it takes for the reorganization of the wake due to the perturbation on fluid. The phase offset, ϕ , is simply a measure of the lateral phase shift of a sine wave from the origin, which does not matter as an absolute variable, per se. However, the relative difference between the phase offset before and after the perturbation, $\Delta\phi$, will be important.

Figure 1.4 shows an impulse response graph, which is the expected behavior of the wake velocity before and after a perturbation. The blue curve represents the pre-perturbation flow signal. The portion of the blue curve extending past the perturbation is a forward projection of the signal had the perturbation not occurred. The red curve is the resulting signal after the perturbation. The difference in phase offset between the signals is shown as $g(\theta; I)/\omega_n$. The exact moment of perturbation with respect to the location along a shedding cycle will be referred to as the phase at instant of perturbation (PIP), denoted by θ . It is the moment at which the perturbation occurs, as an angle relative to the 2π periodicity of shedding. It is of note that θ is referred to in [19] as “phase variable.” This thesis denotes θ as phase at instant of perturbation as to not cause confusion with the phase offset (ϕ) and later with the phase angle provided by the Hilbert transform.

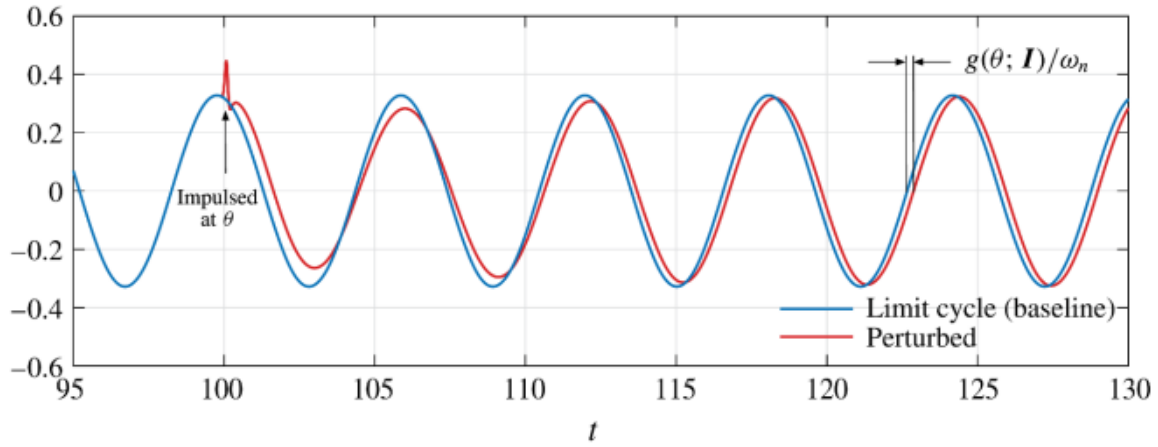


Figure 1.4. Example of the expected response of the velocity signal to perturbation at time 100. The figure's $g(\theta; I)/\omega_n$ represents the phase difference. Source: [19, Figure 2(a)].

The occurrence of the PIP at different points within the shedding cycle is expected to cause a different response in the phase offset of the resulting post-perturbed signal. Therefore, there should be a relationship between θ and $\Delta\phi$. This relationship is defined as the phase-sensitivity function, $Z(\theta)$, given by

$$Z(\theta) = \lim_{I \rightarrow 0} \frac{g(\theta; I)}{I} \quad (1.3)$$

where θ is the PIP and I is the impulse magnitude. An example of a phase-sensitivity function is shown in Figure 1.5. The $Z(\theta)$ function quantifies how the phase difference between signals depends on the PIP. Though it can vary in shape and magnitude, this function is an example of the type of relationship expected in the experimental generation of the phase-sensitivity function.

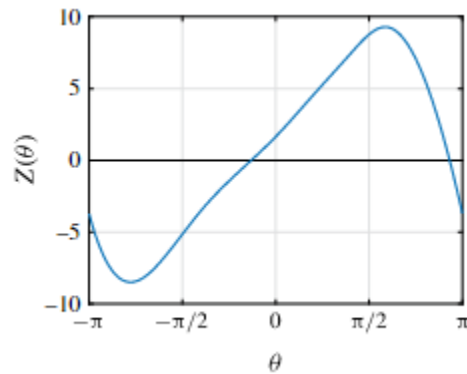


Figure 1.5. Example of a phase-sensitivity function created through simulation. Source: [19, Figure 4(a)].

The determination of the phase-sensitivity function is necessary in phase-reduction analysis to enable the prediction of the wake-synchronization region and to predict potential lock in conditions. The ultimate goal of this research is to assess the feasibility of producing an experimental phase-sensitivity function from wake velocity data. The experimental generation of phase-sensitivity functions can be used to make synchronization predictions but can also be used to validate numerical results as an alternate way for generating phase-sensitivity functions for the same conditions.

CHAPTER 2: Hardware and Facilities

2.1 Recirculating Water Tunnel

To generate the fluid test environment for experimentation, this investigation used an Eidetics International, Inc. flow visualization recirculating water tunnel located at NPS. The tunnel is a model 1520, installed in June of 1988 by the Rolling Hills Research Corporation. A picture of the tunnel is shown in Figure 2.1.

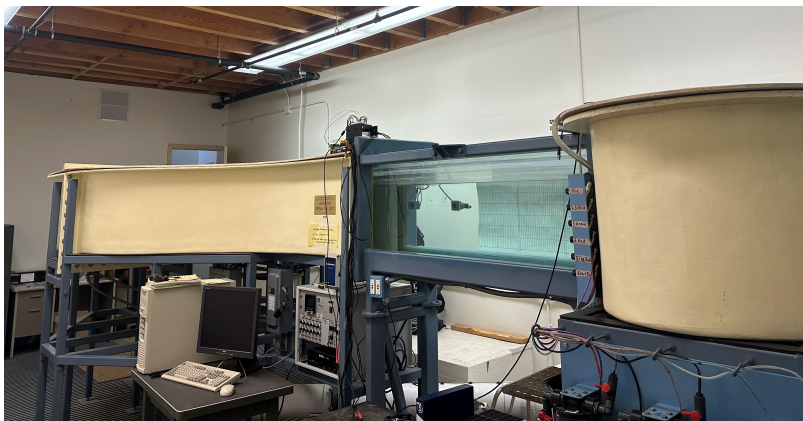


Figure 2.1. Image of the Eidetics model 1520 recirculating water tunnel in the facilities of NPS.

The water tunnel has a 38.1 cm (15") wide, 50.8 cm (20") deep, and 154.2 cm (60") long free surface test section that allows for use of the cylinder and mounting apparatus. All testing was conducted at a water depth of 35.6 cm (14"). The maximum flow speed of the tunnel is approximately 30.48 cm/s (12 in/s), providing more than enough capability to test low Reynolds number flows. Though not formally documented for this tunnel, the minimum speed appears to be in the range of 1.83 cm/s (0.72 in/s), which creates a lower limit for testing. The tunnel is also equipped with a filtration system, which was run periodically to prevent particulate matter from circulating through the test section and affecting the hot-film portion of the fluid velocity sensor.

2.2 Ultrasonic Flow Meter

This experimental set-up used a Dynasonics Series TFX ultrasonic flow meter to measure the free stream velocity in the test section. The sensor works by alternating the transmission and receiving of sound energy between two transducers. They measure the time that elapses between signal sending and receiving which is directly related to the velocity of the fluid through which the energy passes [20]. The flow meter is attached on the outside of the test section wall near the front. This location allowed for the free stream velocity of the incoming flow to be measured prior to the cylinder disrupting the flow.

2.3 Constant Temperature Anemometry System

Thermal anemometry is a method used to measure fluid velocity. It works by measuring the changes in resistance of a small heated element, referred to as the probe, when placed in a moving fluid due to convective heat transfer. For a constant current input, the probe will change temperature, and thus resistance, as flow speed varies because of the effect that flow speed has on convective heat transfer [21]. Therefore, to make measurements, the probe is connected to a module that aims to keep the heated element at a constant temperature while fluid is flowing over it. As the fluid velocity changes, the module rapidly varies the voltage across the probe and therefore the amount of current flowing through the probe to keep a constant temperature. The system outputs the voltage across the sensor to represent the fluid velocity.

The thermal anemometry system was manufactured by TSI Incorporated and consists of a hot film probe and a constant temperature anemometer (CTA) module. The probe is a model 1261A-10W mini boundary layer probe, which sits immersed in the fluid behind the cylinder. It is connected to a model 1750 CTA module through a model 1150 standard probe support and model 1137 mounting block. Figure 2.2 shows the CTA hot film probe and module.

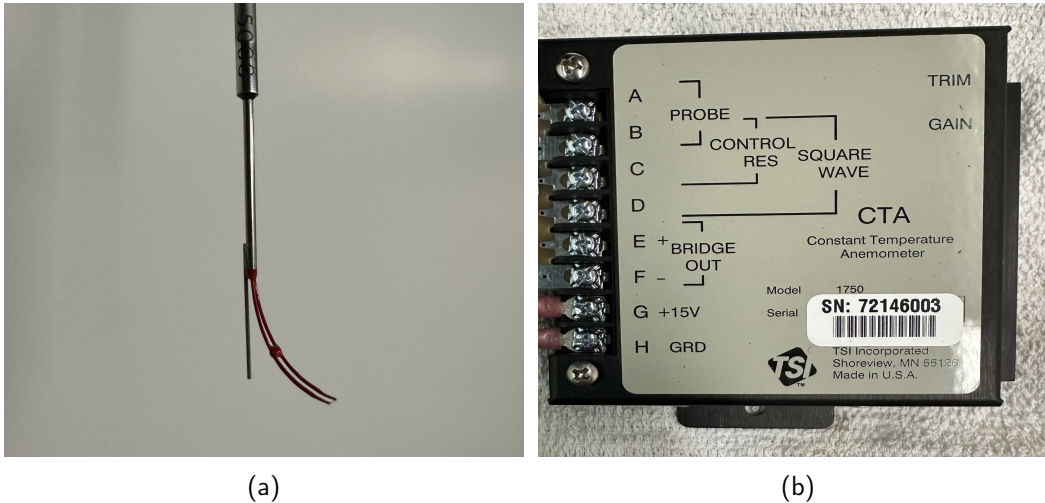


Figure 2.2. The CTA (a) hot film probe and (b) module.

2.4 Cylinder and Mounting Apparatus

The testing setup was built to provide single degree of freedom motion of the cylinder by either translation or rotation. It is also built with the capability for coupled two degree of freedom motions for potential future applications. The components, particularly the selection of stepper motors, were chosen to execute very small motions accurately in a very short time period. Stepper motors work by moving a fixed angle, or step, with each input of electrical current. This allows them to move small distances and achieve high accuracy. This ability is critical to carrying out the desired impulse motion for experimental testing.

The testing setup consists of a cylinder, two stepper motors with encoders, a microprocessor, a linear slide, an acoustic distance sensor, and the various structural components to hold it together. Its configuration is displayed in Figure 2.3.

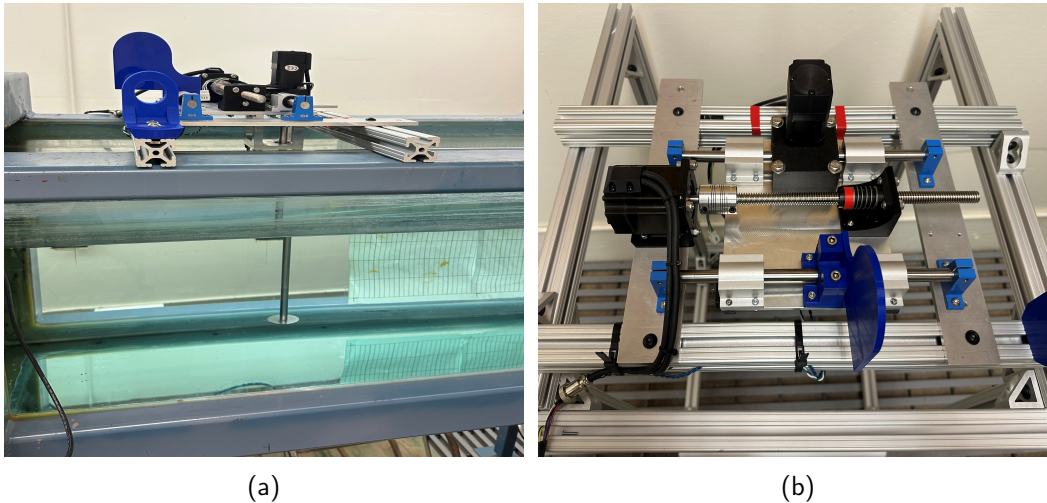


Figure 2.3. The testing apparatus (a) sitting above the free surface test section of the water tunnel and (b) detailed overhead view of hardware configuration.

