Study of Fluid-Structure Interactions of Communication Antennas

by

Maby Boado Amador

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Mechanical and Industrial Engineering
University of Toronto

©Copyright by Maby Boado 2011
Study of Fluid-Structure Interactions of Communication Antennas

Maby Boado Amador

Master of Applied Science

Mechanical and Industrial Engineering
University of Toronto

2011

Abstract

Large structures exposed to the environment such as the collinear omni and large panel communication antennas in this research suffer damage from cyclic wind, rain, hail, ice load and impacts from birds and stones. Stresses from self-weight, ice loading and wind gusts will produce deformations of the structure that will lead to performance deterioration of the antenna. In order to avoid such a case, it is important to understand the static, dynamic and aerodynamic behavior of these structures and thus optimization can be achieved. In this research the current fluid-structure interaction methods are used to model, simulate and analyze these communication antennas in order to assess whether failure would occur under service loads. The FEA models developed are verified against analytical models and/or experiments. Different antenna configurations are compared based on their capacity to minimize vibration effects, stress-induced deformations and aerodynamic loading effects.
In Loving Memory of my Grandparents
Rafael and Aida
Acknowledgments

Without such a patient, understanding, and caring mentor this work would not have been possible. Thus, I would like start by thanking Professor Jean Zu for taking me under her wing and allowing me to grow as a researcher. Her example is, without a doubt, one to follow. I could not have asked for a better supervisor! I would also like to acknowledge the members of my committee: Professor William Cleghorn and Professor Axel Guenther; I am fortunate to have such a wealth of knowledge at my fingertips.

My appreciation to my husband Yariel is immense. His constant support, his words of encouragement and consolation in times of stress and his loving care made my journey through graduate studies much easier and enjoyable. My parents deserve a special mention: my mother for her unconditional dedication and support through my life so I would become the strong and responsible woman I am today and my father for providing me with the opportunity to be where I am, for his technical support and for being a role model to me and my brother. They have always been my biggest fans and I really appreciate that.

I would like to extend my gratitude to all my colleagues in the MIE department, especially to Reza Farshidi, Roshanak Banan and Mohammad Movassat for their technical advice in different aspects of my work. Our many conversations furthered my graduate career at the University of Toronto. I would also like to thank Sinclair Technologies for providing this interesting project and their facilities and resources for experimentation. Special thanks go to Rudy Riemann and Kang Lan for sharing with me their valuable technical experiences.

Last, but not least, this work could not have been possible without the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), Canadian Graduate Scholarship (CGS), MITACS Accelerate, Sinclair Technologies and the University of Toronto. Thank you for believing that we, graduate students, can make a difference.

Sincerely,

Maby Boado
# Table of Contents

List of Tables ................................................................................................................................ vii
List of Figures .................................................................................................................................. viii
List of Appendices ......................................................................................................................... xiii
List of Symbols, Abbreviations and Nomenclature ........................................................................ xiv

Chapter 1 Introduction .................................................................................................................... 1
  1.1 Background and Motivation ............................................................................................... 1
  1.2 Contribution and Objectives ............................................................................................ 5
  1.3 Thesis Overview ................................................................................................................. 5

Chapter 2 Literature Review .......................................................................................................... 7
  2.1 Fluid-Structure Interaction Problems .............................................................................. 7
  2.2 Bluff Body Aerodynamics ............................................................................................... 11
  2.3 Flow-induced Vibrations .................................................................................................. 15

Chapter 3 Modeling and Simulation of SC Series Antennas ....................................................... 20
  2.4 Physical and Material Properties ..................................................................................... 22
    2.4.1 Manufacturer’s Specifications .................................................................................. 23
    2.4.2 Cantilever Force Test and Simulation on the SC281 Antenna .............................. 24
  2.5 Steady Deformation State Analysis .................................................................................. 28
    2.5.1 Fluid Structure Interaction Models ........................................................................ 29
    2.5.2 Validation of the FSI Models ............................................................................... 37
  2.6 Transient Response due to Wind Gusts .......................................................................... 42
    2.6.1 Fluid Structure Interaction Models ........................................................................ 43
    2.6.2 Modal Analysis ....................................................................................................... 48
    2.6.3 Vibration Experiment on the SC279 Antenna ...................................................... 50
  2.7 Wake Induce Transient Response .................................................................................... 54
  2.8 Summary ........................................................................................................................... 60
List of Tables

Table 1: Summary of physical properties of the SC Series Antennas .......................................... 23
Table 2: Summary of material and mechanical properties of the SC Series Antenna ............... 24
Table 3: Summary of mesh statistics for all configurations ......................................................... 31
Table 4: Physical flow model based on Reynolds number ........................................................... 32
Table 5: Summary of results of SC281 configuration ................................................................. 33
Table 6: Summary of results of all antenna configurations .......................................................... 36
Table 7: Comparison of natural frequencies for all SC Series antenna configurations .......... 48
Table 8: Comparison of natural frequencies of vibrations for the SC279 antenna ................. 53
Table 9: Critical regions of resonance for the SC Series antennas ............................................. 56
Table 10: Geometrical properties of main structural components of the SP304 antenna ......... 65
Table 11: Material properties of main structural components of the SP304 antenna .......... 66
Table 12: Aerodynamic results of CFD models ........................................................................... 69
Table 13: Nodes and elements for each component of the SP304 antenna .............................. 73
Table 14: Case analysis with 60m/s wind and 1.27mm radial ice load as parameters .......... 78
Table 15: Results for the SP304 antenna for angle of inclination -15deg to +15deg .......... 81
List of Figures

Figure 1: Photograph of (a) the SP304 and (b) the SC412 antennas (courtesy of Sinclair Tech) .. 4

Figure 2: One-dimensional example of Lagrangian, Eulerian and ALE mesh and particle motion 9

Figure 3: Fluid-structure transfer of information ........................................................................ 10

Figure 4: Illustration of Bernoulli’s principle ........................................................................... 12

Figure 5: Strouhal number as a function of the Reynolds number for circular cylinders ......... 13

Figure 6: Graphical illustration of the boundary layer theory .................................................... 14

Figure 7: Reynolds number dependence of drag coefficient for circular cylinder [81] ............ 16

Figure 8: Cylinder pressure distribution for different Reynolds numbers [82] ....................... 16

Figure 9: Buffeting by the wake of an upstream structure ....................................................... 17

Figure 10: Plot of vortex-shedding frequency versus flow velocity ....................................... 18

Figure 11: SC281 antenna (courtesy of Sinclair Tech.) ............................................................ 20

Figure 12: Definition of the structural system .......................................................................... 21

Figure 13: Mounting system for the SC Series antenna ............................................................ 23

Figure 14: Cantilever test set-up on SC281 antenna (courtesy of Sinclair Tech.) ................. 25

Figure 15: Set-up details (a) clamps and (b) load cell (courtesy of Sinclair Tech.) ............... 25

Figure 16: Failed SC281 sample (courtesy of Sinclair Tech.) .................................................. 26
Figure 17: Analysis settings for cantilever test.......................... 27
Figure 18: Safety factor result for cantilever simulation of SC281.............................................. 27
Figure 19: Cantilever force test results ........................................ 28
Figure 20: Interpolation of information between dissimilar meshes at the domain's interface .... 29
Figure 21: Computational domain for the flow field (not to scale).............................................. 30
Figure 22: Sample mesh for solid and fluid domains of the SC281 configuration....................... 31
Figure 23: Dependency of drag force and drag coefficient on fluid speed................................. 34
Figure 24: Contour plot of pressure distribution on the SC281 antenna under 40m/s wind ...... 34
Figure 25: Deformation and von-Mises stress plots for the SC281 antenna under 40m/s wind .. 35
Figure 26: Relation between aspect ratio and lift, drag coefficient .............................................. 37
Figure 27: Drag coefficient as a function of Reynolds number.................................................. 38
Figure 28: Comparison of FEA and analytical drag force of the SC281 antenna ....................... 39
Figure 29: Maximum deformation results at the free-end of the SC281 antenna’s radome....... 41
Figure 30: Pressure distribution along the leading edge of cylinder for the SC279 ............... 41
Figure 31: Wind gust effect on the structure .............................................................................. 42
Figure 32: Process flow diagram for multi-field simulations with the ANSYS software .......... 44
Figure 33: Total displacement for the SC281 antenna under 76m/s wind gust............................. 45
Figure 34: Contour plots of structural results for the SC281 antenna under 76m/s wind gust..... 46
Figure 35: Total displacement for the SC281 antenna under 95m/s wind gust................. 47

Figure 36: Contour plots of structural results for the SC281 antenna under 95m/s wind gust..... 47

Figure 37: Connections between FSI and modal analyses with Workbench, ANSYS.............. 48

Figure 38: First five mode shapes for the SC281 antenna...................................................... 49

Figure 39: Set-up of the SC279 antenna vibration test............................................................. 51

Figure 40: Accelerometers and base positioning and clamping for the SC279 vibration test...... 52

Figure 41: Sine sweep vibration experimental results for the SC279 antenna ......................... 53

Figure 42: Oscillations motion due to flow induced vibrations.................................................54

Figure 43: Vortex shedding frequency dependence in wind speed for all SC series antennas..... 55

Figure 44: Displacement in the crosswind direction for the SC281 antenna under 11.8m/s wind 57

Figure 45: Displacement in the alongwind direction for the SC281 antenna under 11.8m/s wind 58

Figure 46: Velocity streamlines at different planes for the SC281 antenna under 11.8m/s wind 59

Figure 47: Eddy viscosity representation for the SC281 antenna............................................. 59

Figure 48: SP304 antenna (courtesy of Sinclair Tech.)............................................................ 63

Figure 49: Exploded and assembled CAD models of the SP304 UHF panel antenna ............ 64

Figure 50: Structurally relevant components of the SP304 antenna....................................... 64

Figure 51: Representation of flow around a bluff body............................................................ 67

Figure 52: Computational domain for the flow field............................................................... 68
Figure 53: Lift and drag forces contour plots for the SP304 antenna under 60m/s winds........... 70
Figure 54: Different views of the velocity streamlines of the SP304 antenna under 60m/s wind 70
Figure 55: Velocity vectors on two random planes of the SP304 antenna under 60m/s wind ..... 71
Figure 56: Pressure contour plot the SP304 antenna under 60m/s wind .................................. 71
Figure 57: Connections between components of the SP304 antenna ...................................... 72
Figure 58: Overall mesh and refinement around supporting plates edges of the reflector ........ 74
Figure 59: Supports and input loads for the FEM....................................................................... 74
Figure 60: Maximum deformation results for the 10m/s to 60m/s wind speed range ............... 75
Figure 61: Maximum von-Mises Stress results for the 10m/s to 60m/s wind speed range ......... 75
Figure 62: Deformation contour plots of the SP304 antenna under 60m/s wind...................... 76
Figure 63: Ice loading representation on the FEA model........................................................... 77
Figure 64: Total deformation of the antenna (a) without and (b) with ice loading ................. 78
Figure 65: Inclined configurations of the SP304 antenna (courtesy of Sinclair Technologies)... 79
Figure 66: Definition of sign convention.................................................................................... 80
Figure 67: Sample modified model configuration in the downtilt position............................ 80
Figure 68: Drag coefficient, maximum deformation and safety factor with varying inclination angles ................................................................................................................................. 81
Figure 69: Deformation contour plots of the SP304 antenna front cover............................. 82
Figure 70: Equivalent (von-Mises) stress contour plots for the reflector at maximum inclinations
....................................................................................................................................................... 83

Figure 71: Equivalent (von-Mises) stress contour plot at the supports for -15deg inclination..... 83

Figure 72: Different views of the flow around the inclined antenna ................................. 84

Figure 73: Vorticity contour plot for the antenna at 15deg inclination angle......................... 84

Figure 74: Mode shapes for the first seven natural frequencies of the SP304 antenna .............. 87
List of Appendices

Appendix A: SC412 Product Specifications..........................................................104

Appendix B: SP323 Product Specifications.........................................................105

Appendix C: SP281 Product Specifications.........................................................106

Appendix D: Sample Calculations for the Cantilever Experiment on SC281 Antenna......107