A 0.635 cm (0.25") thick aluminum plate is fixed to four pillow block bearings that slide along a pair of stainless steel rails. This creates a traversing plate that can be translated back and forth by a NEMA 23 stepper motor and lead screw. When the stepper motor spins, it rotates the lead screw which contains a collar attached to the traversing plate and moves the plate 0.254 cm (0.1") per revolution in a horizontal direction. This creates the linear motion for translational test cases. The traversing plate has a circular cut-out and mounting holes that allow for a NEMA 17 stepper motor to be connected above the plate but have its shaft extend down below the plate. The cylinder is connected directly to the shaft using a coupling. This arrangement allows for cylinder rotation directly from the rotational movement of that motor. The coupling also allows various diameter cylinders to be attached to the system. The cylinder sits inside two rotary bearings near the coupling to resist any moment on the cylinder being experienced by the stepper motor shaft. The entire apparatus sits atop the free surface test section, allowing only the cylinder to be immersed into the fluid, while the apparatus sits on the top of the test section. An oversized washer is attached to the bottom of each cylinder to minimize end tips effects on the shedding. A vertical reflecting plate is attached to the traversing plate and positioned in-line with an acoustic sensor for measuring translational displacements.

The motor controlling translational movement is a NEMA 23, with model number 23E1K-

12. It has a step angle of 1.8 degrees, equating to 200 steps per revolution. The attached optical incremental encoder includes 1000 pulses per revolution and has 2 output channels. The motor controlling rotational movement is a NEMA 17, with model number 17HM19-1684D-E1000. This motor has a step angle of 0.9 degrees, for 400 steps per revolution with a two-channel output 1000 pulse per revolution optical incremental encoder.

The motors are controlled by an Arduino microprocessor that receives the desired inputs for motion control and then outputs the proper electrical signals to a model DM542T stepper motor driver manufactured by Leadshine. The motor driver, in turn, provides the proper voltages to the motor for the desired motion. For translation testing, a Senix ToughSonic 14 ultrasonic sensor is used with the reflecting plate to provide an additional measurement, with the encoder outputs being the primary, of the horizontal distance travelled. A model LRS-50-5 power unit provides a 5 volt power supply to the Arduino, while the motor driver is powered by a model LRS-150-24 power supply for up to 24 volts. Both power units are manufactured by Mean Well USA Inc.

The Arduino microprocessor is controlled by a custom-written program that is uploaded directly to it. The inputs to the program are the number of steps desired, the delay between steps, and the type of desired motion. These three parameters create a commanded distance for translation or angle for rotation, and time to complete the movement. The motion can also be set to oscillate a requested number of cycles. However, this study is only using a single, one-direction motion, as the perturbation.

2.5 Data Acquisition System

The encoders, acoustic Senix probe, CTA module, and ultrasonic flow meter all provide outputs in the form of analog voltages which are collected on a National Instruments USB-6363 16 channel X Series data acquisition device. This device collects the analog voltage outputs from the sensors and produces digitized discrete samples at a desired sampling rate. These samples are saved via USB to a computer which writes the data to a file using a custom-written data collection script.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 3:

Equipment Validation

3.1 Purpose and Procedure

Validation is an important process in systems engineering and experimentation. For this effort it is necessary to ensure that the testing apparatus is performing its expected functions. This provides confidence that future results, obtained using the testing apparatus, were actually caused by the various desired input conditions during testing. Additionally, this validation process served as a way to explore the feasibility of potential test cases and debug any issues before final testing.

During test runs, perturbations of the cylinder are extremely small and fast movements. Many of the movements are too small to visually perceive, let alone measure by hand. To aid in the measurement of the cylinder motion, the chosen motors for the testing apparatus included encoders described in Chapter 2. The encoders are designed to pulse between a high and low voltage for every increment that the motor rotates. Therefore, the rotation of the motor can be tracked by the number of pulses, since the number of pulses per revolution of the encoder is known. The goal for validation testing was to use an extremely high sampling rate to consistently detect the expected number of pulses for each movement and measure the time taken to complete a perturbation across a variety of cases. This would give confidence that the system is executing the requested motion when in the testing phase. During the testing phase, the long test runs restrict the sampling rate to be much lower to keep file sizes manageable and the data acquisition system will not detect the majority of the pulses. The quantities of interest for both translation and rotation were the impulse displacement and impulse duration. The actual input parameters to the control software, however, were the number of steps, which will determine how many degrees the motor rotates, and the delay between steps, which controls the angular velocity of the motor. For translation, the NEMA 23 stepper motor rotates a lead screw of 0.254 cm (0.1") per revolution. Therefore, the translation test cases tend to have a higher number of steps requested.

To evaluate various conditions, validation testing was conducted over a variety of cases

that cover the parameter space this research planned to explore. Each case is a unique combination consisting of the number of steps requested, the delay between steps, and whether the cylinder motion is translation or rotation. Each validation case was repeated 10 times to ensure repeatability and generate a data set to allow for the calculations of mean values and 95% confidence intervals for the measured variables.

3.2 Translation Validation

For translational motion, there was a primary and secondary measurement instrument. Primarily, the 1000 pulse per revolution encoder was used, with two output channels. The motor is 200 steps per revolution. Therefore, five pulses per motor step were expected to register on each of the two encoders. As a secondary reference, the Senix ultrasonic sensor was included to provide a secondary measurement point for additional validation. The time was measured by calculating the time difference between the last encoder pulse and the first.

For validation testing, seven different cases were tested with ten runs each, for a total of 70 runs. Tables 3.1, 3.2, and 3.3 show the summary results for pulse detection, time duration, and Senix measurement, respectively. All the tables include columns with the case number and sampling rate. Additionally, Table 3.1 contains the number of pulses expected, number of pulses detected with 95% confidence interval for encoder A, and number of pulses detected with 95% confidence interval for encoder B. Table 3.2 also includes the distance expected and distance measured with 95% confidence interval. Finally, Table 3.3 also contains the time expected and time measured with 95% confidence interval and the measured time overshoot per step.

Table 3.1. Comparison of expected and measured encoder pulses for translational motion with reported confidence bounds of 95%.

Case	Sampling Rate (Hz)	Pulses Expected	Avg. Pulses Detected (A)	Avg. Pulses Detected (B)
TV1	12500	100	100 ± 0	100 ± 0
TV2	12500	100	99 ± 0	100 ± 0
TV3	12500	100	99 ± 0	99.60 ± 0.39
TV4	12500	100	99 ± 0	100 ± 0
TV5	20000	1000	999 ± 0	1000 ± 0
TV6	20000	500	500 ± 0	500 ± 0
TV7	12500	250	250 ± 0	250 ± 0

Table 3.2. Comparison of expected and measured time for translational motion with reported confidence bounds of 95%.

Case	Sampling Rate (Hz)	Time Expected (ms)	Time Measured (ms)	Time Overshoot Per Step (ms)
TV1	12500	129.3	144.40 ± 0.03	0.76
TV2	12500	64.6	78.60 ± 0.04	0.70
TV3	12500	32.3	46.50 ± 0.02	0.71
TV4	12500	12.9	29.70 ± 0.07	0.83
TV5	20000	67.7	158.10 ± 0.04	0.45
TV6	20000	33.7	83.90 ± 0.01	0.50
TV7	12500	33.3	61.60 ± 0.05	0.56

Table 3.3. Comparison of expected and measured distance for translational motion with reported confidence bounds of 95%.

Case	Sampling Rate (Hz)	Distance Expected (10^{-4} in)	Distance Measured (10^{-4} in)
TV1	12500	100	81 ± 6
TV2	12500	100	99 ± 6
TV3	12500	100	93 ± 9
TV4	12500	100	110 ± 8
TV5	20000	1000	1100 ± 5
TV6	20000	500	530 ± 8
TV7	12500	250	280 ± 16

For the results of measured encoder pulses, cases TV5 and TV6 are shown at a higher sampling rate. For these cases, the time delay between steps was the lowest, meaning that the encoder pulses occurred the most rapidly out of all the tests. This drove the need to increase sampling rate to register all of the pulses. From the results, consistent detection of within 1 pulse of the number expected gives confidence that the displacement motion is occurring as expected.

For the time duration validation, each measured time was slightly longer than expected, by a variable amount. However, across all cases, the average time error divided by the number of steps gives a consistent value of 0.55 ± 0.12 milliseconds per step. This is likely representative of the combined amount of time that the Arduino processor took to execute the commands plus the actual time taken by the motor to complete the step. The small overshoot in time is insignificant to the overall performance of the motion, as the expected shedding period is at least two seconds in testing cases.

Comparing the requested and measured distances from the Senix data, the differences in measurement are very small. With such small movements, the error size relative to distance magnitude is naturally quite large, as the sensor will eventually reach its signal to noise

ratio limit. The results confirm that the sensor was validating that the motor was moving according to the controller inputs as shown by the small differences between requested and measured distance of each case. This gives confidence not only that the test cylinder moved the proper distance, but also that the encoder pulses are a valid method for measuring the movement of the cylinder since they provided consistent results.

3.3 Rotation Validation

Rotational motion only had the primary measurement of encoder pulses because the Senix ultrasonic sensor measures relative translational displacement only, not rotational displacement. Given the validation of encoder pulses demonstrated with translational validation previously, the pulse detection and time is sufficient to validate rotational motion. In these cases, the NEMA 17 stepper motor is a 400 step per revolution motor, with a 1000 pulse per revolution encoder. Therefore, the expected measurement is 2.5 pulses per step.

As before, ten runs were conducted over seven cases, for a total of 70 runs. Again, the cases varied in the number of steps and the delay time between steps. The results are summarized in Tables 3.4 and 3.5.

Table 3.4. Comparison of expected and measured encoder pulses for rotational motion with reported confidence bounds of 95%.

Case	Sampling Rate (Hz)	Pulses Expected	Avg. Pulses Detected (A)	Avg. Pulses Detected (B)
RV1	12500	10	10 ± 0	10.1 ± 0.1
RV2	12500	10	10 ± 0	8.6 ± 0.1
RV3	12500	10	10 ± 0	10.4 ± 0.2
RV4	12500	10	10 ± 0	10 ± 0
RV5	12500	100	102 ± 0	102.4 ± 0.2
RV6	12500	50	49.8 ± 0.3	50.4 ± 0.2
RV7	12500	25	24.9 ± 0.1	24.9 ± 0.2

Table 3.5. Comparison of expected and measured time for rotational motion with reported confidence bounds of 95%.

Case	Sampling Rate (Hz)	Time Expected (ms)	Time Measured (ms)	Time Overshoot Per Step (ms)
RV1	12500	102.0	115.30 ± 0.07	3.33
RV2	12500	51.0	64.80 ± 0.05	3.45
RV3	12500	25.5	43.70 ± 0.11	4.55
RV4	12500	10.2	22.00 ± 0.10	2.9
RV5	12500	33.2	66.20 ± 0.09	0.83
RV6	12500	32.3	45.10 ± 0.09	0.64
RV7	12500	30.6	42.20 ± 0.07	1.16

The recorded encoder pulses show a similar result to translation. Every case was either on the expected value or within 2.5 pulses. This means the motor moved the requested amount to within 1 step. A major difference with rotation is that there was a larger delay between steps, which means that there was more stopping and starting of the motor. The starting and stopping creates a higher likelihood in a miscalculation of pulses for either of the encoders because there is not a whole number of pulses per step. Therefore, a full step has the possibility of registering as 2 or 3 pulses. However, the motor can only move a single fixed increment.