Appendix E: Deflection Prediction for Steady Deformation State of SC281 Antenna........108

Appendix F: SP304 Product Specifications..........................................................109

Appendix G: Sample Results form SP304 Initial Study........................................110

Appendix H: Modal Analysis Procedure for the SC Series Antennas.......................112
# List of Symbols, Abbreviations and Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Cross sectional area</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$C_{D_0}$</td>
<td>Amplified drag coefficient</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Lift coefficient</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>Turbulence constant</td>
</tr>
<tr>
<td>$D$</td>
<td>Outer diameter of circular cylinder</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>$F_D$</td>
<td>Drag force</td>
</tr>
<tr>
<td>$F_L$</td>
<td>Lift force</td>
</tr>
<tr>
<td>$f_n$</td>
<td>Natural frequency of vibration</td>
</tr>
<tr>
<td>$f_S$</td>
<td>Frequency of vortex shedding</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration</td>
</tr>
<tr>
<td>$I_o$</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>$I_F$</td>
<td>Fatigue importance factor</td>
</tr>
<tr>
<td>$k$</td>
<td>Turbulence kinetic energy</td>
</tr>
<tr>
<td>$L$</td>
<td>Characteristic length</td>
</tr>
<tr>
<td>$L_0$</td>
<td>Overhang beam length</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Total antenna length</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$P_{vs}$</td>
<td>Static pressure for fatigue design</td>
</tr>
<tr>
<td>$q$</td>
<td>Distributed load</td>
</tr>
<tr>
<td>$r$</td>
<td>Radial thickness of ice layer</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$St$</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>$V$</td>
<td>Mean fluid velocity relative to the body</td>
</tr>
<tr>
<td>$V_{cr}$</td>
<td>Critical speed</td>
</tr>
<tr>
<td>$V_X$</td>
<td>Component fluid velocity in x direction</td>
</tr>
<tr>
<td>$V_Y$</td>
<td>Component fluid velocity y direction</td>
</tr>
<tr>
<td>$V_Z$</td>
<td>Component fluid velocity z direction</td>
</tr>
<tr>
<td>$X$</td>
<td>Vibration amplitude</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>Displacement (vibration) signal</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Damping ratio</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Boundary layer thickness</td>
</tr>
<tr>
<td>$\delta_{\text{MAX}}$</td>
<td>Maximum beam deflection</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Turbulence kinetic energy</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic fluid viscosity</td>
</tr>
<tr>
<td>$\mu_t$</td>
<td>Turbulent viscosity</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic fluid viscosity</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The proliferation of wireless devices such as portable two-way radios, cellular telephones, personal digital assistants (PDA), GPS units and wireless networking has demanded substantial improvements of wireless communication technology. The most important element of a communication system is the antenna since it transmits and receives the electromagnetic waves. Antennas can be classified in different ways; common antenna types are dipole, monopole, isotropic radiator, horn, microstrip, reflector, lens, traveling-wave and frequency-independent [1]. Panel antennas are a type of reflector antenna in which an array of driven elements is mounted in front of a flat, metallic reflector [2]. These antennas can operate in ultra high frequency (UHF) bands, which are between 300 MHz and 3 GHz and have moderate to high gains. They have a clean appearance as they are generally enclosed by a radome, which is a waterproof structure that protects the antenna. They can be clamped to poles in different configurations and at any desired height. Collinear omni and large panel antennas have gained popularity for two way radio communications, usually using narrowband frequency modulation, but digital services are on the rise.

1.1 Background and Motivation

When designing, optimizing or just selecting a commercially available antenna, electromagnetic characteristics such as gain, radiation pattern and bandwidth are generally the most used parameters to judge the efficiency and adequacy of an antenna. Mechanical and structural characteristics generally fall to a second level of importance. However, as proven by Wang,
Duan and Qiu [3] and by Bahadori and Rahmat-Samii [4], deformations of the structure holding the antenna greatly affect the antenna’s electromagnetic characteristics. Many of these antennas are placed outside and thus they are exposed to environmental effects. Any distortions of the reflecting surface can make the electromagnetic waves differ in phase, which will result in decrease of gain [5].

There is research done in the optimization of electromagnetic properties of reflector antennas [4,6-9] and a few researchers have looked into the combined optimization of structural mechanics and electromechanics, but mainly for small parabolic antennas [3,10]. However, for large scale (several meters long) panel antennas, cyclic wind, rain, hail, and ice loading effects and impacts from birds and stones are much more damaging and have a more substantial effect on the performance of the antenna. Stresses from self-weight, ice loading and wind gusts will produce deformations of the structure that will lead to performance deterioration of the antenna. To my knowledge, no analysis has been performed on structural analysis and optimization of communication antennas.

At the present, design of the commercial supporting structure of panel antennas mainly relies on the trial and error method and common sense, which is an unpredictable and perhaps naïve design method. Therefore, manufacturers of these types of antennas, such as Sinclair Technologies, will greatly benefit from this research as they will be able to implement the results from this study in future designs.

Wind characteristics vary considerably with location, topography of surrounding terrain and time. In addition to a steady wind there are effects of gusts which last for few seconds and have a considerable effect in the structural performance of the antenna. Therefore, it is crucial to understand the interaction that exists between the antenna structure and the surrounding flow field in order to predict the deformations and stresses that this antenna will experience. By predicting the static and dynamic behaviour of the antenna under all service loads optimization will be possible.

Wind produces mainly three different types of effects on structure: static, dynamic and aerodynamic. The type of structure dictates its response to service loads. For instance, when the
structure deflects in response to wind load then the dynamic and aerodynamic effects should be analysed, in addition to static effect. In principle there are the following possibilities for this problem:

1. The wind load and ice build-up on the structure causes a steady deformation state.
2. The fluid flow leads to a time-dependent movement of the structure, which is caused by one of the following effects:
   (a) A transient wind field exists even far away from the structure (e.g., change in wind direction or in strength, sudden gust of wind).
   (b) Due to the shape of the structure, the flow becomes time-dependent in the wake of the structure (e.g., generation of a von Kármán vortex street past bluff bodies impinged with a constant wind).

This is a multiphysics problem since the fluid flow in a fluid domain has to interact with the structure in a solid domain. Therefore, in this thesis a computational fluid dynamic solver is combined with a computational structural dynamics solver in order to model these fluid-structure interactions around the antenna’s radome. Some of these phenomena involve a time-variant problem domain for the antenna system, which must be taken into consideration in order to accurately represent the physical interactions.

A fluid-structure interaction problem is a combination of two distinct physical parts: the flow field and the structural field. These parts require separate domains, meshes and numerical procedures to compute their respective solutions. In order for these domains to interact there is the need of an interface that allows data transfer between the domains. The transferring of data which are the boundary conditions is also an important feature of fluid-structure interactions [6]. It must be evident by now that to solve this problem it is essential to develop a numerical simulation as both analytical and experimental models are too complex.

It is difficult to develop analytical models of the system since interactions between the antenna and the surrounding flow fields, and between components, are complex. Experimental work is also limited by the amount and kind of data possible to collect from wind tunnel test. For instance, detailed flow fields and structural features, such as velocity field data, surface pressure and structural stresses, are very difficult to measure with experiments [7]. Furthermore,
numerical models and simulations can decrease time and costs associated with experimental approaches. These are the reasons why the structural analysis of these antennas will be mainly based on numerical simulations; however, it is always important to validate the simulations against experiments and/or analytical models.

The configuration of the Sinclair Technologies’ SP Series will be utilized as the most complex model and ultimate goal for the analysis; however, other simpler models such as the SC Series will be also analyzed and used as validation stages, since experimental data and simple analytical validation models are available for those. Figure 1 shows photographs of these antennas.

![Figure 1: Photograph of (a) the SP304 and (b) the SC412 antennas (courtesy of Sinclair Tech)](image)

ANSYS commercial suite will be used as the finite element analysis (FEA) and computational fluid dynamics (CFD) solvers. Once a base analysis has been performed, improvements and, ultimately, optimization can be achieved. By minimizing deformations of the antenna structure
and hot spots (concentration of stress regions), an optimum performance of the communication antenna will be obtained.

1.2 Contribution and Objectives

The main contribution of this thesis is the application of the current fluid-structure interaction methods to the simulation and analysis of communication antennas, specifically, to collinear omni and large panel antennas.

The objectives of this thesis are:

- to model and simulate different configuration of communication antennas, taking into account technical constraints and environmental factors
- to evaluate static and dynamic structural responses of the antenna's components, connections, and subsystems to service loads
- to compare different antenna configurations based on their capacity to minimize vibration effects, stress-induced deformations and aerodynamic loading effects
- to study the effects of physical properties and configurations on structural response of the antennas
- to identify the most likely structural components to fail under service loads

1.3 Thesis Overview

Chapter 1 presents a brief background review of the communication antennas, service environment and loads, and the effects of structural failure on the antennas’ performance. This review is tied to the motivation behind this work and the suggested methodology to analyze the problem at hand. The outline, objectives and main contribution of this thesis are presented as well.

Chapter 2 summarizes the most relevant concepts and advancements concerning fluid structure interaction problems, bluff bodies aerodynamics, flow-induced vibrations and body stresses and
deformations. Fundamental discoveries that even go back to the mid-1400s are highlighted; however, special emphasis is drawn to the advancements over the last two decades.

Chapter 3 presents the procedures behind the modeling and simulations of the SC Series of communication antennas. The chapter begins with definitions of the physical and material properties of the different antenna configurations under analysis. Some of the material and mechanical properties of the antenna radome given by the manufacturers are validated against a cantilever force test and its corresponding Finite Element simulation. Then, the remaining three main sections explore the steady deformation response and the transient response due to wind gust and flow induced vibrations. The steady deformation state analysis is validated by means of analytical models and/or experimental results. First, the SC281 and SC323 simulation aerodynamic results are compared against literature and a wind tunnel test, respectively. Then, the structural results are validated against an analytical model. The natural frequencies of vibrations and model shapes of all the antennas obtained with a Finite Element Method are compared against analytical results and a modal experiment on the SC279 antenna.

Chapter 4 presents the procedures behind the modeling and simulations of the SP Series of communication antennas. This chapter is in many ways an extension of the previous chapter since similar analyses, methods and models are developed to understand the static and dynamic behavior of the communication antennas. These antennas are under similar service loading condition as of the SC Series, but now ice build-up and inclination of the structure are considered. The physical components of the antenna are larger in number and the connections amongst them are much more complex; therefore, simplifications and concessions are made in order to develop models that represent reality as accurately as possible, but that are also efficient.

Chapter 5 summarizes the results obtained from this investigation and highlights the areas for improvement and future work. A detailed breakdown of contributions and fulfilment of objectives is also presented. It restates the objectives and contributions and provides a framework for future research and development.
Chapter 2

Literature Review

This chapter summarizes the most relevant concepts and advancements concerning fluid structure interaction problems, bluff bodies aerodynamics, flow-induced vibrations and body stresses and deformations. Fundamental discoveries that even go back to the mid-1400s are highlighted; however, special emphasis is drawn to the advancements over the last two decades. An understanding of the advancement in these fields is essential to develop and analyze analytical and numerical models for the real life problems under considerations. These principles help in the understanding of results presented in subsequent chapters.

2.1 Fluid-Structure Interaction Problems

Current computer capabilities have allowed the proliferation of the fluid-structure interaction (FSI) modeling field. Researchers have explored the fields of computational fluid dynamics (CFD) and computational solid mechanics (CSM) for quite some time now; however, the latest computing advancements have made possible the development of very demanding simulations for real-world problems. The design of many engineering systems such as stability and response of an aircraft wing, flow of blood through arteries, response of bridges and tall buildings to wind and oscillation of heat exchangers rely heavily on the analysis of fluid-structure coupling. However, these problems are generally too complex for an analytical or experimental study and thus numerical simulations are needed. This section describes the most relevant advancements in the FSI field.
The first studies in the FSI modeling field emerged at the same time during the late 1970’s, but by different researchers: Belytschko and Mullen [8-10], Hughes and Liu [11,12], DeRuntz, Felippa and Park [13-15] and Geers [16]. FSI simulations have been applied to a variety of field since then, but its popularity has increased over the last two decades. Areas of application include, but are not limited to bioengineering, aerospace and rotor dynamics. The vast number of biomedical applications include arterial blood flow [17-22], aortic heart valves [23-26], heart and ventricle [27-30], lung modeling [31], and aortic aneurysm [32-35]. Turbomachinery analysis and design have been advanced by the research of flexible assemblies of turbomachinery [36-38], single-blade pump propeller [39] and flexible composite propellers [40]. There is also a variety of other applications that have also benefited from the advancements in the FSI field such as cloth dynamics [7,41-44], singing hydrofoils [45], nuclear reactor steam generator tube bundles [46], bridges [47,48], and shape optimization studies [49]. Surprisingly, very few of these investigations performed verification and validation studies of their FSI solvers [36].

The traditional coordinate system choice for studies in solid mechanics and fluid mechanics fields is Lagrangian and Eulerian coordinate systems, respectively. In the Lagrangian coordinate system the computational mesh moves with the material, while in the Eulerian the mesh is fixed in space and the material moves relative to it. The choice of moving mesh is very economical and resolves the material boundaries very accurately; however, deformations must be limited since the distortions in the mesh will lead to numerical instability and ultimately inaccuracies [50]. On the other hand, this issue with large deformations gets resolved with the fixed computational mesh, but the additional complexity of the convective terms associated with the transport of the material through the mesh gets introduced [50]. As a result, for problems where both fluid and solid domains are present, such as fluid-structure interaction problems, neither the Lagrangian nor the Eulerian formulations are ideal for the entire domain. This is the reason why they are usually modeled independently and a very complex coupling algorithm is introduced between them.

The Arbitrary Lagrangian-Eulerian (ALE) method was developed in an attempt to combine the benefits of the above classical kinematical descriptions, while minimizing their respective weaknesses. In the ALE description, the nodes of the computational mesh may be moved with
the continuum in normal Lagrangian fashion, or be held fixed in Eulerian manner, or, as suggested in Figure 2, be moved in some arbitrarily specified way to give a continuous rezoning capability [51]. The freedom offered by the ALE method in moving the computational mesh results in two major advantages. First, greater deformations of the continuum can be handled with the ALE description than would be allowed by a Lagrangian method. Second, higher resolution is offered by the ALE description than by a purely Eulerian approach.

ALE methods were first introduced in the finite difference and finite volume contexts. Important developments were made, among others, by Noh [52], Franck and Lazarus [53], Trulio and Hirt et al. [54]. The method was subsequently adopted in the finite element context and early applications are to be found in the work of Donea et al. [55], Belytschko et al. [56] and Hughes et al. [57]. This is the method used by the commercial software ANSYS, which will be used throughout this thesis.

![Figure 2: One-dimensional example of Lagrangian, Eulerian and ALE mesh and particle motion](image)

The problem under analysis in this thesis involves two physics fields: solid and fluid. Coupling between these fields is required in order to understand their relationships and influences on each other. Coupling involves an exchange of information, such as stresses, velocities and/or displacements, across the interface. The coupled system is called one-way if there is no feedback between the subsystems and two-way if there is feedback. An example of a two-way coupled
system is the flow of blood in the heart. The walls of the blood vessels are highly elastic and deformed under the pulsating blood flow. At the same time, the flow itself is driven by the contraction of the heart muscles, that is, by the deformation of the blood vessels. An example for a one-way coupled system would be the interaction of a standing walking human with the steady flowing wind: the pressure exerted by the wind will give rise stresses on the human body, but the deformations in the human body are so small that they will not have an effect on the fluid. The following diagram illustrates the data transfer for one-way coupling and two-way coupling schemes. Both of these schemes will be utilized in the course of this thesis.

![Diagram](image)

*Figure 3: Fluid-structure transfer of information for (a) one-way coupling and (b) two-way coupling*

Generally, individual fluid and structural problems are solved using different methods and/or solvers; however, they are linked by a third program that transfers the required data through the interface. Data transfer is not trivial, since the data structures contained within the two solution methods are likely to be different and an interpolation scheme is required when computational nodes of the fluid and solid meshes are not collocated along the interface [58]. The most demanding scenario is a fully transient model with full coupling between the domains, since an accurate solution can only be achieved by iterating to convergence between fluid and structure within each time step. This process requires numerous stops and restarts of the solution methods, which make this approach demanding on computational resources. Consequently, when applying separate analysis methods to, for example, wind-antenna interaction, approximations are
invariably introduced to simplify the analysis but at a cost to the detail and accuracy of the solution.

Regarding the application there are different levels of complexity. The simplest case is the steady state one-way coupling, i.e. transferring the static pressure loads from the fluid to the structure for one analysis. For this case maximum deformations and stresses will be obtained in dependence of the dynamic input conditions for the fluid. The more complex cases are the analyses of a transient fluid field (e.g., change in wind direction or in strength, sudden gust of wind) and of a time-dependent flow in the wake of the structure (e.g., generation of a von Kármán vortex street past bluff bodies impinged with a constant wind). These analyses require a two-way coupling approach where transfer of deflections is necessary at every coupling step.

2.2 Bluff Body Aerodynamics

The history of aerodynamics dates back to the early 1500's when Leonardo da Vinci (1452-1519) first observed and then Galileo Galilei (1564-1642) established the fact that air offered resistance to the movement of solid objects. In 1726 Newton published the theory of air resistance in which he established that the drag experienced by objects moving relative to air was proportional to the dimension of the body, the density of the fluid and the square of the relative velocity [59]. This theory is correct for low flow speeds; however, it felt short in predicting the effects of the flow on the upper surface which add to the total lift force. Nevertheless, this work was sufficient to gain him the title of one of the first aerodynamicists.

During the 1700’s and 1800’s three researchers revolutionized the field of fluid mechanics; their names were Daniel Bernoulli, Orborne Reynolds and Vincenc Strouhal. In 1738 Bernoulli published what is now called the Bernoulli's principle, which states that for an inviscid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy [60]. In other words, the highest speed for a flowing fluid occurs where the pressure is lowest, and the lowest speed occurs where the pressure is highest (see Figure 4 for a graphical illustration of this principle).
Bernoulli’s equation can be written as:

\[ p + \frac{1}{2} \rho V^2 + \rho gh = \text{constant} \]  

(1)

where, \( p \) is the pressure at the point under analysis, \( \rho \) is the density, \( V \) is the velocity, \( h \) is the elevation and \( g \) is the gravitational acceleration.

Figure 4: Illustration of Bernoulli's principle

In 1851 George Gabriel Stokes first introduced a dimensionless number that describes the ratio of inertial forces (resistant to change or motion) to viscous forces (heavy and gluey) [61]. However, it was not until 1883 that this concept was popularized by Reynolds, after which it took the name of Reynolds number \((Re)\) [62]. This number is generally characterized by the fluid properties of density and viscosity, the relative velocity between the flow and the object, and the characteristic dimensions of the object (e.g. length of plate or diameter of cylinder). It is commonly expressed as [60]:

\[ Re = \frac{\rho VL}{\mu} = \frac{VL}{v} \]  

(2)

where, \( Re \) is the dimensionless Reynolds number, \( \rho \) is the fluid density, \( V \) is the mean velocity to the body relative to the fluid, \( L \) is the characteristic length, \( \mu \) is the dynamic viscosity and \( v \) is the kinematic viscosity of the fluid.
Reynolds number is used to determine whether a flow will be laminar or turbulent. If \( Re \) is high (> \( 3 \times 10^5 \)), inertial forces dominate viscous forces and the flow is turbulent; if \( Re \) number is lower than \( 3 \times 10^5 \) then viscous forces dominate and the flow is laminar.

Parallel to the studies of Reynolds, another physicist named Strouhal investigated the vortex shedding process around a cylinder [63]. He formulated another dimensionless parameter describing the oscillating flow mechanism, which is now called Strouhal number. It is usually defined as:

\[
St = \frac{f_s L}{V}
\]  

(3)

where, \( St \) is the dimensionless Strouhal number, \( f_s \) is the frequency of vortex shedding, \( L \) is the characteristic length and \( V \) is the velocity of the fluid.

Figure 5 shows the relationship between Strouhal number and the Reynolds number. More details about the Strouhal number will be given in a latter section.

Figure 5: Strouhal number as a function of the Reynolds number for circular cylinders.
Data from Achendach and Heinecke [64], Lienhard [65] and Roshko [66]
Graph by MIT OCW.
Other relevant advancements in the field of aerodynamics occurred in the late 1890’s and early 1900’s when Lord Rayleigh [67] and Frederick Lanchester [68] independently proposed theories relating circulation of a fluid flow to lift. Lanchester described a model for the vortices that occur behind wings during flight, while Rayleigh related flow circulation to frictional forces. Lanchester’s theory was the foundation for Ludwig Prandtl’s boundary layer, thin-airfoil, and lifting-line theories [69]. These theories constitute the beginning of modern aerodynamics. Prandtl understood the differences in magnitude of the inertial and viscous forces close and far from the object’s surface.

![Figure 6: Graphical illustration of the boundary layer theory](image)

The velocity of the fluid \( u \) increases with height \( y \). The boundary layer thickness \( \delta \) is the distance it takes to arrive to 99% of the nominal velocity \( u_0 \).

With the support of Prandtl, Theodore von Kármán analyzed the repeating patterns of swirling vortices seen at the back of a bluff body, now called Kármán vortex street [70]. He observed that vortex street will only occur over a specific range of Reynolds numbers, which is dependent on the size and shape of the body. This observation serves as base for the current vortex-induced vibration theories.
2.3 Flow-induced Vibrations

The study of flow-induced vibration (FIV) of structures is of great importance because it applies to many fields of engineering, for example, vibration of cables under sea and of large structures under wind. These vibrations can also be experienced by flexible antennas under high winds as it will be discussed later on. Comprehensive reviews on this topic can be found in the articles of Sarpkaya [71], Griffin and Ramberg [72], Bearman [73], Parkinson [74], and Williamson and Govardhan [75,76] and in books by Blevins [77], Naudascher and Rockwell [78] and Summer and Fredsøe [79]. There are different types of FIV; however, long and slender structures such as the antennas under analysis in this thesis experience mainly buffeting effects caused by turbulence and vortex shedding vibrations. Flutter and galloping effects could also be experienced, but they are less likely.

When a structure develops aerodynamic forces which are in phase with the motion, transverse oscillations may occur. This phenomenon is called galloping. It is characterized by the progressively increase of amplitude of transverse vibration with increase of wind speed. Non circular cross-section structures are more susceptible to this type of oscillation. However, in the case of antennas with circular cross section, galloping could occur due to ice build-up.

Vortex shedding occurs when the flow separates from the body and creates eddies that alternate sides of the structure. At low \( Re \) number (\( Re < 0.5 \)) the flow pattern is very similar to that for laminar flow [80]. Once the flow increases to \( 2 < Re < 30 \) the flow begins to separate from the body and by the time is reached \( Re = 90 \) the vortex formation start to alternate, while traveling downstream. This wake is then what it is commonly called vortex street or von Karman vortex street. Due to the high frequencies of the vortex shedding von Karman streets usually excite the higher order eigen modes with high stresses, but the amplitudes are small. When these vortices reach their maximum size, just before they separate from the structure, the velocity of the flow passing the structure is maximum and hence, by Bernoulli’s Law, the pressure is minimum. Due to this phenomenon the structure experiences alternating forces in a direction perpendicular to that of the flow. At high \( Re \) number (\( Re > 3*10^5 \)) the separation point moves rearward from the body and the flow becomes so turbulent that the vortex street pattern cannot be defined [80]. The following figures illustrate this concept.
Flutter, on the other hand, occurs even if there is no separation of the flow from the body. Flutter is a self-excited oscillatory instability in which aerodynamic forces act to feed energy into the oscillatory structure and progressively increase the amplitude of the motion, counteracting the structural damping [80]. It occurs at velocities that exceed the critical, which is the speed at which the effective damping of the structure reaches zero. Above this speed disturbances in the flow cause the oscillations to grow.