The results for time of rotational movement reflect the same trend as the results from translation. Each measured time is again slightly longer than expected, resulting in an average overshoot of 2.4 ± 0.34 milliseconds per step. This value differs from the translational error per step, however, the stepper motor is a different size motor than the stepper motor controlling translation.

Overall, the results give confidence that both translational and rotational motion of the cylinder satisfies the desired performance to create the perturbations desired. This estab-

lished confidence is necessary because the data sampling rate during actual testing has a much slower sampling rate to accommodate a larger data collection time. A slower sampling rate means that only a small number of pulses are expected to be detected, as the encoder pulses happen very rapidly. Therefore, the motion during actual testing will be assumed to be accurate given the validation process demonstrated despite not detecting every encoder pulse.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 4: Data Collection

4.1 Probe Location

The location of the CTA probe in the cylinder's wake affects the quality of the measured velocity signal. In general, the downstream location must be far enough away from the cylinder to avoid the recirculation region where vortices are forming. However, vortices continually dissipate as they move downstream, making the signal weaker if the probe is too far from the cylinder. Therefore, there is some optimal distance downstream. Similarly, the lateral position will impact the measurement quality of the wake velocity. Therefore, a singular position must be determined that presents the strongest periodic velocity signal to enable a quality analysis.

The x-axis and y-axis for describing the probe location are defined as shown in Figure 4.1, from an overhead view. The downstream, X_p , and lateral, Y_p , positions of the probe are nondimensionalized by the cylinder diameter because the location relative to the cylinder is what drives the signal quality. The coordinates can be represented as $(X_p/d, Y_p/d)$ in order to relate the position to the cylinder diameter. Since the diameter drives the wake behavior, the relative location of the probe for a given cylinder diameter should not change with different cylinder sizes.

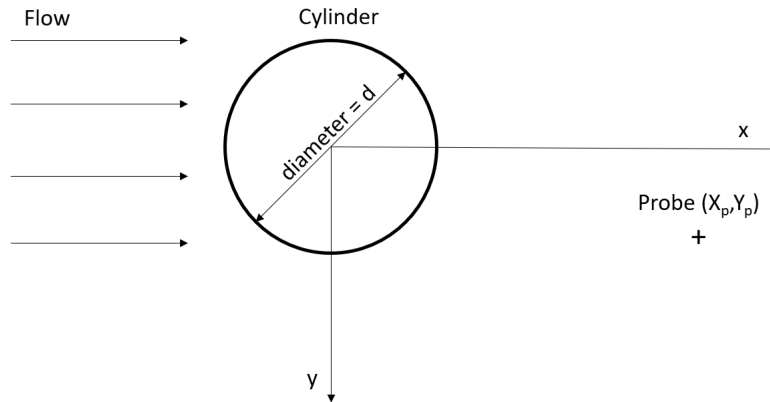


Figure 4.1. Depiction of the coordinates X_p and Y_p for the probe location from an overhead view. The origin of the coordinate system is the center of the cylinder.

The figure shows how the x and y axes are oriented relative to the incoming flow, which is moving left to right across the cylinder. Therefore, the downstream direction is positive in the x-direction and the bottom of the figure represents the positive y-direction.

In order to determine the best probe location, multiple (X_p, Y_p) locations were tested over various Reynolds numbers. A time history of wake velocity was recorded at each location for two minutes per flow speed. These time histories were analyzed to determine their frequency content using the fast Fourier transform (FFT). Three examples of the resulting frequency spectra are shown in Figures 4.2, 4.3, and 4.4 from strongest to weakest velocity signal strength.

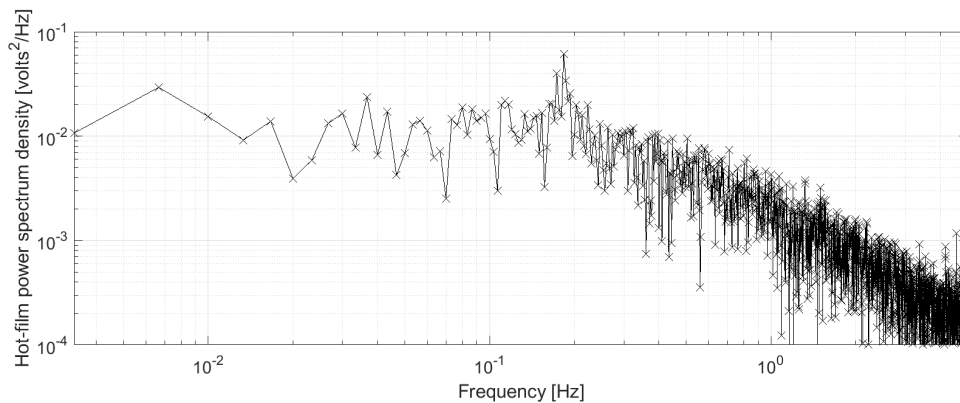


Figure 4.2. Frequency content of $(X_p/d, Y_p/d) = (4.5, 0.5)$ for Reynolds number 500.

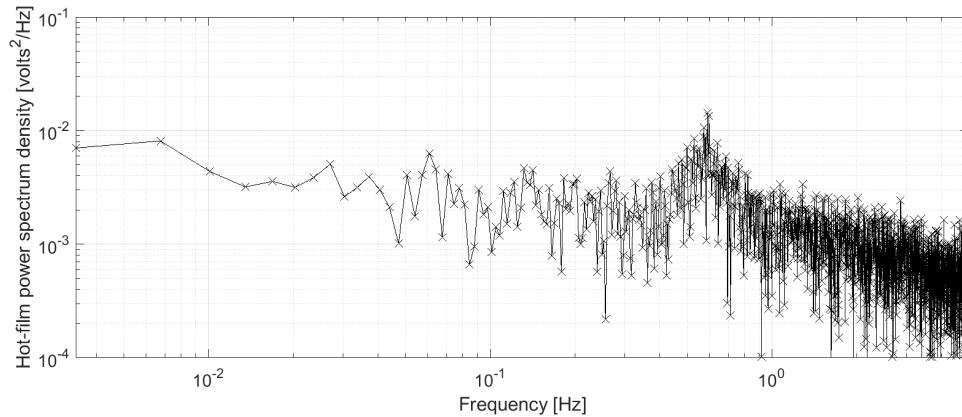


Figure 4.3. Frequency content of $(X_p/d, Y_p/d) = (6.0, 1.5)$ for Reynolds number 2000.

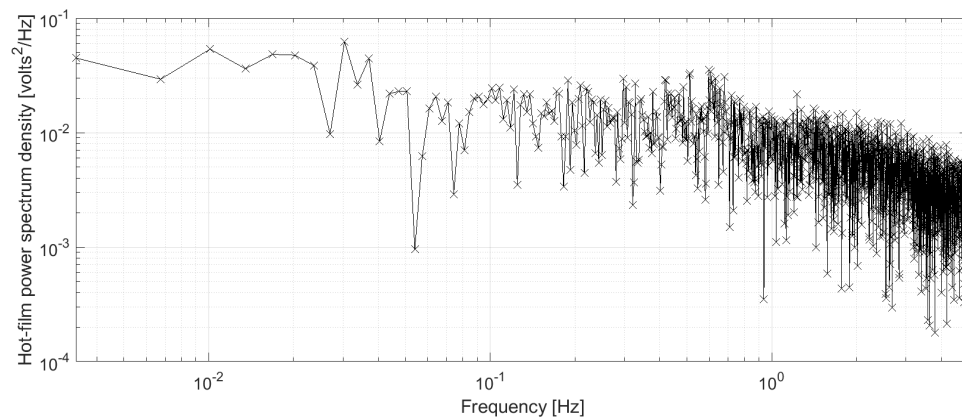


Figure 4.4. Frequency content of $(X_p/d, Y_p/d) = (3.0, 1.5)$ for Reynolds number 2000.

The quality of the location is determined by the strength of the signal spike at the dominant frequency. It was found that the downstream position of $(X_p/d) = 4.5$ and lateral position of $(Y_p/d) = 0.5$, produced the most consistent quality signal over multiple Reynolds numbers, one of which is shown in Figure 4.2. This probe position is tangent to the cylinder and far enough downstream for the vortices to have consistent behavior across the sensor. Figure 4.3 shows a noticeable spike at the dominant frequency, however the actual power of the signal is much lower, making it a less desirable result. The results in Fig. 4.4 show a considerably weaker velocity signal, as there is no apparent spike to indicate the dominant frequency. All three example spectra show that the signal is very broadband, made up of many frequencies at varying power.

4.2 Data Description

With the probe position decided, phase-reduction testing was started. The phase behavior is expected to be dependent on Reynolds number. Therefore, this study was mainly focused on collecting testing data at a single Reynolds number of 300. This is the Reynolds number used by the UCLA group for their numerical study described in Chapter 1. A number of runs were also collected for Reynolds number 200 and 1000 to examine the effects of Reynolds number on determining the signal phase from the wake velocity data.

For the phase-reduction testing, a total of five channels of data were collected during each run. They included the Senix distance sensor, encoder channels A and B, the ultrasonic flow sensor, and the CTA sensor. Therefore a relatively slow sampling rate of 25 Hz was used to keep the overall file size manageable since the runs were four minutes long. For translational cases, the Senix was collected to provide a backup data source. However, it provides no useful data for rotation but is still recorded as a “dummy” channel to maintain consistency in the data file structure and number of collected channels. The use of each of the other channels will be explained further in Chapter 5.

4.3 Testing Procedure

Consistent execution of the experimental runs is important to ensure repeatability and validity in data across all runs. Therefore, a testing procedure was implemented. Before data collection started for the first run of each case, the CTA probe was immersed in the test section for at least 2 minutes to allow the probe to reach its operating temperature before collection begins. The probe stayed immersed in the water in the same position relative to the cylinder across all runs. Additionally, the water tunnel was brought to its desired speed and given sufficient time to ensure that the flow was consistent. Finally, the program for providing motor control was uploaded to the Arduino before data collection, making it ready to execute motion commands immediately when needed.

Once these conditions were met, data collection began. The data collection program records the measured signals from all channels and continuously writes the data to a file. At approximately two minutes into a run, a command signal was given to the Arduino to perform the desired impulse cylinder motion. The impulse motion is a short duration movement in one direction, consistent with UCLA’s model of a perturbation. The data

collection is continuous through this point and continues collecting for another two minutes after the perturbation occurs. Therefore, at the end, the run has four total minutes of data, with about two minutes each for pre-perturbation and post-perturbation flow. Immediately after data collection ends, the motor is commanded to move the cylinder back to its original position. There must be a sufficient pause before beginning the next data collection run to avoid collecting the effects of this resetting movement in the next run. This wait time is dependent on the shedding cycle period for the conditions of interest. As a rule of thumb, this study paused for enough time to allow at least 10 shedding cycles after the movement.

4.4 Testing Matrix

Phase-reduction analysis involves evaluating the phase difference between the pre- and post-impulse wake velocity signal as the impulse magnitude goes to zero. However, physical limitations that exist for any testing apparatus prompted this study to explore a range of decreasing magnitudes towards the weakest possible perturbation. To achieve this, the test cases varied both the perturbation duration and the distance that the cylinder travels. The desired time is a percentage of expected shedding period and the distance is a percentage of cylinder diameter. The impulse velocity must be a small percentage of the free stream velocity as well, which creates a highly constrained testing matrix. This is because as the duration is decreased, the displacement distance must decrease as well to keep the velocity from increasing. The test matrices for translational and rotational motion are shown in Tables 4.1 and 4.2, respectively. For each test case, data was collected from 25 separate runs.

Table 4.1. Translation testing matrix.

Case	% of Shedding Period	Desired Time (s)	% of Cylinder Diameter	Desired Distance (10^{-3} in)
T1	5.0	0.113	0.5	2.5
T2	2.5	0.057	0.5	2.5
T3	2.5	0.057	0.3	1.5

Table 4.2. Rotation testing matrix.

Case	% of Shedding Period	Desired Time (s)	% of Full Rotation	Desired Angle (deg.)
R1	10.0	0.227	0.5	1.8
R2	5.0	0.113	0.5	1.8
R3	2.5	0.057	0.5	1.8

The testing matrices were created with the goal of keeping the impulse time, distance, and velocity below 5% of the shedding period, cylinder diameter, and free-stream velocity, with the exception of case R1. While trending these towards zero, the parameters are limited by the physical abilities of the motors. For translation, the limits are lower due to the lead screw acting in the manner of a $\frac{1}{10}$ reduction gear, giving a finer resolution of movement. Since the rotational motor is connected directly to the cylinder, the smallest possible rotation angle is 0.9 degrees.