It is important to note that the types of oscillations illustrated above are called self-excited since they can occur in a uniform flow without external disturbances. However, since natural wind is not steady and oscillations of the structure can occur due to velocity fluctuations, another form of
vibration called buffeting could also take place. This type of excitation is generally induced by the wake of an upstream structure [77]. If the two structures differ greatly in size or shape, this excitation is usually not significant, which is the case in this research since structures nearby the communications antennas are generally large building, etc.

![Figure 9: Buffeting by the wake of an upstream structure](image)

Fluid flow around a circular cylinder has been researched extensively because of its common occurrence in different applications, for example, heat exchangers [83] and struts [84]. Strouhal and Rayleigh [67] were the first to systematically study the vibrations produced by a flowing fluid on a circular cylinder. Comprehensive review of advancements regarding flow around a single cylinder can be found in articles by Morkovin [85], Gerrard [86], Coutanceau and Defaye [87], Williamson [88], Sumer and Fredsøe [89] and Zdravkovich [90]. A good review paper of vibration analysis of two cylinders in cross-flow can be found at [91].

Another important characteristic of FIV is what it is commonly called lock-in. This phenomenon has been of interest to fluid dynamic researchers for the prediction of structural responses. It is known that the frequency at which vortices are shed from the bluff body is directly proportional to the velocity of the flow [92]. However, when the vortex-shedding frequency reaches the natural frequency of the structure, it does not further increase with flow velocity. What actually happens is that the shedding frequency remains ‘locked in’ to the natural frequency of the structure. Once the flow velocity passes a certain point the linear dependence of shedding frequency upon flow velocity resumes. Within the synchronization region, large body motions
are observed since the structure undergoes near-resonant vibration, that is why the phenomenon has been extensively researched.

As previously mentioned, the Strouhal number \( (St) \) relates the frequency of the vortex shedding \( (fs) \) from a structure to the characteristic length \( (L) \) (or diameter of the cylinder, \( D \)) and the flow velocity \( (V) \). Furthermore, the value of the \( St \) number varies accordingly to the different regimes of the Reynolds number and the shape of the body (e.g. circular, D-section and triangular). As previously mentioned, for the range of the \( Re \) where the \( St \) number remains constant the relation between the shedding frequency \( (fs) \) and the flow velocity \( (V) \) is linear for a given cylinder [93],

\[
fs = \frac{St \cdot V}{L} \tag{4}
\]

If the \( Re \) is lower than about \( 10^5 \), then the vortex shedding is predominantly periodic and the value of the \( St \) number can be assumed to be around 0.15 for structures of rectangular cross-section and 0.2 for structures of circular cross-sections. It is important to note that if the body is oscillating near or in the lock-in region, this relationship is not applicable. Serious oscillations of slender structures is likely when the natural frequency is less than the frequency of vortex shedding at the given maximum wind velocity.
When Reynolds number is in the turbulent regime, the hydrodynamic forces on the circular cylinder fluctuate with time due to the vortex shedding. Schewe [94] reported the experimental results of the drag coefficient $C_D$ and lift coefficient $C_L$ over a wide range of Reynolds number. In general, the $C_D$ and $C_L$ are defined by,

$$C_d = \frac{F_d}{\frac{1}{2} \rho V^2 D}$$  \hspace{1cm} (5) \\
$$C_l = \frac{F_l}{\frac{1}{2} \rho V^2 D}$$  \hspace{1cm} (6)

where, $\rho$ is the fluid density, $F_d$ is the drag forces on a unit length of a cylinder in the flow direction, $F_l$ is the lift forces on a unit length of a cylinder in the cross-flow direction, $D$ is the cylinder’s diameter and $V$ is the mean velocity to the body relative to the fluid.

According to Schewe’s results, the force coefficients and the vortex shedding frequency are not sensitive to Reynolds number as long as the latter is in the subcritical regime ($300 < Re < 3\times10^5$).
Chapter 3
Modeling and Simulation of SC Series Antennas

This chapter presents the study of fluid-structure interactions of the SC Series communication antennas. The SC Series is a collinear omni series of antennas that are typically installed in remote locations and thus are exposed to environmental effects. These effects from self-weight and wind gusts produce large deformations of the structure that could result in performance deterioration. Therefore, to assess whether these service loads would result in structural failure, fluid-structure interactions need to be studied.

This antenna series was chosen for this first study as they generally experience similar service loads as the SP Series, but they have much simpler geometry and boundary conditions, and fewer components and connections. Furthermore, due to their simple and common geometry (a circular cylinder), there are available analyses in literature for comparison and validation of the Finite Element (FE) simulations. There are also several experimental tests performed at the Sinclair Technologies facility which can be also compared against the numerical simulations.
Generally speaking, the purpose of a structural analysis is to ensure the adequacy of the design from the viewpoint of safety and serviceability of the structure. As seen in Figure 12 a structural system is composed of mainly three parts:

1) the prescribed excitations, such as loads, vibrations, settlements and thermal changes;
2) the structural model; and
3) the structural responses as the result of the analysis process, i.e. displacements, strains, stresses and reactions.

In all cases, a structure must be idealized by a mathematical model so that its behaviors can be determined by solving a set of mathematical equations.

As previously mentioned, there are three main possibilities for the problem under analysis. The first possibility is that the wind load and ice build-up on the structure cause a steady deformation state. In this case, a one-way coupling model should be set up so that the pressure forces from the steady wind can be directly transferred to the structural model and superimposed to the ice build-up load. The second possibility is that the transient wind field, due to change in wind direction or strength, leads to a time-dependent movement of the structure. In this case, a two-way coupling model is necessary so that the effect of the wind on the structure and vice versa can be fully captured. Lastly, constant wind passing bluff bodies can result in wake formation, which in turn, can lead to a time-dependent movement of the structure. Similarly to the second case, a two-way coupling model is appropriate when modeling this scenario.

This chapter will begin with definitions of the physical and material properties of the different antenna configurations under analysis. Some of the material and mechanical properties of the antenna radome given by the manufacturers are validated against a cantilever force test and its corresponding FE simulation. Then, the remaining three main sections explore the steady
deformation response and the transient response due to wind gust and flow induced vibrations. The steady deformation state analysis is validated by means of analytical models and/or experimental results. First, the SC281 and SC323 simulation aerodynamic results are compared against literature and a wind tunnel test, respectively. Then, the structural results are validated against an analytical model. The natural frequencies of vibrations and model shapes of all the antennas obtained with a FEM are compared against analytical results and a modal experiment on the SC279 antenna. All FEA models are full size to allow for a direct comparison to the experimental tests.

2.4 Physical and Material Properties

There are four main configurations within the SC series that will be studied, namely the SC281, SC412, SC323 and SC279. The reasons for analyzing these configurations are simple:

- All configurations are comprised of the same two structurally relevant components, namely a radome and a base pipe, differing only in length and diameter. This variation then serves as a parametric study.
- There are experiments for different antenna configurations that serve as validation methods for the collective FEA model. For example, a vibration test is available for the SC279 antenna; however, an aerodynamic test is only available for the SC323 configuration.
- All configurations are currently under use, thus, understanding their structural behavior under service loads is beneficial to Sinclair Technologies.

The radome is the structure that protects the electrical components of the antenna against environmental factors. For the case of the SC Series, it is a hollow circular cylinder attached to the base pipe by a series of screws. This base pipe is then secured to the ground pole by clamps that allow a range of inclination angles of the antenna. The top end of the pipe is enclosed by a cap to avoid water, ice and dust entering the antenna. This type of antenna is sometimes positioned horizontally, in which case another clamp is placed at the opposite end. However, only the study of the vertical configuration will be presented in this work and the inclined configurations are left for future studies. As Figure 13 shows, the antenna configuration is that of
a cantilever beam with fix-free boundary conditions. Appendices A-C show further details regarding mechanical and electrical specifications of the different configurations.

![Figure 13: Mounting system for the SC Series antenna](image)

### 2.4.1 Manufacturer’s Specifications

Table 1 lists the physical properties of the main two components of these antennas. The radome of the antenna is made of a Polyester Resin mixture and layers of fiberglass, generally coated with high gloss polyurethane enamel paint, while the base pipe is Aluminum 6061-T6. Table 2 shows the material properties of these two components as specified by the manufacturers.

**Table 1: Summary of physical properties of the SC Series Antennas**

<table>
<thead>
<tr>
<th>Model</th>
<th>Overhang Length</th>
<th>Outer Diameter</th>
<th>Inner Diameter</th>
<th>Cross-sectional Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC323</td>
<td>1413mm (45.125in)</td>
<td>51mm (1.75in)</td>
<td>38.1mm (1.5in)</td>
<td>902.73 mm$^2$</td>
</tr>
<tr>
<td>SC279</td>
<td>3739mm (147.2in)</td>
<td>77.7mm (3.06in)</td>
<td>67.56mm (2.66in)</td>
<td>1156.84 mm$^2$</td>
</tr>
<tr>
<td>SC281</td>
<td>5220mm (205.5in)</td>
<td>117mm (4.5825in)</td>
<td>103.5mm (4.0755in)</td>
<td>2337.93 mm$^2$</td>
</tr>
<tr>
<td>SC412</td>
<td>5626mm (221.5in)</td>
<td>117mm (4.5825in)</td>
<td>103.5mm (4.0755in)</td>
<td>2337.93 mm$^2$</td>
</tr>
</tbody>
</table>
Table 2: Summary of material and mechanical properties of the SC Series Antenna

<table>
<thead>
<tr>
<th>Part</th>
<th>Radome</th>
<th>Base Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Polyester Resin Reinforced</td>
<td>Alum 6061-T6</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>1,700</td>
<td>2,700</td>
</tr>
<tr>
<td>Young’s Modulus [MPa]</td>
<td>31,026</td>
<td>68,948</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>Tensile Ultimate Strength [MPa]</td>
<td>331</td>
<td>310</td>
</tr>
<tr>
<td>Tensile Yield Strength [MPa]</td>
<td>331</td>
<td>276</td>
</tr>
</tbody>
</table>

2.4.2 Cantilever Force Test and Simulation on the SC281 Antenna

Fiberglass composites have a unique manufacturing method in which resin is gradually added to the fiber matrix. Hence, the final product properties may vary from sample material properties. To verify the material and mechanical properties given by the manufacturer a simple cantilever force experiment was carried out at the Sinclair Technologies facility. This experiment also served as validation method for the FEA modeling of the system.

The sample used for the experiment was the SC281 antenna that has 2857mm overhang length. Given the large longitudinal dimensions of the antenna it is complex to perform a load test with the antenna in the service (vertical) position. In order to simplify the procedure, the antenna was installed horizontally and clamped by the aluminum base to the test fixture (see Figure 14). These clamps were installed at 25.4mm (1.0in) from the aluminum pipe end. The free end was supported by a sling and clevises, which in turn was attached to an overhead crane. A 8900N (2000lbf) load cell was installed between the sling and the crane (see Figure 15). The load was applied at the free end at an 80 degree angle so as the sample bends the load angle would be closer to 90 degrees. The reaction force was measure with a MTS 407 Signal Conditioner and Measuring Tape at 76.2mm (3.0in) displacement intervals.
The sample failed at approximately 508mm (20in) under 5836N (1312lbf) of pulling load. As Figure 16 shows, the sample fractured as expected in the junction between the radome and the base pipe, where maximum bending stresses should occur. It can be seen the failure was a combination of fiber breakage (shown by the small loose threads) and matrix cracking (shown by the large cracks) resulting in the failure of the component. This is a typical behaviour of fiber reinforced composites.
Given that the moment of inertia of the radome cross-section is $3.37 \times 10^6 \text{mm}^4$ (8.10 in$^4$), the maximum bending stress at the fracture area can be calculated to be 287.87MPa (41,752psi) and the modulus of elasticity at failure is 26502.70MPa (3843892psi). For procedure, formulation and calculations regarding this experiment refer to Appendix D. As it can be seen the experimental modulus of elasticity is lower than the 31026MPa given by the manufacturer, which means that the sample fractured earlier than expected. This discrepancy might come from the manufacturing method itself, as explained at the beginning of the section. Another factor that might have contributed to an early rupture is the creation of concentration of stress areas in the radome at the clamping section due to uneven distribution of clamping pressure or localized plastic deformation at the time of clamping.