CHAPTER 5:

Data Reduction and Analysis Techniques

5.1 Overall Process

The goal of the analysis process is to determine the phase offset, ϕ_1 and ϕ_2 , for the pre-perturbation signal and post-perturbation signal and to determine the PIP, θ , for each run. The analysis utilizes two methods to calculate ϕ : a curve-fit method and a Hilbert transform method. Ultimately, the phase offset difference $\Delta\phi$ for a single run is represented by an average value from a portion of the $g^*(\theta, t)$ function produced by the Hilbert transform method. The PIP is calculated as the instantaneous phase of the signal at the time of perturbation. These measurements are needed to ultimately produce the phase-sensitivity function, $Z(\theta)$.

To analyze the collected data for each run, it must first be parsed. The continuous time history wake velocity signal is separated into pre-perturbation and post-perturbation segments using the encoder pulses. The detected encoder pulses are used to mark the point in time at which the perturbations occurred. Since the slower sampling rate does not detect every encoder pulse, a theoretical pulse window is constructed to determine the earliest possible start and latest possible end times of the perturbation. This is accomplished by assuming the first detected pulse is the actual first pulse and determining the time where the last possible pulse would occur based on the time delay and number of steps from this pulse. This becomes the end of the theoretical pulse window. At the same time, the last pulse detected is assumed to be the actual last pulse. Based on the time delay between steps and number of steps commanded, the earliest possible time for a pulse based on this pulse is also calculated, becoming the beginning of the window. It is known that the perturbation occurred within this theoretical window, but there is uncertainty as to the exact start and end since the acquisition system did not record every pulse.

In Figure 5.1, the theoretical window is shown as red dashed lines over the raw data. For all runs, the earliest (leftmost) limit of the window is used as the time at which the perturbation starts, and that time will be evaluated to calculate the PIP. The PIP, defined in Chapter 1, is

the phase angle relative to an individual shedding period at which the perturbation occurred. Because the PIP is dependent on the time of perturbation, the theoretical window presents uncertainty. When only a single pulse was detected, the theoretical window had a value of double the desired impulse time. Therefore, the largest possible error on the time of perturbation is equal to desired impulse time. Since the maximum impulse time is 5% and 10% of the shedding period for translation and rotation, respectively, the maximum possible error is still very small relative to the shedding cycle during which it occurs.

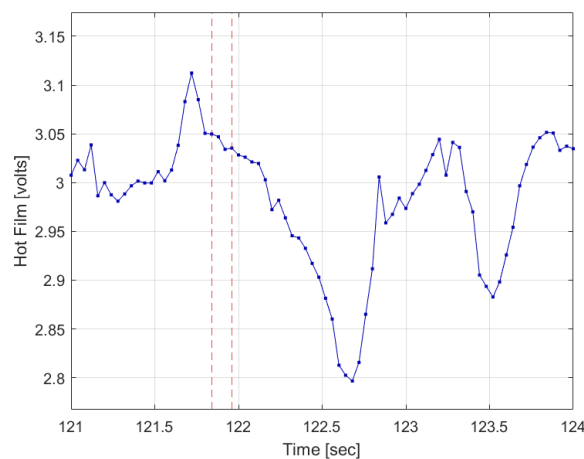


Figure 5.1. The perturbation occurs within the theoretical window, depicted as red dashed lines over the raw data in blue.

Another consideration for the analysis is that the probe is located downstream of the cylinder but the impulse is applied to the cylinder. Therefore, it takes some amount of time for the vortices to shed and reach the probe. This means the effects of the perturbation in the wake will not be registered by the probe until the first vortex after the perturbation reaches the probe. To account for this, the theoretical time window is shifted to the point later in time at which the probe actually measures the impulse effects. This time was calculated as the downstream distance of the probe from the cylinder divided by the free-stream velocity. This makes the beginning of the post-perturbation cycle approximately the time at which the signal should begin demonstrating reorganized wake behavior at the probe location.

The UCLA group is calculating the forces directly on the cylinder in their simulations, which means they do not have a delay between the time of perturbation and its registered effects. Additionally, they are measuring the PIP directly on the cylinder force signal, whereas

the experimental approach is measuring the PIP from downstream vortices. Though they are related, the slight uncertainty in X_p and the convective velocity of vortices moving downstream means there is expected uncertainty in the calculation of the PIP.

5.2 Curve-Fit Approach

The initial method for analysis was a sinusoidal least-squares curve-fit approach for the entire pre-perturbation signal and post-perturbation signal. The ideal case is that each single sine wave would capture the behavior of the entire respective signal. However, Figure 5.2 shows how the experimental data has disruptions in the expected behavior which results in the inability to fit a single representative sine wave to the data. The time history shows that the flow demonstrates the expected periodic behavior, but there are many irregular regions in the flow, three of which are circled in red. These irregular regions are characterized by a disruption in the expected periodic signal of the fluid velocity. They are identifiable by short regions of low amplitude. These rapid fluctuations of the signal is not consistent with the expected flow behavior. Therefore, the fitting of parameters becomes inaccurate as it attempts to capture these irregular regions along with the rest of the signal.

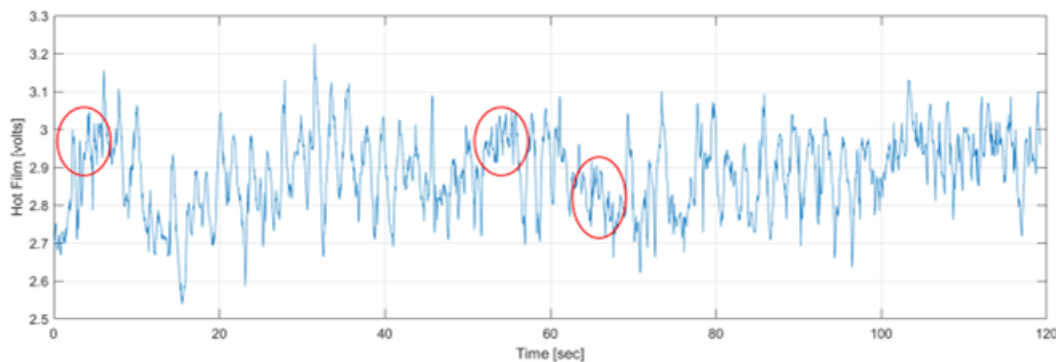


Figure 5.2. Time history of Reynolds number 300 pre-perturbation flow. Irregular regions are circled in red.

If these irregular regions simply disturbed the amplitude, but did not change the underlying phase offset, a curve fit on the entire signal could still possibly provide a valid ϕ . However, Figure 5.3 shows an example of how the irregular regions causes two parts of the same signal to become significantly out of phase from each other. The figure shows a post-perturbation signal, with the expected times for peak values as vertical lines. If the signal

has a near constant frequency and phase offset for each cycle, the peaks should appear on or very close to the vertical lines. Initially, the peaks circled in green approximately align with the expected peak values before the time interval denoted by the black bracket, which represents an irregular region. The result is that the following peaks (circled in red) become significantly out of phase with those before the disrupted signal. Therefore, fitting a single sine wave to this data is not useful to capture the phase offset because of a lack of consistency throughout the signal.

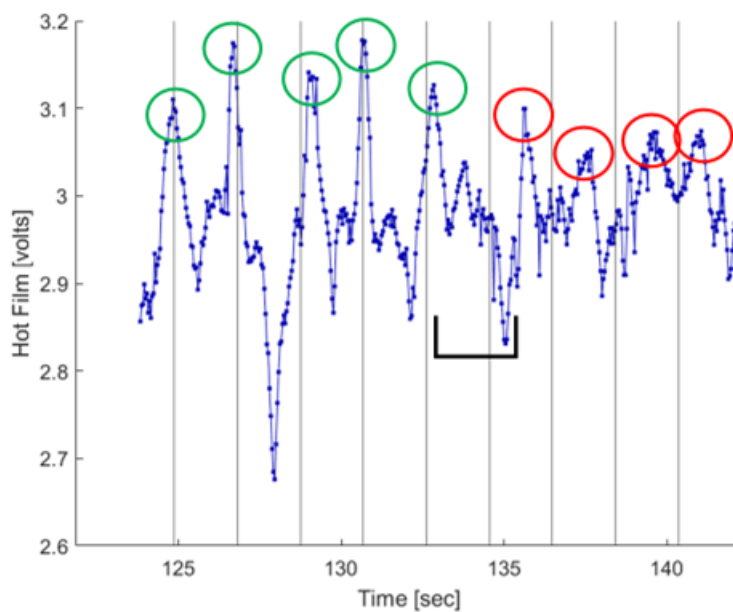


Figure 5.3. Time history of Reynolds number 300 post-perturbation flow. The vertical lines represent expected locations of peak values based on the identified shedding frequency.

This behavior in the raw signal prompted the analysis to use a cycle-by-cycle curve-fitting process to identify the phase offset and frequency before and after the perturbation. The occasional irregular behavior in the shedding process which appears in the wake velocity means that this analysis will only be able to characterize a short time period immediately before and after the perturbation. The approach provides the benefit of allowing cycles to be unaffected by an irregular region that occurs prior to it. To perform the cycle-by-cycle fits, the raw velocity data is first run through a band-pass filter with frequency limits of 75% and 125% of the measured shedding frequency determined from an FFT. This is done

to eliminate the effects of noise on the curve-fitting and provide consistency with Hilbert Transform method, which is discussed next.

A sine wave was initially fit to each cycle. The curve fit uses a least-squares error calculation to the equation

$$y = a \cos(\omega t) + b \sin(\omega t) + c \quad (5.1)$$

where a , b , and c are fitting parameters determined from a least squares fit and ω is the measured shedding frequency. This fit can then be represented by a single equation of

$$y = A \sin(\omega t + \phi) + C \quad (5.2)$$

where $A = \sqrt{a^2 + b^2}$, $\phi = \tan^{-1}(\frac{a}{b})$ and $C = c$.

During the curve fitting process, it was found that there is slight variability in frequency across consecutive cycles. Because of this, ω was a fitting parameter for each cycle as well, rather than using a single frequency value corresponding to the maximum energy from the FFT. In a cycle-by-cycle fit with variable frequency, the definition of time zero becomes important because it inherently affects the assignment of the phase offset. Using the global time zero of the signal is problematic because slight differences in frequency over a long period of time create a large difference in the assignment of a phase offset. That means that two consecutive cycles with the same actual phase offset could have significantly different calculated phases offsets due to a small difference in the frequency used for the curve fit. Therefore, a local time zero is defined for each cycle to be fit, so that each phase offset is more accurate across consecutive uninterrupted cycles with slightly different frequencies.

Variable frequency fitting allows for more accurate phase offsets, but it also creates a slightly different period for each cycle. The fit for each cycle must include only the number of points contained in one period to avoid shifting the next cycle's local time zero to a different relative point within the cycle, thus changing the calculated phase offset. To accomplish this, two curve-fits are performed consecutively for each cycle. The first fit uses the period associated with the average measured frequency, which is known to be slightly inaccurate for any given cycle. However, that fit is used to determine the actual frequency of the cycle and thus the actual number of points that should be included in the fit. Then, the second fit uses the newly determined cycle frequency over the updated number of points in

its period to create the final curve fit for the cycle. When repeated from cycle to cycle, the assigned phase offsets of consistent consecutive cycles should be nearly constant.

An example of the cycle-by-cycle fit on filtered data is shown in Figure 5.4. Each different colored line represents an individual cycle fit, which are able to capture the behavior of each cycle of the filtered signal until the irregular region around time 133. The benefit of this method of curve fitting is that the irregular region no longer affects the fitting of the cycles before it. However, it drives the need for a local solution, where only the first 5 signals in this run are averaged to assign a phase offset for the signal. This is not ideal, but, it is clear that no single phase offset can be assigned to the whole signal. The time that the signal appears to be consistent will be the time interval over which it is analyzed to determine the phase offset.