Figure 17 shows the boundary conditions of a simple structural static model simulating the described experiment. This model was developed in order to compare it against the experimental results. In the simulation, the base pipe and radome were bonded together to mimic the clamping force between them. The base pipe was fixed in all degrees of freedom and the prescribed displacement was applied at the opposite end of the cantilever cylinder. Since the yield stress and the ultimate stress are considered to be the same for the radome (fiberglass is very brittle and
behaves like a ceramic), then, if the stress in the material surpasses the yield stress, it can be assumed to have fractured. Therefore, in the analysis, the displacement was steadily increased until the safety factor (ratio of the material yield strength and the design stress or von-Mises stress) of the radome just dropped below one. At that point the radome was considered to have failed and the applied load was removed.

Figure 18 shows the resultant factor of safety close to failure, while Figure 19 compares the results obtained from the experiments against those from the simulation. As it can be seen the experiment and FEM results are in close agreement, more so until the force reached approximately 3000N (less than 5% error). From that point on the simulation slightly over predicts the force required to displace the beam (maximum 7% error). The main explanation for the small discrepancy in results is the modeling of the fix-end boundary condition. The FEA model considers the beam to be attached to a rigid support, but in reality the connection between the radome and the base pipe and between the base pipe and the clamps is elastic. Thus, the force required to displace a given amount is slightly higher in the FEA model.

**Figure 17: Analysis settings for cantilever test**

**Figure 18: Safety factor result for cantilever simulation of SC281**
2.5 Steady Deformation State Analysis

When wind speed and orientation remain constant, the antenna experiences what it is commonly called in literature steady deformation state due to this wind pressure. This is the simplest scenario of the three possibilities outlined in Chapter 1 and for this case a one-way coupling model is needed. In this scenario, the resultant pressure on the antenna’s interface from the steady wind is directly transferred to the structural model.

The solution of such a multi-field simulation usually requires two separate solvers, one for the fluid (CFD) and one for the structure (FEA) that run in sequential order. They exchange information at the interface, namely the antenna’s outer surface [38]. In other words, the fluid pressure on the antenna obtained with the CFD model is applied as a boundary or load condition in the FEA simulation. In the present work the two commercially available solvers ANSYS CFX 12.0 and ANSYS Mechanical 12.0 have been applied as CFD and FEA solver respectively. Both have different meshing requirements, therefore different meshes are generated for the fluid field and the solid field. The mesh must not be identical at the interface, but must consist of the identical geometrical surface. If the nodes do not coincide, interpolation of information will take place.
2.5.1 Fluid Structure Interaction Models

The first step towards developing the FSI model is to setup the computational domain for the flow field as seen in Figure 21. Four main regions are defined: 1) the inlet, 2) the outlet, 3) the tunnel walls, and 4) the antenna wall. At the left boundary (inlet) a velocity component in the “z” direction is given, while the velocity components in the other directions are zero. The pressure gradient in the flow direction is zero. At the right boundary (outlet) the pressure and the velocity gradients are zero. The other four boundaries (tunnel walls) and the antenna have a free-slip boundary condition, that is the velocity component and the pressure gradient perpendicular to the boundary are zero. The fluid medium for these analyses is air at 25°C and 1 atm, which is represented by a large box enclosing the antenna. The dimensions of the fluid domain vary with each analysis and they are directly proportional to the diameter of the antenna.
If an infinite fluid medium wants to be modelled by a finite mesh, the presence of artificial boundaries may produce reflections which contaminate the solution [95]. To overcome this problem the mesh should be extended to sufficient distance such that the response is obtained before the reflections arrive. It has been shown that the computational domain size in the cylinder spanwise direction must be larger than 4D in order to simulate the three-dimensional wave flow accurately [96].

In order to reduce the computational efforts the FEA unstructured mesh is only refined in the region surrounding the antenna and it is allowed to be coarser in the farther reaches of the computational domain. Similarly, when meshing the structural domain, regions with small details or sharp angles are refined. A bonded contact region between the radome and the base pipe was created. The base pipe was fixed in all degrees of freedom. Sample meshes for the solid and fluid domains of the SC281 simulation can be seen in Figure 22.
There are many element types available: plane, shell, beam, truss, contact and solid, to mention a few. Since the radome structure is very long and slender, beam element might be the most appropriate to model it. However, in order to perform the FSI analysis the solid and fluid domains must have a surface interface to transfer forces and displacements between each other. A beam model would not be able to provide that interface and the three dimensional surface forces, required for the FSI analysis. Therefore, for the solid model SOLID186, SOLID187, CONTA174, TARGE170 and SURF154 elements were used. On the other hand, for the fluid domain the 3D fluid element Fluid142 was used. A summary of the total number of elements and nodes for all simulations can be seen in Table 3.

Table 3: Summary of mesh statistics for all configurations

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Fluid Domain</th>
<th>Solid Domain</th>
<th>Fluid Domain</th>
<th>Solid Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC323</td>
<td>312238</td>
<td>24511</td>
<td>55441</td>
<td>123971</td>
</tr>
<tr>
<td>SC279</td>
<td>384610</td>
<td>27550</td>
<td>60951</td>
<td>159178</td>
</tr>
<tr>
<td>SC281</td>
<td>409388</td>
<td>29795</td>
<td>72901</td>
<td>172231</td>
</tr>
<tr>
<td>SC412</td>
<td>432521</td>
<td>31569</td>
<td>77012</td>
<td>183443</td>
</tr>
</tbody>
</table>
The FEM models of the antenna were subjected to loads representing a uniformly distributed flow with constant velocity acting in the z-direction as seen in Figure 21. Wind loads were applied gradually to ensure that external work was converted to internal energy without introducing significant kinetic or viscous energy. The complete simulation ran until a convergence criterion was reached, that is the change in deflection from iteration to iteration is less than a certain value in the case of a steady state simulation [97].

The SC281 configuration was first analyzed under constant wind speed conditions ranging from 10m/s to 80m/s ($8.74 \times 10^4 < Re < 6.44 \times 10^5$), which is just above the maximum rated speed for this antenna (76m/s). Each run took approximately 45min with an AMD QuadCore (2.4GHz) computer that has a 4Gb RAM and 512Mb Video Card.

<table>
<thead>
<tr>
<th>Physical model</th>
<th>Range of velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>0-30 m/s</td>
</tr>
<tr>
<td>Turbulent k-ε model</td>
<td>40-80 m/s</td>
</tr>
</tbody>
</table>

The k-ε turbulence model was used for velocities greater than and equal to 40m/s. In the k-ε model, the turbulent viscosity is calculated as a function of the turbulence parameters kinetic energy $k$ and its dissipation rate $\varepsilon$ using [97],

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$  \hspace{1cm} (7)

where, $C_\mu$ is the turbulence constant (defaults to 0.09), $k$ is the turbulence kinetic energy, $\varepsilon$ is the turbulence kinetic energy dissipation rate and $\rho$ is the fluid density.

The k-ε model entails solving partial differential equations for turbulent kinetic energy and its dissipation rate. The following table summarizes the results obtained from the steady state fluid-structure interaction models for the SC281 antenna within the 10m/s to 80m/s wind speed range.
Table 5: Summary of results of SC281 configuration

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8.05E+04</td>
<td>31.30</td>
<td>0.84</td>
<td>0.10012</td>
<td>17</td>
<td>0.0001930</td>
<td>9.84</td>
<td>&gt;10</td>
</tr>
<tr>
<td>20</td>
<td>1.61E+05</td>
<td>124.46</td>
<td>0.84</td>
<td>0.10018</td>
<td>20</td>
<td>0.0002392</td>
<td>11.32</td>
<td>&gt;10</td>
</tr>
<tr>
<td>30</td>
<td>2.42E+05</td>
<td>279.74</td>
<td>0.83</td>
<td>0.10029</td>
<td>37</td>
<td>0.0004730</td>
<td>24.18</td>
<td>&gt;10</td>
</tr>
<tr>
<td>40</td>
<td>3.22E+05</td>
<td>497.25</td>
<td>0.77</td>
<td>0.10070</td>
<td>69</td>
<td>0.0008456</td>
<td>43.03</td>
<td>6.4</td>
</tr>
<tr>
<td>50</td>
<td>4.03E+05</td>
<td>723.47</td>
<td>0.71</td>
<td>0.10117</td>
<td>103</td>
<td>0.0012474</td>
<td>62.99</td>
<td>4.2</td>
</tr>
<tr>
<td>60</td>
<td>4.83E+05</td>
<td>748.35</td>
<td>0.51</td>
<td>0.10119</td>
<td>113</td>
<td>0.0013287</td>
<td>69.22</td>
<td>4.0</td>
</tr>
<tr>
<td>70</td>
<td>5.64E+05</td>
<td>988.82</td>
<td>0.50</td>
<td>0.10180</td>
<td>152</td>
<td>0.0017739</td>
<td>93.10</td>
<td>3.1</td>
</tr>
<tr>
<td>80</td>
<td>6.44E+05</td>
<td>1309.50</td>
<td>0.53</td>
<td>0.10251</td>
<td>197</td>
<td>0.0023244</td>
<td>121.07</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Figure 23 shows the resultant drag forces ($F_D$) and drag coefficient ($C_D$) for the range of wind velocities under study. Drag load was found as the “$z$” components of the resultant wind force. As it can be seen the drag force increase linearly as the velocity increases and the drag coefficient remained constant at approximately 0.84 until the fluid velocity reached somewhere between 40-50m/s, which corresponds to a Reynolds number between $3.22 \times 10^5 < Re < 4.03 \times 10^5$. From that point on there was a drop in the drag coefficient to about 0.5 and the drag force followed. As it would be expected, the drag force increased with increased wind speed until what is commonly called “region of drag crisis”. Generally, when the fluid around a circular cylinder reaches $Re = 4 \times 10^5$, the turbulent boundary layer remains attached to the surface past its maximum thickness and thus the rear wake becomes narrower. This decrease in wake turbulence causes a significant decrease in pressure drag and a small increase in friction drag. Until that point the drag coefficient is independent of the Reynolds number or velocity of the fluid, but after, the drag coefficient decreases giving rise to what it is called the drag crisis. Eventually, the $C_D$ increases at $Re > 10^6$; however, this study concludes at $Re = 6.44 \times 10^5$. It is also important to note that the drag crisis need not always occur at $Re = 4 \times 10^5$. Roughness of the cylinder surface or unsteadiness in the free stream can cause boundary layer transition at much lower Reynolds number.
As Figure 24 shows, the wind pressure on the surface of the antenna behaves as expected. At the leading edge of the cylinder a stagnation point is formed where the oncoming flow is brought to rest. The pressure here is equal to the stagnation pressure and it is shown having the highest values of the color legend. To either side of the stagnation point the flow accelerates around the forward surface of the cylinder producing a drop in the pressure. Once the flow slows down at the rear of the cylinder, the pressure becomes negative. It is important to note that the pressure shown is absolute, so to obtain the relative pressure, the atmospheric pressure needs to be subtracted.
The effect of the fluid pressure on the structure is shown in Figure 25, where the total deformation and the equivalent stresses for the SC281 antenna under 40m/s wind are seen. This behaviour is typical for the range of winds speed under study, but the displacement and stress values varying accordingly.

Based on the FEA results, the SC281 antenna is able to withstand steady winds of up to 80m/s without experiencing plastic deformations since the minimum safety factor is 2.3. Depending on the company’s design guidelines, the antenna could be rated for higher wind speeds; however, it is important to remember that this analysis does not considered wind direction and speed changes or any other type of dynamic behavior that can results in much higher stresses at similar top speeds (sections 3.3 and 3.4 cover these behaviors). The maximum bending moment occurs at the base of the antenna, where the radome gets fixed to the base pipe. The maximum bending moment for the SC281 antenna is 3253.7Nm at 80m/s.

Similar numerical simulations were developed for the remaining configurations under analysis, namely SC412, SC279 and SC323. These configurations were each ran at 44m/s (100mph), which is the typical speed at which the company provides performance and mechanical...
properties to the customers (see Appendices A-C). By analyzing these models a simple parametric study with respect to the aspect ratio L/D of the circular cylinder can be carried out.

Table 6: Summary of results of all antenna configurations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SC323</td>
<td>27.71</td>
<td>69.02</td>
<td>0.81</td>
<td>0.3205</td>
<td>0.0037</td>
<td>3.29</td>
<td>10.291</td>
</tr>
<tr>
<td>SC279</td>
<td>48.12</td>
<td>297.30</td>
<td>0.82</td>
<td>0.3050</td>
<td>0.0001</td>
<td>79.27</td>
<td>0.00135</td>
</tr>
<tr>
<td>SC281</td>
<td>44.62</td>
<td>600.62</td>
<td>0.83</td>
<td>0.5505</td>
<td>0.0008</td>
<td>89.49</td>
<td>0.00110</td>
</tr>
<tr>
<td>SC412</td>
<td>48.08</td>
<td>646.97</td>
<td>0.83</td>
<td>0.7428</td>
<td>0.0010</td>
<td>127.78</td>
<td>0.00142</td>
</tr>
</tbody>
</table>

As one can see the aspect ratios for these antennas are in a high range. Most of the literature shows results for rigid circular cylinder with aspect ratios in the range of 0 < L/D < 10 and for flexible cylinders with L/D >> 100. Therefore, no comparison can be drawn against literature as the aspect ratios for these antennas fall somewhat in between the typical research. Based on the results shown in Figure 26, it does not seem to be a significant correlation between the aspect ratio and the measured coefficient of drag and lift under a constant flow of air at 44m/s. As a general trend it could be said that the coefficient of drag is directly proportional to the aspect ratio and that the coefficient of lift is inversely proportional; however, the amount of data collected is not enough for a strong conclusion. The SC279 and the SC412 have similar aspect ratios, resulting in very similar $C_L$. On the other hand, their resultant $C_D$ values are slightly different. The SC323 has the smallest aspect ratio of the four and solely its result dictates the above described trend, which is another reason why the analysis is not conclusive.
The highest deformation is experienced by the SC412 antenna, which is an expected result since it has the highest aspect ratio with the longest radome. It is interesting to note that, even though the SC281 does not have the longest radome or highest aspect ratio, it experiences the maximum stresses and thus the lowest safety factor at the given speed.

2.5.2 Validation of the FSI Models

The accuracy of FEA simulation results depends strongly on having the problem properly represented. It is recommendable to verify the numerical model by comparing it against analytical solutions, whenever possible, and/or experimental data, if available. In this section the FEA simulations described in section 3.2 are validated by means of analytical models and/or experimental results. First, the SC281 and SC323 simulation aerodynamic results are compared against literature and a wind tunnel test, respectively. Then, the structural results are validated against an analytical model.

Total drag force is a combination of the skin friction drag and the form drag. For the analyses on this thesis the skin friction drag is ignored since the surface of the radome is smooth (polyurethane enamel paint) and the fluid velocity is relatively high ($8\times10^4 < Re < 6\times10^5$). According to Achenbach [98] and Schewe [94] the coefficient of drag around a circular rigid
cylinder is related to the $Re$ as shown in Figure 27. In the same graph the values obtained with the FEA simulation for the SC281 antenna are shown for comparison. As it can be seen the obtained $C_D$ values are higher than the literature and they are not as sensitive to the changes in Reynolds number, as experimental work shows. The literature shows a drastic drop of the drag coefficient at around $Re = 3 \times 10^5$. While a substantial decrease is also seen with the numerical simulations, it is not as drastic. There are several reasons that could explain this discrepancy. Firstly, surface roughness of the literature’s work and this thesis’ models might be different. Surface roughness on the façade of the cylinder can affect the location of the separation point and the extent of the wake on the leeward face, upon which the resultant drag force is dependent [89]. The discretization of the cylinder’s surface and the errors associated with the possible under-resolution that result from it could cause the flow around the cylinder to experience some characteristics more typical of a rough-cylinder analysis. Secondly, these experimental results are for infinitely rigid cylinders and the FEA simulations are for a finite antenna that is more leaning towards a flexible cylinder regime.

Figure 27: Drag coefficient as a function of Reynolds number
Utilizing the drag coefficients obtained from Achenbach [98] and Schewe [94], the expected drag force can be calculated with the following formulation,

$$F_D = \frac{1}{2} \rho V^2 C_D A$$

(8)

where, $F_D$ is the force of drag, $\rho$ is the density of the fluid (air), $V$ is the speed of the object relative to the fluid, $A$ is the reference area ($D*L$) and $C_D$ is the drag coefficient.

Figure 28 shows a comparison between the expected drag force (obtained with above formulation) and the FEA results obtained with ANSYS. As it can be seen there is discrepancy between the FEA and the analytical results. This is, however, expected since the drag force is directly proportional to the drag coefficient and discrepancies in the drag coefficient were already seen and explained.

Figure 28: Comparison of FEA and analytical drag force of the SC281 antenna

Furthermore, drag force calculations involved possible sources of error due to estimation of drag coefficients. This difference in $C_D$ could also be due to the finite element simulation mesh itself. As demonstrated in [99] mesh refinement has a significant effect on the value obtained for the $C_D$. Three different CFD meshes were examined for the 30m/s simulation, which is one of the ones that have better agreement with the analytical results. Using 69639, 201957, and 409388 elements, respectively, the outcomes were drag forces deviating from the analytical results by 7.8% for the coarsest, 3.7% for the medium and 1.1% for the finest grid. These results ratify the
The finer the mesh, the more accurate the results. However, in this case further refinement of the mesh was impractical as the computational time and processing capabilities would not allow the solution to converge. Therefore, one of the main suspects for the discrepancy in results is poor grid-resolution, which becomes more relevant as the Reynolds number increases.

Experimental data for the SC323 antenna was collected from the company in order to compare it against the FEA simulation results. The antenna was tested at 44.9m/s (100.5mph) air speed on a single-return, closed-throat tunnel with a 2m x 3m (84in x 120in) rectangular test section. Loads taken from the external balance were converted to engineering units through calibration via a data acquisition and control device. Accelerometers were installed in the antenna in such a way that measurements occurred perpendicular to the wind direction. The experiments concluded that the drag load on the antenna was approximately 115.5N (26lbs). When this value is compared to the 69N obtained with the FEA simulation, there is a 40% difference. However, taking into consideration that not much is known regarding the setup and procedure of the experiment or accuracy of the test equipment, and that the results are in the same order of magnitude, their agreement should be considered successful.

In order to validate the FEA structural simulation, the deformations on the structure due to the transferred wind pressure are compared against an analytical model. Considering the input pressure into the structural model (drag force from the wind resulting from FEA model) to be correct, the deformation at the tip of the antenna can be calculated by:

\[
\delta_{MAX} = \frac{F_D L_0^4}{8 L_T E I_0}
\]

where, \(\delta_{MAX}\) is the maximum deflection, \(F_D\) is the drag force, \(L_0\) is the overhang length, \(L_T\) is the total antenna length, \(E\) is the elastic modulus and \(I_0\) is the moment of inertia. Derivations of the above equation can be seen in Appendix E.

As Figure 29 shows, both methods resulted in a similar trend, in which the total deformation of the radome structure increases as the wind speed increases. The deformation increase rate is somewhat constant until the region of drag crisis, during which time there is a visible plateau,
followed by another linear region. Overall, the difference between the simulation and the analytical results is less than 10% and they follow a similar trend for the most parts; therefore, it can be said that the FEM and the analytical model are in good agreement. The small discrepancies between the models can be explained by the distribution of the load. For the analytical model the load was evenly distributed along the length of the radome, while for the FEA model there was a load variation along the length of the cylinder due to the experienced deflection. To demonstrate this point, Figure 30 shows the pressure variation at the leading edge of the circular antenna radome as the distance from the fix-end increases.

![Graph showing maximum deformation results at the free-end of the SC281 antenna’s radome](image)

**Figure 29: Maximum deformation results at the free-end of the SC281 antenna’s radome**

![Graph showing pressure distribution along the leading edge of cylinder for the SC279](image)

**Figure 30: Pressure distribution along the leading edge of cylinder for the SC279**
2.6 Transient Response due to Wind Gusts

The wind velocity at any location varies considerably with time. In addition to a steady wind, there are effects of gust which last for a few seconds and yield a more realistic assessment of wind load. In practice, the peak gusts are likely to be observed over a range of time between 3s and 15sec, while the average wind gust duration is 3-5sec. Therefore, five-seconds transient analyses of the air flow over the cylindrical antenna are performed. Two wind directions are important for the analysis of structures: alongwind and transverse wind (crosswind). For this section, this definition is irrelevant since the antenna is symmetrical; however, for the SP Series only along-wind is considered, since it has higher structural effects than crosswind. A pre-stressed modal analysis of the antennas is also developed in this section in order to investigate the natural modes of vibration of the structures. This FE vibration model is verified against a vibration experiment on the SC279 antenna.

Exposure factor of the structure to wind gust varies according to the general roughness of the terrain over which the wind has been blowing before it reaches the building. To determine the exposure factor experiments onsite need to be performed. However, since the location of the communication antennas under study varies considerable, it would be nearly impossible to collect data from all possible scenarios. Hence, exposure factor is ignored and wind gust speed is simply selected as the maximum rated speed by the company. Furthermore, the wind is not constant over the length of the antenna; however, for simplification purposes it will be regarded as so.

![Figure 31: Wind gust effect on the structure](image)

Figure 31: Wind gust effect on the structure
2.6.1 Fluid Structure Interaction Models

Changes in wind speed and direction result in stresses and deflections of the solid structure. At the same time, resulting deflections of the solid field have an impact on the fluid field, which has to adapt to the modified boundary. Furthermore, if unsteady effects are considered, the fluid field not only acts as a driving force, but also as a damping influence on the solid field since fluid mass has to be displaced during the motion of the structure which requires additional energy [38]. The CFX solver calculates how the fluid responds to the motion of the antenna, while the ANSYS solver calculates how the antenna deforms as a result of the pressure resulting from the movement of the fluid. For this multi-field simulation a two-way coupling model is necessary since the structural deformation affects the fluid solution, and the fluid solution affects the structural deformation.

In Figure 32 the simulation process flow utilized by the two ANSYS solvers is explained. Exchange of information between the solvers occurs via the interface. While CFD provides the forces, FEA returns the resulting deflections and the two meshes are adapted to the new geometry. The complete simulation is running until a convergence criterion is reached, which in the case of a transient FSI run occurs when the selected real time duration is reached. The framework for the coupling is provided by the ANSYS Multi-field solver using the MFX setup. Details can be found in the documentation provided by ANSYS [97].
The setup for these models is similar to the one in section 3.2; the difference is that the flow field is given an initial velocity and the transient behaviour of the antenna is analysed. If the k-ε turbulence model were to be used, as in the previous section, the accurate modeling of such flow patterns is unlikely. For problems like that, Large Eddy Simulation (LES) turbulence model should be used, which provides more accurate results but at an extremely high computational cost. LES is an approach which solves for large-scale fluctuating motions and uses "sub-grid" scale turbulence models for the small-scale motion.

Furthermore, the fluid domain setup is identical to the steady deformation state analysis. It is important to note that the outlet boundary condition is a must for this simulation. Openings cannot be used with LES since fluid re-entering the domain could destabilize the solution. Outlet boundary condition enforces the use of artificial walls for fluid trying to re-enter the domain. In order to simulate wind gust, the input boundary is given 0m/s speed in all directions and the fluid domain is then initialized with the desired speed in the cross-flow direction. The time step size is set as 0.1s, for a total of 50 steps to reach the 5s mark.
The SC281 antenna is selected for this analysis since it resulted in the lowest safety factor of the four model antennas for a given speed during the static analysis. Therefore, it should represent the worst case scenario, which is what is important for design validation purposes. The antenna is first tested at the maximum rated speed by the company (76m/s) and if the antenna passes that test, in other words, if the factor of safety is above 1, the wind gust speed is increased until the antenna structurally fails. Each run took approximately 8.5hrs with an AMD QuadCore (2.4GHz) computer that has a 4Gb RAM and 512Mb Video Card.