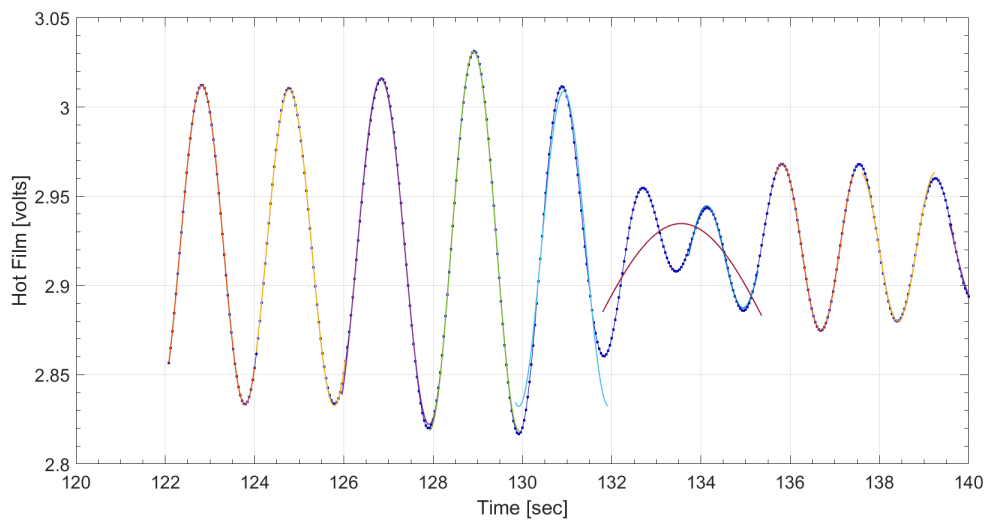


Figure 5.4. Time history of Reynolds number 300 post-perturbation flow with segmented curve fits each individual cycle with variable frequency. Each curve fit is represented by the various colors.

Once the pre-perturbation and post-perturbation cycle-by-cycle curve fits were finished, the phase difference is calculated as $\Delta\phi = \phi_2 - \phi_1$ where ϕ_1 and ϕ_2 are the phase angles from the consistent portions of the pre- and post-perturbation signals, respectively. $\Delta\phi$ is the curve-fit equivalent of $g(\theta; I)$ as defined in Chapter 1 because it is the measurement of the phase difference between signals.

5.3 Hilbert Transform Method

The second method this investigation examined was the use of the Hilbert transform, using the built in Matlab function in the signal processing toolbox. The broadband nature of the signal makes it difficult to extract useful information without filtering. To make the signal usable, the same band-pass filter was applied to the raw wake velocity data before performing the Hilbert transform. Additionally, the data must be shifted to have a zero mean before applying the Hilbert transform. The resulting data has a real and imaginary part for each point. Calculating the angle in the complex plane for each pair gives the instantaneous phase angle, which corresponds to $(\omega t + \phi)$ in Eqn. 5.2. The PIP, θ , is the instantaneous phase angle at the time of perturbation.

The calculation of $\Delta\phi$ is slightly different in the Hilbert method, as there are now phase angles at every given point in time history rather than phase offsets being assigned to each cycle. To calculate a phase offset at any point, the instantaneous phases can be subtracted at their corresponding points in time. However, given the fact that the signals take place over two separate time periods, the phase angles cannot be compared directly. This is because there is no way to determine how the signals "line up" in time to subtract their instantaneous phase angles. Therefore, a baseline sine wave with zero phase offset is created for each signal at their starting times. Subtracting each baseline sine wave's instantaneous phase from the respective signal's instantaneous phase gives the phase offset for each signal that can then be subtracted from each other to produce the phase difference. This phase difference is represented as $g^*(\theta, t)$, instead of simply $g(\theta)$, since the phase difference varies over time.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 6:

Results and Discussion

Based on the challenges of a non-constant shedding frequency and irregular regions in the flow, the effectiveness of the previously described analysis techniques vary depending on the run. The accuracy of the measurements of θ and $\Delta\phi$ are reliant on the quality and consistency of the signal around the time of perturbation. Therefore, the generated phase-sensitivity function is the best estimate for the given data, but may not be accurate enough to validate numerical results. The following results for the curve-fit and Hilbert methods are shown utilizing two separate runs, in an effort to demonstrate how the analysis process can be successful for some runs, but unsuccessful for others.

6.1 Curve-Fit Results

As noted, the variability of the frequency between cycles is a challenge to the curve fitting technique. Figure 6.1 shows the frequencies of curve fits over time for two different post-perturbation signals. Each data point represents the frequency of the best curve fit for that particular cycle, and the black line represents the determined shedding frequency for the signal from an FFT. The less suitable run, (a), shows a higher amount of variation in the first few cycles right after the perturbation compared to the more suitable run (b). The more successful runs show consistency in the frequency over a larger number of consecutive cycles right before and right after the perturbation, which is the region of interest. Though the less suitable run shows various regions of consistency in the signal, they are later in time which is away from the region of interest. Each of the first five cycles shows a significant difference in frequency from the cycles before or after them. Meanwhile, the signal in (b) shows nearly 10 cycles of fairly consistent frequency before a significant change.

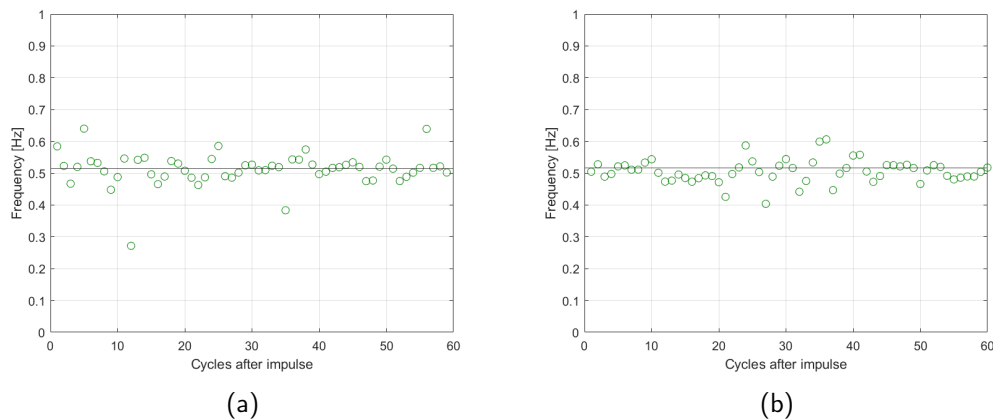
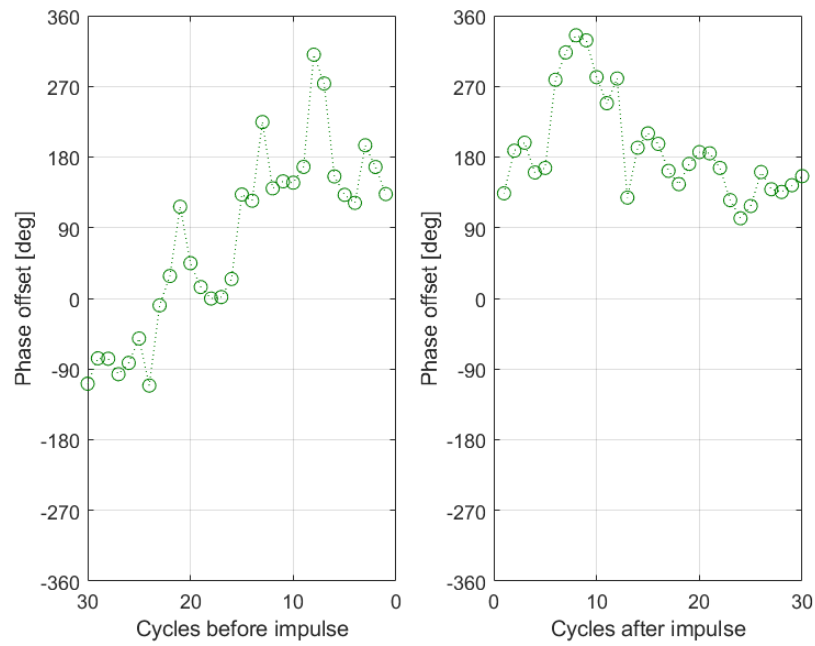
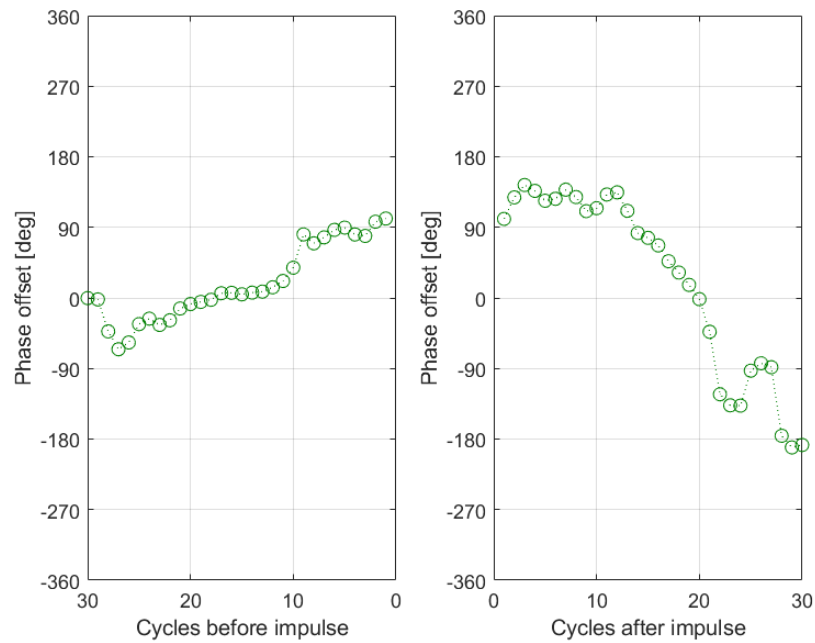


Figure 6.1. The determined frequency of each cycle of a post-perturbation signal for (a) a less suitable run and (b) a more suitable run at Reynolds number 300.

The consistency of the calculated frequencies over multiple cycles tends to be an indicator of the consistency of the measured phase offsets over those same cycles. The plots in Figure 6.2 show the assigned phase offsets by cycle for the same two runs, both for the pre-perturbation and post-perturbation signals. The pre-perturbation signal in (a) shows a change of about 75 degrees over the last three cycles before the impulse. The post-perturbation phases show moderate consistency from cycles two to five, within a range of about 60 degrees. This makes it difficult to assign a single accurate value to the phase offset just before and after the perturbation. On the other hand, in (b), there is enough consistency just prior to and just after the impulse to estimate the change in the phase offset caused by the impulse. It appears that the approximately eight cycles before and after impulse show consistent enough behavior to assign a single, average phase offset to both the pre- and post-perturbation portions of the signal.