Figure 33 shows the total displacement of the radome’s free-end under a 76m/s wind. As it can be seen, the wind gust provokes and initial maximum displacement, followed by a series of oscillations. A peculiarity of the outcome is that the radome never displaces against the wind direction. However, it is important to note that the results are limited by the resolution of the analysis. The time step was set to 0.1sec, and thus the behavior of the antenna in between the time steps is unknown. Attempts to increase the amount of steps were unsuccessful. The solution would not converge due to lack of processing capabilities.

Figure 33: Total displacement for the SC281 antenna under 76m/s wind gust
It is important to verify that the antenna can withstand wind gusts of up to 76m/s. To do so, the safety factor for the antenna is shown in Figure 34 along with the maximum deflection and stresses. As it can be seen the maximum stresses are experienced at the base of the radome and they represent a 1.6 safety factor, which means that the antenna will not fail under the given wind load.

In order to investigate at what point the antenna will yield under high speed wind gusts, the nominal velocity was gradually increased until the safety factor reaches 1, at which point the antenna starts to yield. The antenna responded to wind gusts of 95m/s as seen in Figure 36. The deflection at the tip of the antenna reached 436mm, which is 8.4% of the total length and almost 4 times the radome’s diameter. Figure 36 shows that the equivalent stress at the base of the radome matches the yield stress of the material, which suggests that winds of 95m/s will start to plastically deform the antenna. Nevertheless, it is up to the designer to select an allowable factor of safety and rate the maximum allowable environmental conditions accordingly.
Figure 35: Total displacement for the SC281 antenna under 95m/s wind gust

Figure 36: Contour plots of structural results for the SC281 antenna under 95m/s wind gust
(a) Maximum deflection (b) Maximum von-Mises stress (c) Minimum safety factor
2.6.2 Modal Analysis

This section presents the mode shapes and natural frequencies resulting of free-vibration modal analyses of the four antenna configurations. These frequencies can be later compared against the vortex shedding frequencies in order to analyze the dynamic behaviour of the antenna under steady winds. Furthermore, as Figure 37 shows, these models are fully linked to the FSI models so that it would also serve as a validation method. If the results from the modal analysis coincide with the analytical model, then the boundary conditions and material properties of the structure are guaranteed to be properly applied.

Figure 37: Connections between FSI and modal analyses with Workbench, ANSYS

To excite the natural frequencies of vibrations, the antennas are given the maximum displacement that a 44m/s (100mph) wind gust would result on and then they are released. ANSYS Workbench defaults to 0.02 as damping ratio. The first five natural frequencies of each antenna model can be seen in Table 7 and the corresponding mode shapes for the SC281 are seen in Figure 38.

Table 7: Comparison of natural frequencies for all SC Series antenna configurations

<table>
<thead>
<tr>
<th>Mode</th>
<th>SC323</th>
<th>SC279</th>
<th>SC281</th>
<th>SC412</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEA</td>
<td>Analytical</td>
<td>FEA</td>
<td>Analytical</td>
</tr>
<tr>
<td>1</td>
<td>17.8 Hz</td>
<td>17.84 Hz</td>
<td>4.1 Hz</td>
<td>4.12 Hz</td>
</tr>
<tr>
<td>2</td>
<td>111.2 Hz</td>
<td>111.80 Hz</td>
<td>25.7 Hz</td>
<td>25.82 Hz</td>
</tr>
<tr>
<td>3</td>
<td>311.5 Hz</td>
<td>313.04 Hz</td>
<td>71.9 Hz</td>
<td>72.31 Hz</td>
</tr>
<tr>
<td>4</td>
<td>606.8 Hz</td>
<td>613.44 Hz</td>
<td>140.7 Hz</td>
<td>141.70 Hz</td>
</tr>
</tbody>
</table>
Figure 38: First five mode shapes for the SC281 antenna
The overall impression from these results is that the natural vibration frequencies achieved with the analytical model correspond very well with those obtained from the FEM. Discrepancies between the models increase as the modes increase. The maximum difference is seen at the 5th mode of vibration of the SC412 antenna and they differ in approximately 9.4%. Maximum amplitudes of vibration are always seen during the first mode, but they are still much smaller than deformations from external forces. For example, the maximum vibration deformation of the SC281 antenna is 13.94mm, which is significantly smaller than the 89.9mm deformation experienced during constant wind at 44m/s.

2.6.3 Vibration Experiment on the SC279 Antenna

In order to verify the FEA vibration model it was decided to conduct a modal experiment on the SC279 antenna. This antenna configuration was selected as it is one of the shorter models being analyzed and thus it fits vertically in the facility. A variety of force excitation test are available to determine the natural frequency of structural systems. Some of the most popular methods include random noise excitation, transient/shock test and sine sweep methods. Random noise vibration tests are very common in aerospace and military application, where events that have multiple inputs, such as aircraft take off and transportation over rough terrain, are to be simulated. A potential drawback to these random methods is that the signal-to-noise ratio may be poor, which leads to lower-quality FRF. Sinusoidal sweep methods sweep across a specified range of frequencies at a specified rate. This test allows for higher RMS input loads and oftentimes lead to much cleaner FRF. Shock vibration tests are not as effective in very large structures as in small structures. An instrumented hammer with a built-in force sensor can be used to excite the structure; however, given the size of the antennas under analysis, a large impact force is required to excite them. Therefore, a sinusoidal frequency sweep test was selected as the most appropriate method for this case.

The antenna was mounted onto a metal pole fixture, so that it is in a vertical position (see Figure 39). The bottom of the pole fixture had a plate that was secured to the Thermotron Model DS-842 shaker table platform. This shaker platform generates vibration at a controlled frequency and requires a control system to operate. As shown in Figure 40, five accelerometers were secured
onto the antenna radome. The first one was placed at the base of the shaker to read the input motion and the remaining ones were with placed along the antenna with a separation of approximately 914mm (36in) between them. The signal from the accelerometers was read with a SignalCalc Dynamic Signal Analyzer from Data Physics Corporation. The response signal, $x(t)$, is the displacement (vibration) signal measured by the accelerometers. The vibration analyzer performs a Fast Fourier Transformation (FFT) of the time domain signals obtained from the sensors. Based on the input and output signals, the analyzer can determine the natural frequency (resonance) of the structure. The antenna was subject to a sinusoidal frequency sweep from 5-500Hz.

Figure 39: Set-up of the SC279 antenna vibration test
Three sets of data were recorded to ensure repeatability and their results were averaged. More test runs were not possible due to time constraints. The results obtained from the accelerometer at the free-end of the antenna can be seen in Figure 41. As it can be seen the first natural frequency of 4.1Hz could not be captured since the frequency sweep started at 5Hz; however, the following natural frequencies were very well captured.

One possible cause of deviation between the FEA and experiments results is the assumed boundary conditions. The cantilever beam boundary condition assumes that the end of the cylindrical beam is fixed to a rigid structure. In reality, this assumption is not completely accurate. The beam is clamped using two pieces of metal that are fastened with two screws. The whole clamp and beam structure is mounted on a stand on top of the shaker table. This means that some elastic displacement could take place at the base. In order to compensate for this deviation, further studies on the real boundary conditions would be needed.
Furthermore, the shaker table base that attached the antenna’s base pipe to the table had a resonant frequency that fell within the range for this test. Hence, interferences from it could have affected the results as well. It was also observed that when the antenna passed through the resonant frequencies the vigorous antenna movement resulted in vibrations of the cables connecting the accelerometers. The instability of the accelerometer cables makes the accelerometers’ readings unreliable during those intervals.

![Graph](image.png)

**Figure 41: Sine sweep vibration experimental results for the SC279 antenna**

**Table 8: Comparison of natural frequencies of vibrations for the SC279 antenna**

<table>
<thead>
<tr>
<th>Mode</th>
<th>FEA</th>
<th>Analytical</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.1 Hz</td>
<td>4.12 Hz</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>25.7 Hz</td>
<td>25.82 Hz</td>
<td>27.2 Hz</td>
</tr>
<tr>
<td>3</td>
<td>71.9 Hz</td>
<td>72.31 Hz</td>
<td>75.9 Hz</td>
</tr>
<tr>
<td>4</td>
<td>140.7 Hz</td>
<td>141.70 Hz</td>
<td>147.8 Hz</td>
</tr>
<tr>
<td>5</td>
<td>232.1 Hz</td>
<td>234.24 Hz</td>
<td>236.2 Hz</td>
</tr>
</tbody>
</table>
2.7 Wake Induce Transient Response

The procedures from the above section are extended to simulate the unsteady excitation of the antenna under a uniform and constant wind flow field. Besides the mean lift and drag force acting on the cylinder, there are fluctuating lift and drag forces which cause the vibration of long and slender structures, even under constant wind [100]. These fluctuations are generally defined by alternating flow and the most significant pressure fluctuations act on the sides of the body in the wake behind the separation point [77]. When the Reynolds number is in the range $90 < Re < 10^5$, vortices form alternate sides of the cylinder are shed. When these vortices reach their maximum size, just before they separate from the structure, the velocity of the flow passing the structure is maximum and hence, by Bernoulli’s Law, the pressure is minimum. Due to this phenomenon the structure experiences alternating aerodynamic forces in a direction perpendicular to that of the flow. This wake behind the structure is commonly called von Karman vortex street. At high Re number ($Re > 3*10^5$) the separation point moves rearward from the body and the flow becomes so turbulent that the vortex street pattern cannot be defined [80].

As Figure 42 shows, flow-induced vibrations (FIV) are generally in the direction perpendicular to that of the wind.

![Figure 42: Oscillations motion due to flow induced vibrations](image)

When the design or rate wind speed is greater than the critical wind speed (speed at which the natural frequency of the antenna coincides with the vortex shedding frequency) the structure is likely to fall into the resonance area for a period of time. When the structure is in resonance the oscillations gradually increase. At that point, there is a lock-in and the frequency of oscillation does not continue rising with increasing wind speed (please see section 2.3 for further details).
Once the wind speed has exceeded the critical wind speed by approximately 30% the structure leaves the lock-in period and it goes back to shedding at the prescribed frequency.

It is desirable to avoid such a case, but is very difficult to design around it since the lower modes of vibrations occur at relatively low wind speed, which are highly likely to happen. Nevertheless, cross-wind loads due to vortex shedding in the first and second models should be investigated to fully understand the dynamic behaviour of the antennas under wind loads. It is interesting to note that for flexible cylinders, the response is generally broad banded (wide-band random shedding) and pronounced lock-in does not occur. Because of the complexity of the vortex shedding phenomenon analytical method that estimate the response of the structure to the vortex shedding dynamic induced loads are complex.

As previously stated, it is generally accepted that periodic vortex shedding does not exist in the super-critical regime of flow over a smooth cylinder [101]. However for investigational purposes the vortex shedding frequency is modeled against wind speeds for the 10m/s to 70m/s range according to the following formulation,

\[ f_s = \frac{StV}{D} \]  

where, \( f_s \) is the vortex shedding frequency, \( St \) is the Strouhal number (0.2 for cylinders at \( Re < 10^5 \)), \( V \) is the flow velocity and \( D \) is cylinder’s diameter.

![Figure 43: Vortex shedding frequency dependence in wind speed for all SC series antennas](image)
The graphs of the SC281 and SC412 coincide since the shedding frequency is only dependent on the cylinder diameter (not length) and those configurations have equal diameters. The above graph aids in the understanding of the possible unstable structure response. For example, the SC323 could only have two lock in periods (17.8Hz and 111.2Hz) since the third resonant frequency (311.5Hz) would fall out of the range of wind speeds.