(a)

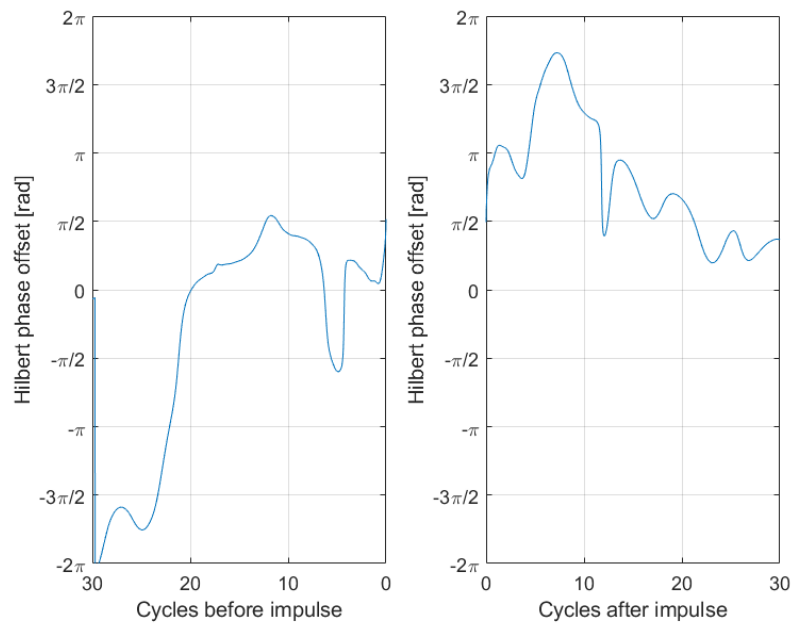


(b)

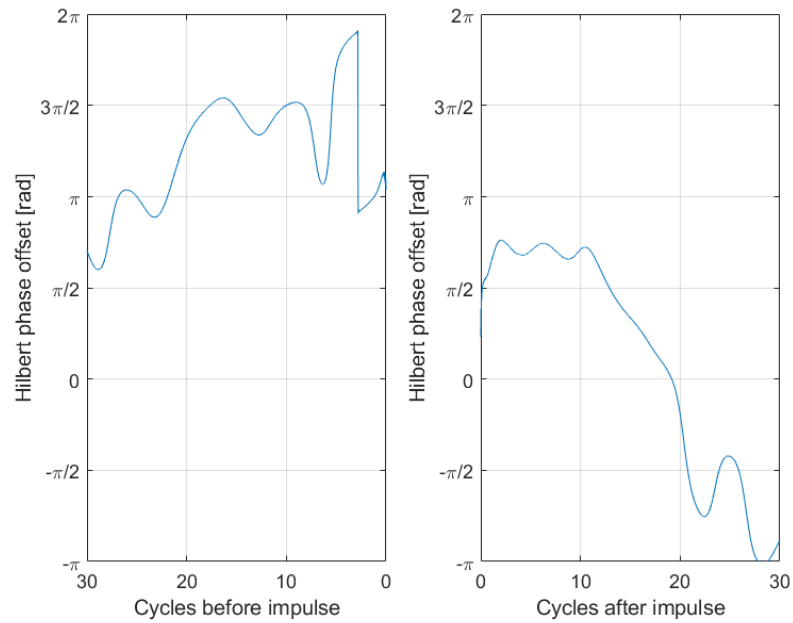
Figure 6.2. The determined phase offset on a cycle by cycle basis for the pre- and post-perturbation signals of (a) a less suitable run and (b) a more suitable run at a Reynolds number 300.

6.2 Hilbert Transform Results

Because the underlying signal is the same, the Hilbert Transform results are not expected to be significantly different than the curve fitting method results. However, since the Hilbert transform method is producing instantaneous phase angles at every data point, it does not have any potential error from the partitioning of the signal into exact single cycles. Figure 6.3 shows the phase offset, relative to a sine wave, for the same pre- and post-perturbation signals displayed previously in Figure 6.2 (a) and (b). Looking at both signals in the local region around the perturbation, signal (b) generally shows more consistency than signal (a) which was demonstrated in the curve fit method.



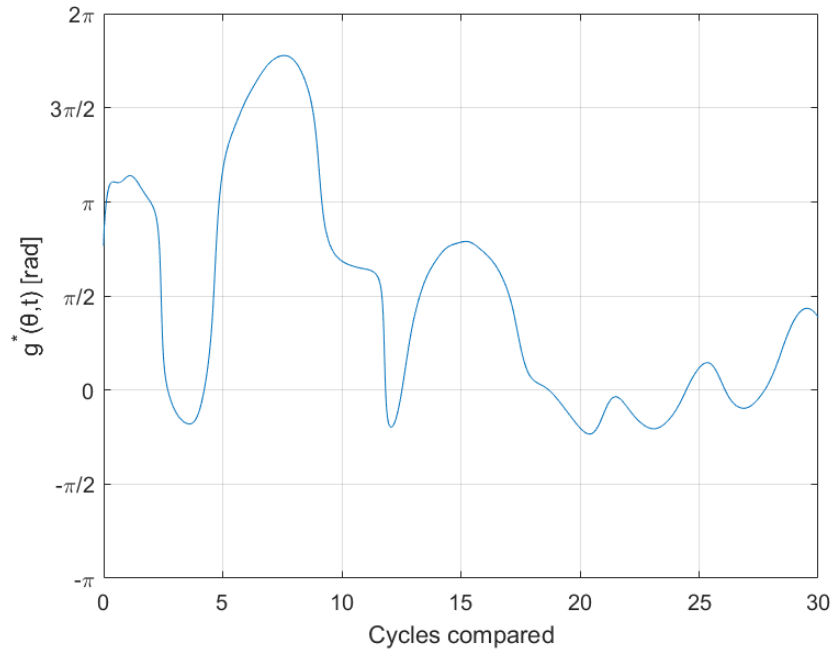
(a)



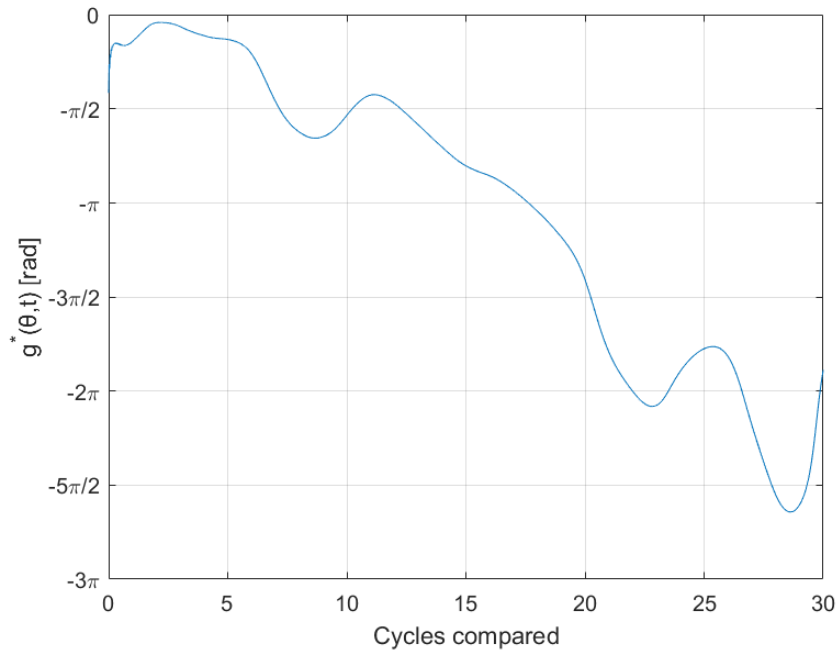
(b)

Figure 6.3. The calculated phase offset, relative to sine wave, by the Hilbert method for the pre- and post-perturbation signals of (a) a less suitable run and (b) a more suitable run at Reynolds number 300.

As the pre-perturbation Hilbert transform produced phase offsets represent the same value as ϕ_1 , they are then subtracted from their respective post-perturbation Hilbert transform phase offsets, ϕ_2 . This difference forms $g^*(\theta, t)$, which is the Hilbert equivalent of the $\Delta\phi$ function but over time during a single run. Using the full $g^*(\theta, t)$ result, an average is taken to get a single value for $g(\theta)$ for each run. In the ideal case, the result over time would be a constant value when both the pre- and post-perturbation signals have a constant phase offset over time. However, it has been demonstrated that each signal has varying levels of consistency in phase offset. Therefore, small regions of consistent behavior just before and just after the perturbation are the areas of interest for estimating the average phase difference, for each particular run. The corresponding $g^*(\theta, t)$ for the runs previously shown are contained in Figure 6.4. In (b), the region of approximately 1 to 7 cycles shows how the Hilbert analysis can produce a quality estimate for the phase difference. The value only changes slightly over this region, giving greater confidence that it is accurately able to represent the difference between the pre- and post-impulse vortex shedding phases. For (a), there is very little evidence of any identifiable consistent region in the first 1 to 10 cycles. The value fluctuates over almost 2π radians making the assignment of a single phase difference far less certain for this run.



(a)



(b)

Figure 6.4. The calculated $g^*(\theta, t)$ function by the Hilbert method for (a) a less suitable run and (b) a more suitable run at Reynolds number 300.

The average $g^*(\theta, t)$ for each individual run is represented at the corresponding PIP on the following plot of $g(\theta)$. The region of $g^*(\theta, t)$ to average for the assignment of a phase difference was determined on a run by run basis. Therefore, the confidence interval of each data point is affected by the variability in $g^*(\theta, t)$ as well as the size of the region used for calculating the average value for $g(\theta)$. Figure 6.5 shows the $g(\theta)$ function over all of the translational cases. The red data shows case T1 while the green data shows case T2 and the blue data shows case T3. The uncertainty bars represent a 95% confidence interval on the reported mean value taken from the $g^*(\theta, t)$ function. The black dashed curve shows the approximate shape of the $g(\theta)$ function from the data points.

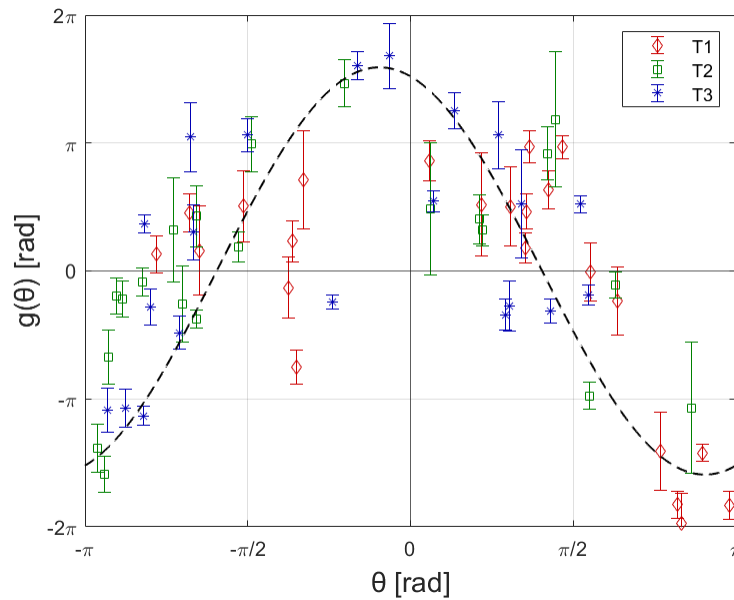


Figure 6.5. Calculated phase-sensitivity function for all translational cases at Reynolds number 300.

All of the previous examples have been from translational runs. However, the same analysis process was applied to the rotational impulse cases, with a $g(\theta)$ shown in Figure 6.6 for rotational case R3. Again, the black dashed line represents the estimated shape of the $g(\theta)$ function from the given data.

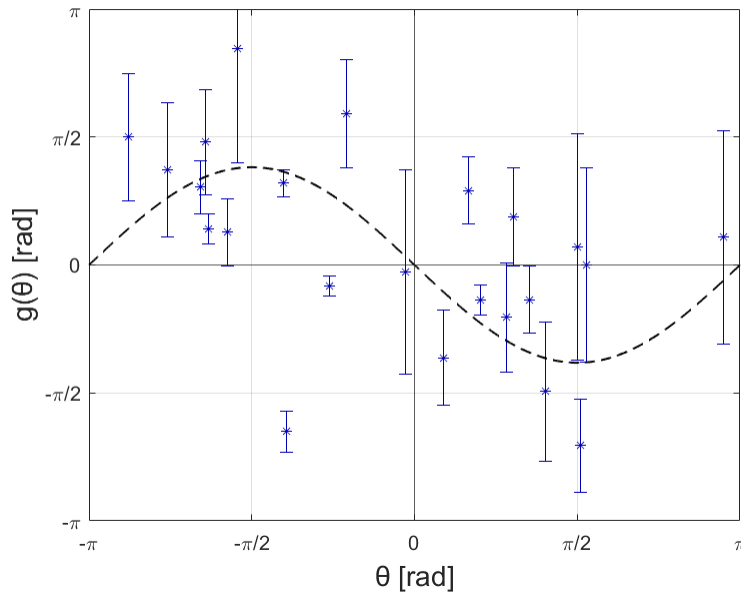


Figure 6.6. Calculated phase-sensitivity function for rotational case R3 at Reynolds number 300.

6.3 Alternate Reynolds Numbers Exploration

The results have shown some challenges in the ability to consistently determine phase information from a fluid's wake velocity across multiple runs. However, this study focused on testing at a Reynolds number of 300 to support UCLA's numerical validation study, done at that Reynolds number. To briefly examine the characteristics of other Reynolds numbers, a small number of runs were collected and examined for Reynolds numbers of approximately 200 and 1000. The respective pre-perturbation unfiltered time histories are shown in Figures 6.7 and 6.8. From the comparison of the two signals, it is clear that the higher Reynolds number flow is subject to more high-frequency noise and more irregular regions in the collected CTA signal. It appears to be less consistent than the lower Reynolds number wake velocity signal. Following the same trend, the lower Reynolds number of 200 signal provides more consistent behavior than the Reynolds number 300 cases displayed previously. It has identifiably consistent shedding and very few regions of irregular behavior. This trend suggests that lower Reynolds number experimental testing may provide data that is more suitable to a global solution due to less disruption in the signal.

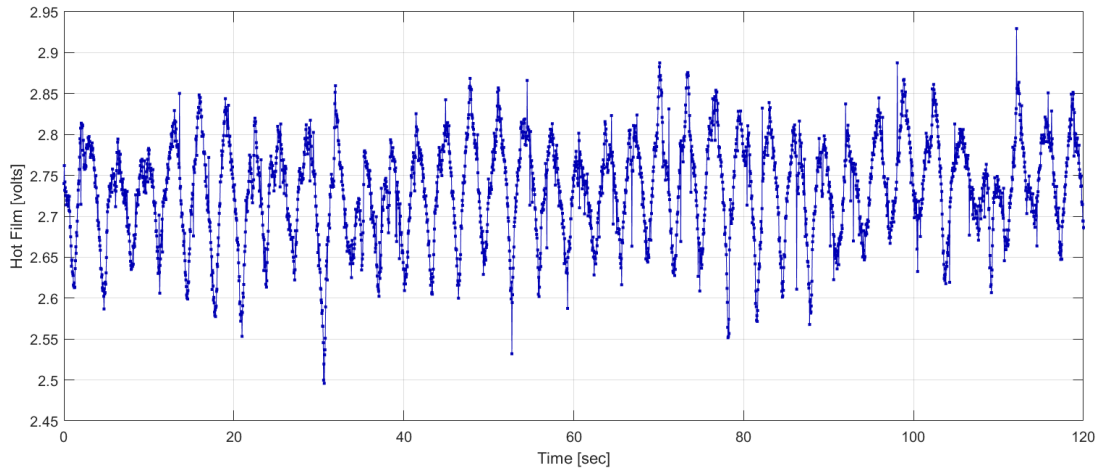


Figure 6.7. Time history of Reynolds number 200 pre-perturbation signal.

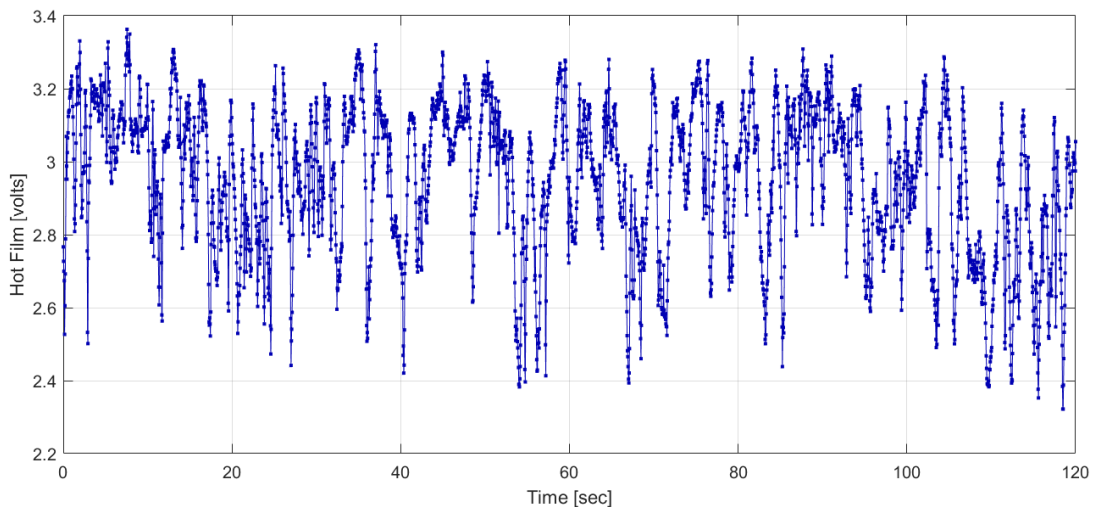


Figure 6.8. Time history of Reynolds number 1000 pre-perturbation signal.

The Reynolds number 200 case also shows promise when initially analyzing the frequencies on a cycle-by-cycle basis. Figure 6.9 shows the same cycle-by-cycle frequency determination as was shown in Figure 6.1, but for Reynolds numbers 200 (a) and 1000 (b). The plot shows that the Reynolds number 200 run has drastically less variability in cycle by cycle frequency as compared to both the Reynolds number 300 and 1000 cases. This is a promising sign for future calculations of phase offsets. It is of note that the Reynolds number 1000 case used a larger cylinder diameter in order to lower the shedding frequency. This lower shedding

frequency seems to provide similar regions of consistency as with the Reynolds number 300, but still suffers from disruptions in the underlying signal.

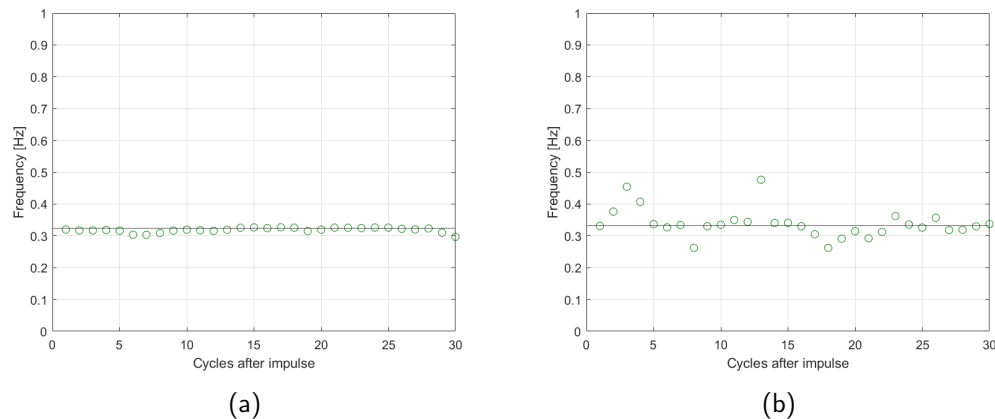
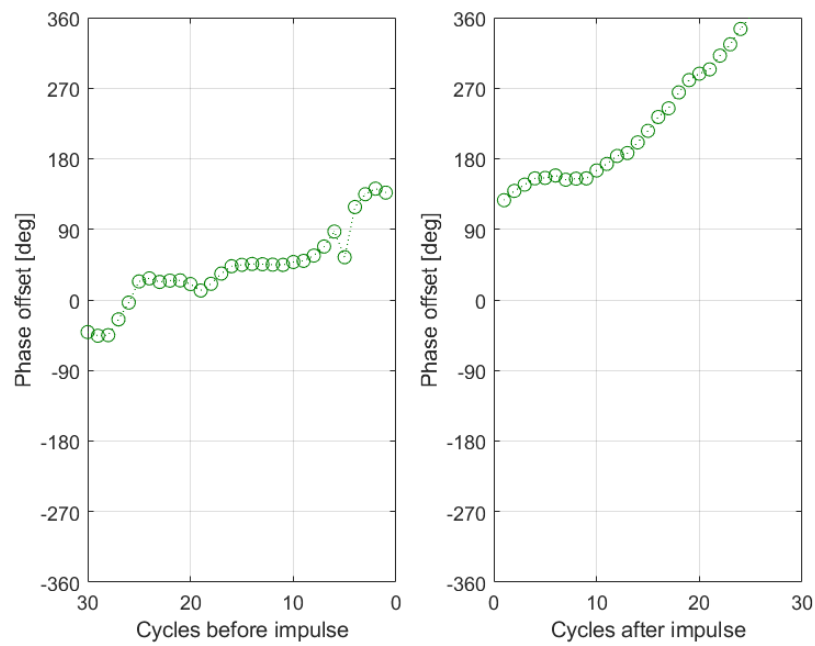
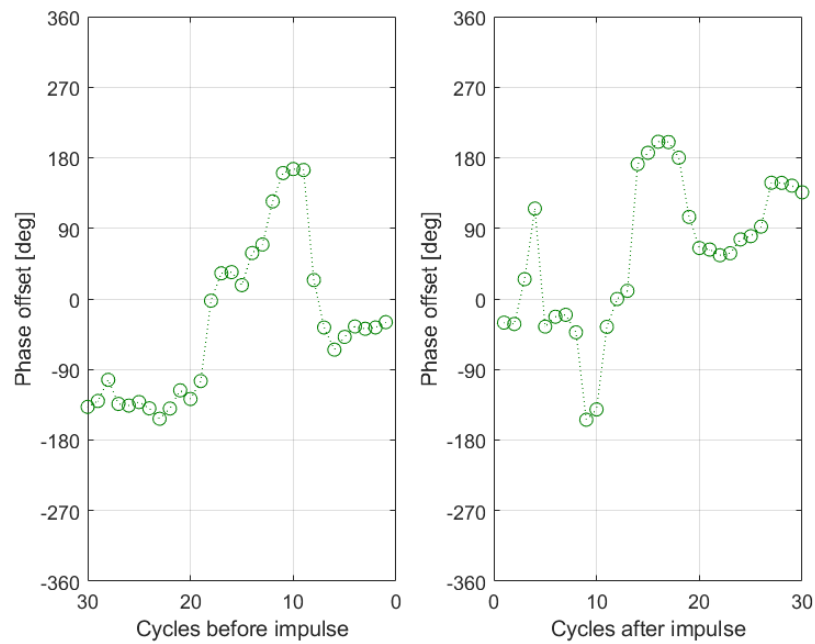


Figure 6.9. The determined frequency of each cycle of a post-perturbation signal for Reynolds number (a) 200 and (b) 1000 runs.

The consistency of cycle-by-cycle frequency across cycles for the Reynolds number 200 results indicates that the signal is far more stable across longer time periods. This is confirmed by Figure 6.10, which shows the phase offsets from the cycle-by-cycle method for both Reynolds numbers. Reynolds number 1000 (b) shows similar results to the previously shown Reynolds number 300 runs, with a very short region around the time of perturbation that could be averaged. The Reynolds number 200 phase offset shows a much longer consistent region just after the perturbation. The slow growth calculated of the phase offset over time is likely partially due to the imperfection of the cycle-by-cycle fitting process, compounding over time.



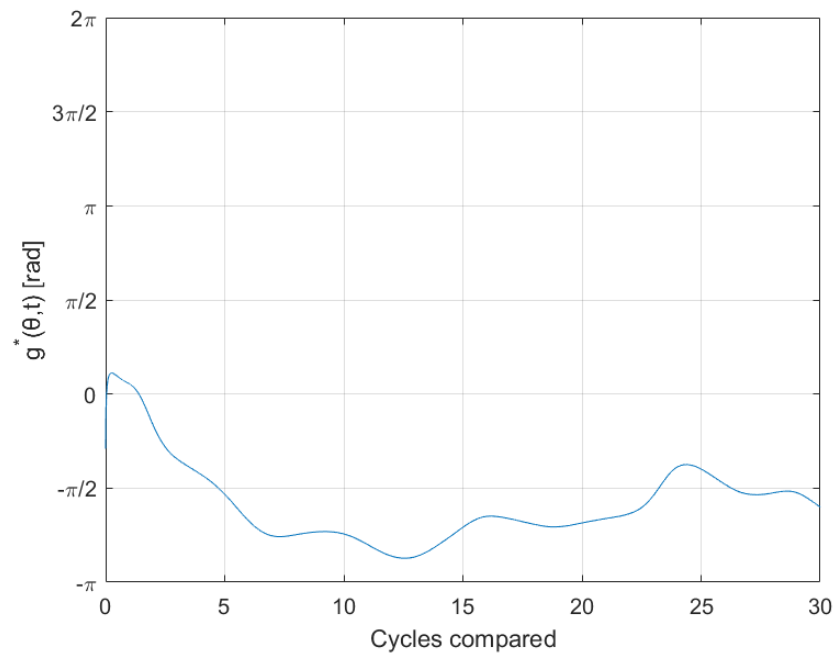
(a)



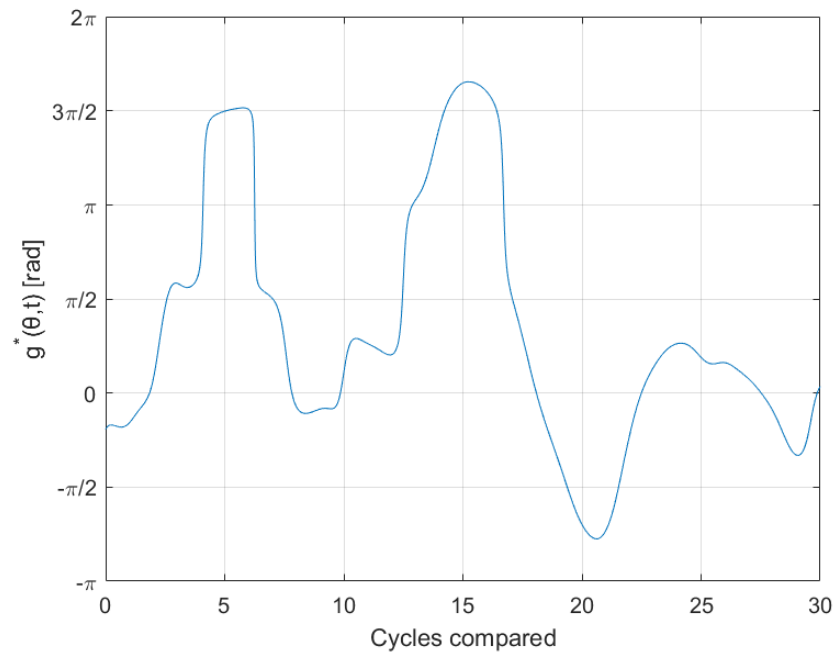
(b)

Figure 6.10. Assigned phase angles for individual cycles for Reynolds number (a) 200 and (b) 1000 curve fits.

The easiest way to see the phase quality of the signal is by looking at the $g^*(\theta, t)$ function, shown in Figure 6.11. For the $g^*(\theta, t)$ shown, Reynolds number 200 in (a) shows a much more reasonable phase difference over time. This run does not show a very large consistent region around the time over perturbation, however, the signal shows an much less variable signal throughout. This suggests the possibility of being able to obtain a $g^*(\theta, t)$ that is near constant for a global solution. The Reynolds number 1000 results in (b) show a significant amount of disruptions and are similar in quality to the Reynolds number 300 results. This reinforces the concept that the lower shedding frequency of the signal seems to provide more consistency in phase offset, but the three-dimensionality of the higher Reynolds number flow negatively impacts the amount of disruptions within the signal.



(a)



(b)

Figure 6.11. Calculated $g^*(\theta, t)$ function for Reynolds numbers (a) 200 and (b) 1000.

CHAPTER 7:

Concluding Remarks

7.1 Fundamental Challenges

As demonstrated in the results section, irregular regions in the flow that disrupt the wake velocity signal create the need for a localized phase offset determination. These disruptions appear to be more frequent with an increase in Reynolds number, likely due to three-dimensionality of the flow. This reduces the quality of the measured fluid velocity by the hot-film sensor. Therefore, low Reynolds number experiments provide the highest probability of being able to compute a global solution for the phase difference between the entire pre- and post-perturbation signals.

The variability of the vortex shedding frequency over consecutive periods is the fundamental challenge to analyzing wake data to calculate phase information. This is still an issue even in the small regions before and after the perturbation that are not disrupted. For the cycle-by-cycle curve fitting approach, changes in frequency introduce a small amount of error in the number of data points that make up one single complete period for which each cycle is fit. Including slightly too many or too few points in the fit along with re-zeroing the starting time of each fit causes the phase offset determined by the least-squares fit to contain an error. This small error adds up over many cycles to become problematic. For the Hilbert transform method, the instantaneous phase angles are being compared to the phase angle of a baseline sine wave with a constant frequency. This comparison between a variable frequency signal and constant frequency signal inherently cause the estimated phase offset relative to the baseline signal to be changing instead of a constant value. As the frequency of a signal approaches a constant value across cycles, the phase offset difference becomes closer to being constant, as shown by the Reynolds number 200 case.

7.2 Conclusions

This thesis has demonstrated the challenges of determining accurate phase information from experimental wake velocity data at Reynolds number 300. The overall periodic behavior, and

approximate shedding frequency of the wake, is easily identifiable. However, the phase of the signal seems to be incredibly sensitive to even slight inconsistencies in the flow in the form of irregular regions and variable shedding frequency. While it is still possible to analyze the data and produce a phase-sensitivity function, the results have large amounts of uncertainty. The collection of a large number of runs has documented irregular regions throughout the signal as well as the variability of the measured shedding frequency within the same flow. These inconsistencies create error in the determination of both ϕ_1 and ϕ_2 , as a single phase offset cannot apply over many cycles at these flow conditions. However, the analysis process described, has demonstrated limited success in the ability to analyze Reynolds number 300 data, subject to the stability of the flow around the time of perturbation.

Based on the observed trend that increasing the Reynolds number causes an increase in the range of values to capture the phase offset during a run, it is likely that the difficulty in determining phase dynamics for these signals stems from the increase in three-dimensional behavior in the wake. As the Reynolds number increases, wake structures become more complex and three-dimensional. These create inconsistent results in the collection of wake velocity data at a single point with the hot film probe. Increasingly complex behavior would likely require a more robust method of data collection to possibly examine the phase dynamics of even slightly three dimensional wakes.

7.3 Future Work

Though the generation of a phase-sensitivity function proved difficult at Reynolds number 300, future work should examine the same process for lower Reynolds numbers with lower shedding frequencies to confirm the potential effects of three dimensional flow and shedding frequency on the determination of the signal phase from wake velocity data. Follow on studies should focus on Reynolds number 200 or lower data to examine phase. They should also examine the effects of shedding frequency by holding a constant low Reynolds number over a variety of cylinder diameters.

For Reynolds number 300 or higher flows with relatively high shedding frequency, follow on studies can be conducted to explore a strategy of directly measuring the resultant forces on a cylinder from vortex shedding rather than measuring the wake velocity. This would likely require a significant increase in the Reynolds number so that a sufficiently large force

is generated on the cylinder. This strategy would reduce the challenges faced with wake velocity data and may result in a more consistent signal to determine phase dynamics.

THIS PAGE INTENTIONALLY LEFT BLANK

List of References

- [1] V. Strouhal, “On a special kind of toner excitation,” *Annals of Physics*, vol. 241, no. 10, pp. 216–251, 1878 [Online]. Available: <https://hdl.handle.net/2027/uc1.b4433702>
- [2] J. Cooper, “Aeroelastic response,” in *Encyclopedia of Vibration*, S. Braun, Ed. Elsevier, 2001 [Online]. Available: <https://doi.org/10.1006/rwvb.2001.0125>
- [3] A. Roshko, “On the development of turbulent wakes from vortex streets,” NASA, Tech. Rep. NACA-TR-1191, 1954 [Online]. Available: <https://ntrs.nasa.gov/citations/19930092207>
- [4] J. Klamo, “Effects of damping and Reynolds number on vortex-induced vibrations,” Ph.D. dissertation, California Institute of Technology, Pasadena, CA, USA, 2007 [Online]. Available: <https://resolver.caltech.edu/CaltechETD:etd-11292006-120631>
- [5] O. Wehrmann, “Reduction of velocity fluctuations in a Karman vortex street by a vibrating cylinder,” *The Physics of Fluids*, vol. 8, no. 4, pp. 760–761, 1965 [Online]. Available: <https://doi.org/10.1063/1.1761299>
- [6] G. Koopmann, “The vortex wakes of vibrating cylinders at low Reynolds numbers,” *Journal of Fluid Mechanics*, vol. 28, no. 3, pp. 501–512, 1967 [Online]. Available: <https://doi.org/10.1017/S0022112067002253>
- [7] N. Ferguson, “The measurement of wake and surface effects in the subcritical flow past a circular cylinder at rest and in vortex-excited oscillation,” MASc Thesis, University of British Columbia, Vancouver, BC, CA, 1965 [Online]. Available: <http://hdl.handle.net/2429/37776>
- [8] T. Sarpkaya, “Vortex-induced oscillations: A selective review,” *Journal of Applied Mechanics*, vol. 46, no. 2, pp. 241–258, Jun. 1979 [Online]. Available: <https://doi.org/10.1115/1.3424537>
- [9] O. M. Griffin and S. E. Ramberg, “Some recent studies of vortex shedding with application to marine tubulars and risers,” *Journal of Energy Resources Technology*, vol. 104, no. 1, pp. 2–13, Mar. 1982 [Online]. Available: <https://doi.org/10.1115/1.3230377>
- [10] P. W. Bearman, “Vortex shedding from oscillating bluff bodies,” *Annual review of fluid mechanics*, vol. 16, no. 1, pp. 195–222, 1984 [Online]. Available: <https://www.annualreviews.org/doi/pdf/10.1146/annurev.fl.16.010184.001211>

- [11] E. Naudascher and D. Rockwell, *Flow-Induced Vibrations: An Engineering Guide*. Mineola, NY, USA: Dover Publications, 2005.
- [12] G. Parkinson, “Phenomena and modelling of flow-induced vibrations of bluff bodies,” *Progress in Aerospace Sciences*, vol. 26, no. 2, pp. 169–224, 1989 [Online]. Available: [https://doi.org/10.1016/0376-0421\(89\)90008-0](https://doi.org/10.1016/0376-0421(89)90008-0)
- [13] C. H. Williamson and R. Govardhan, “Vortex-induced vibrations,” *Annu. Rev. Fluid Mech.*, vol. 36, pp. 413–455, 2004 [Online]. Available: <https://doi.org/10.1146/annurev.fluid.36.050802.122128>
- [14] T. Sarpkaya, “A critical review of the intrinsic nature of vortex-induced vibrations,” *Journal of fluids and structures*, vol. 19, no. 4, pp. 389–447, 2004 [Online]. Available: <https://doi.org/10.1016/j.jfluidstructs.2004.02.005>
- [15] M. Khodkar, J. T. Klamo, and K. Taira, “Phase-locking of laminar wake to periodic vibrations of a circular cylinder,” *Physical Review Fluids*, vol. 6, no. 3, pp. 034 401–2, 2021 [Online]. Available: <https://doi.org/10.1103/PhysRevFluids.6.034401>
- [16] T. Sarpkaya, *Wave forces on offshore structures*. New York, NY, USA: Cambridge university press, 2010.
- [17] O. Reynolds, “An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels,” *Philosophical Transactions of the Royal society of London*, no. 174, pp. 935–982, 1883 [Online]. Available: <https://doi.org/10.1098/rstl.1883.0029>
- [18] B. E. Rapp, *Microfluidics: Modelling, mechanics and mathematics*. Elsevier Oxford, UK, 2017.
- [19] K. Taira and H. Nakao, “Phase-response analysis of synchronization for periodic flows,” *Journal of Fluid Mechanics*, vol. 846, p. 2, 2018 [Online]. Available: <https://doi.org/10.1017/jfm.2018.327>
- [20] *Series TFXD transit time ultrasonic flow meter operations and maintenance manual*, Racine Federated Inc., Racine, WI, USA, May. 2013 [Online]. Available: https://www.instrumart.com/assets/Dyna_TFXD_Manual.pdf
- [21] *TSI thermal anemometry probes*, TSI Inc., Shoreview, MN, USA, 2007 [Online]. Available: https://tsi.com/getmedia/2e3fafd5-8037-40a9-aa38-4fa05a1d3ef3/Hotwire_Catalog_2980465?ext=.pdf

Initial Distribution List

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California



DUDLEY KNOX LIBRARY

NAVAL POSTGRADUATE SCHOOL

WWW.NPS.EDU

WHERE SCIENCE MEETS THE ART OF WARFARE