The critical speed for the four antennas at the first three natural modes are summarized in Table 9. Between $0.5V_{cr} < V < 1.3V_{cr}$ the antenna is likely to resonate since the natural frequencies match the FIV frequencies. It is indeed widely accepted that there is not vortex shedding of smooth cylinders in supercritical regime [101]. Therefore, for wind speed greater than 25-30m/s vortex shedding is not likely to occur, therefore it is enough to analyze the first 2-3 natural modes of vibrations. Furthermore, the velocity need not to be very high, but it has been found that significant vibration does not occur unless the velocity is greater than 5 m/s, which could reduce the analysis to 1 or 2 natural modes per antenna configuration [102].

\[\text{Table 9: Critical regions of resonance for the SC Series antennas}\]

<table>
<thead>
<tr>
<th>Vibration Mode</th>
<th>SC323 $V_{cr}$ [m/s]</th>
<th>SC279 $V_{cr}$ [m/s]</th>
<th>SC281 $V_{cr}$ [m/s]</th>
<th>SC412 $V_{cr}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>4.5</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>2nd</td>
<td>28.5</td>
<td>10.0</td>
<td>11.8</td>
<td>10.1</td>
</tr>
<tr>
<td>3rd</td>
<td>79.8</td>
<td>18.8</td>
<td>32.9</td>
<td>28.34</td>
</tr>
</tbody>
</table>

The setup for these models is a combination of the models from sections 3.2.1 and 3.3.1. Just as the models in the static analysis the flow field is given a constant uniform speed starting from the inlet boundary, but much like the wind gust analysis the transient behaviour, rather than the static behaviour of the antenna, is analysed. The time step size is set as 0.1s, for a total of 50 steps to reach the 5s mark. The SC281 antenna is selected for this analysis since it is the one that results in the lowest safety factor of the four model antennas for a given speed during the static analysis. Therefore, it should represent the worst case scenario, which is what is important for design validation purposes. As future work and if the partnering company is interested, similar analysis can be performed for the rest of the antennas.
The critical speed that excites the first natural mode is 1.8m/s, which is way below 5m/s and thus, it should not be strong enough to produce oscillations. The following critical speed is 11.8m/s and this is the mode that is most likely to be excited with constant wind speeds. The third mode of vibration could be excited at 31.9m/s constant wind, but it is also less likely to occur. For investigational purposes all there models were run to confirm the hypothesis. Each run took approximately 11hrs with an AMD QuadCore (2.4GHz) computer that has a 4Gb RAM and 512Mb Video Card.

Each critical speed excited the structure in different manners. The antenna responded with some perpendicular-to-the-flow motion to the first and third critical velocities. However, the amplitudes of vibrations were less than 5% of the radome’s diameter, which is rather small. For the first critical speed, only one full oscillation cycle was seen and it died out before the 1sec mark. The model for the third critical speed experienced chaotic displacement for the first 3sec and then the vibrations were damped. The following graphs show the total displacement in the alongwind and crosswind directions of the radome’s free-end for the second run at 11.8m/s wind speed. It is important to note that the results are limited by the resolution of the analysis. The time step was set to 0.1sec, and thus the behavior of the antenna in between the time steps is unknown. Attempts to increase the amount of steps were unsuccessful. The solution would not converge due to lack of processing capabilities.

Figure 44: Displacement in the crosswind direction for the SC281 antenna under 11.8m/s wind
As it can be seen in Figure 44, the second model experienced larger amplitudes of vibrations when compared with the first model. The vibrations were somewhat symmetrical with respect to the rest position. All vibrations died after 3sec and all it was left was a constant deflection of the structure, which closely correlates with the steady state response of the structure under similar wind speed (20mm for a 11.8m/s wind speed for the transient analysis versus 17mm for a 10m/s wind for the steady state analysis). The maximum vibration amplitude was 67mm, which is approximately 60% of the antenna’s diameter.

No amplification of the vibrations was seen at the given speed as predicted by the literature, which questions the ability of the model to capture the resonance phenomena. The following figures show contour plots of the velocity streamlines at planes of different heights along the length of the antenna. It is evident that there is vortex formation and that analyzing this case in three dimensions was important since the behavior of the flow varies along the span of the cylinder. This result is in agreement with what has been shown in the literature, that is, when a cylinder is exposed to a steady constant flow, the wake formed downstream of the cylinder is three dimensional even for laminar flow, but only as long as the Reynolds number is larger than 170 [99,103]. Figure 47 shows the vortex formation downstream at the antenna surface. It can be seen how the flow separates before it reaches the half way mark of the cylinder.

Figure 45: Displacement in the alongwind direction for the SC281 antenna under 11.8m/s wind
Figure 46: Velocity streamlines at different planes for the SC281 antenna under 11.8m/s wind

Figure 47: Eddy viscosity representation for the SC281 antenna
Drag amplification, $C_{D_0}$, due to FIV can be calculated based on the estimated FIV amplitude $X$ normalized by the diameter $D$. In the case of fixed cylinders [77],

$$C_{D_0} = C_D (1 + 2.1 \frac{X}{D})$$

(11)

Based on the above equation, the drag amplification for the SC281 antenna under steady winds of 11.8m/s is 1.86.

2.8 Summary

This chapter presented a fluid-structure interactions study of the Sinclair Technologies SC Series communication antenna. The three main possibilities for the problem under analysis were investigated for four antenna configurations within the SC series (SC281, SC412, SC323 and SC279). First, the steady deformation state of the antenna under uniform and constant wind was studied. Second, the transient wind field, due to change in wind direction or strength leading to a time-dependent movement of the structure was studied. Third, the time-dependent movement of the structure due constant wind passing bluff bodies was also studied. The most relevant results are summarized below:

- The cantilever force test performed on SC281 antenna served as validation method for the FEA modeling of the system. The sample failed at approximately 508mm (20in) under 5836N (1312lbf) of pulling load, while the maximum bending stress at the fracture area and the modulus of elasticity at failure were calculated to be 287.87MPa (41,752psi) and 26502.70MPa (3843892psi), respectively. These results were compared against the manufacturers’ specifications.

- One-way coupling models were used to study the static behavior of the antenna under constant wind pressure.

- The analysis of the SC281 antenna for the range 10m/s to 80m/s ($8.74*10^3 < Re < 6.44*10^5$) concluded that the drag force increased linearly as the velocity increased. Furthermore, the drag coefficient remained constant at approximately 0.84 until the fluid velocity reached somewhere between 40-50m/s. From that point on there was a drop in the drag coefficient to about 0.5 and the drag force followed.
• It was also found that there is no significant correlation between the aspect ratio and the measured coefficient of drag and lift under a constant flow of air at 44m/s.

• The minimum safety factor, maximum deflection and maximum bending moment of the SC281 antenna under 80m/s wind were 2.3, 197mm and 3253.7Nm, respectively.

• The FEA simulations were found to be in good agreement with the literature, analytical models and experiments. Possible explanations for the discrepancies were explored.

• Two-way coupling models were used to capture the time-dependent movements of the antennas under the influence of wind gusts.

• The SC281 antenna was studied at the maximum rated speed by the company (76m/s) and it was found that the wind gust provokes an initial maximum displacement, followed by a series of oscillations. A peculiarity of the outcome was that the radome never displaced against the wind direction.

• Maximum stresses were seen at the base of the radome and they represented a 1.6 safety factor, which means that the antenna will not fail under 76m/s wind gusts.

• The deflection at the tip of the antenna reached 436mm for wind gust speeds of 95m/s, which is 8.4% of the total length and almost 4 times the radome’s diameter.

• The equivalent stress at the base of the radome matched the yield stress of the material, which suggested that wind gusts of 95m/s will start to plastically deform the antenna.

• The natural frequencies and mode shapes for all the antenna configurations were found with the FEA model. Maximum amplitudes of vibration were seen during the first mode, but they were still much smaller than deformations from external forces.

• The sine sweep experiment performed on the SC279 antenna did not captured the first natural frequency of 4.1Hz since the frequency sweep started at 5Hz; however, the following natural frequencies were very well captured. This experiment validated the FEA model.

• Two-way coupling models were used to model the flow induced vibrations of the antennas under constant and uniform winds.
• The critical speeds for which the natural frequency of the antenna coincides with the vortex shedding frequency and results in large vibration amplitudes were found for the four antenna configurations.

• The FEA models showed different behaviors of the SC281 antenna for each critical speed. The antenna responded with some perpendicular-to-the-flow motion to the first and third critical velocities (1.8m/s and 32.9m/s). However, the amplitudes of vibrations were less than 5% of the radome’s diameter. The second critical velocity (11.8m/s) resulted in larger amplitudes of vibrations. All vibrations died after 3sec and all it was left was a constant deflection of the structure, which closely correlates with the steady state response of the structure under similar wind speed (20mm for a 11.8m/s wind speed for the transient analysis versus 17mm for a 10m/s wind for the steady state analysis). The maximum vibration amplitude was 67mm, which is approximately 60% of the antenna’s diameter.

• No amplification of the vibrations was seen at the given speed as predicted by the literature, which questions the ability of the model to capture the resonance phenomena.

• It was also shown that the wake formed downstream of the cylinder is three dimensional even for laminar flow, but only as long as the Reynolds number is sufficiently high.

It is up to the designer to apply the above summarized results into the design and optimization of the antennas. Several measures could be applied to minimize undesired vibrations. The structure could be strengthened or stiffened and its mass could be increase. The damping of the structure could be increased by using visco-elastic materials or special dynamic absorbers. Furthermore, changing the aerodynamic characteristics by adjusting the aspect ratio or by adding aerodynamic spoilers could also decrease the adverse vibrations.
Chapter 4
Modeling and Simulation of SP Series Antenna

This chapter is in many ways an extension of the previous chapter since similar analyses, methods and models are developed to understand the static and dynamic behavior of the communication antenna, but in this case the SP Series, rather than the SC Series, is analyzed. These antennas are under similar service loading condition as of the SC Series, but now ice build-up is considered since the surface area is considerably larger. The effect of changing the inclination angle of the antenna is also investigated. The physical components of the antenna are larger in number and the connections amongst them are more complex; therefore, simplifications and concessions need to be made in order to develop models that represent reality as accurately as possible, but that are also efficient.

The SP Series is an ultra-high frequency (UHF) panel antennas designed for mission critical applications where reliability and durability are the major concerns [104]. The 3D virtual model provided by Sinclair Technologies for investigating the structural strength of the SP304 UHF Panel Antenna is displayed in Figure 49. This model includes only the structural components of the antenna; however, only a few of those parts are essential in the structural analysis. The major components
that will have a significant contribution to the mechanical strength of the antenna are: (1) radome cover, (2) the radome back, (3) reflector and (4) panels-supporting foam (see Figure 50). The radome is structurally important since it is in direct contact with the supporting plates and bolts, and with the ice and wind loadings. The reflector provides rigidity to the assembly, while the foam supports the cover against buckling.

*Figure 49: Exploded and assembled CAD models of the SP304 UHF panel antenna*

*Figure 50: Structurally relevant components of the SP304 antenna*
The chapter begins with definitions of the physical and material properties of the different components of the SP304 antenna. Then, the remaining two main sections explore the static response of the antenna due to wind pressure and ice loading. Different scenarios are explored in order to reach conclusion regarding the structural damage the antenna experiences under service loads. The FEA models were validated against literature; however, no validation analytical models or experiments were conducted in this chapter due to the complexity of the problem. However, since the methods and models of this chapter are the same as those applied in the previous chapter, and since those methods and model were already validated, it is assumed that the FEA models from this section are correct also reliable. The natural frequencies of vibrations and model shapes of the antenna are obtained with a FEM. In the present work, geometric, materials and changing boundary conditions non-linearities are not considered since the structural deformations taking place are small.

3.1 Physical and Material Properties

The following table highlights the most relevant physical properties of each component of the SP304 antenna. It is important to note that the overall weight of the antenna as modeled in the FEM is 15.1kg, while the physical weight of the antenna is 21.1kg. Therefore, the electrical and non-structurally relevant mechanical components must account for the remaining 5.0kg. To include all the components into the model to accurately reproduce the weight of the antenna would make the FEM unnecessarily complex and run time would increase significantly. A viable solution would be to add “point masses” at points of mass concentrations, but this could have a considerable adverse effect on the dynamic analysis.

<table>
<thead>
<tr>
<th>Part</th>
<th>Cover</th>
<th>Foam</th>
<th>Reflector</th>
<th>Back</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length X [m]</td>
<td>0.48158</td>
<td>0.45403</td>
<td>0.46355</td>
<td>0.47447</td>
<td>0.48158</td>
</tr>
<tr>
<td>Length Y [m]</td>
<td>0.1699</td>
<td>0.18237</td>
<td>0.0762</td>
<td>0.087884</td>
<td>0.20219</td>
</tr>
<tr>
<td>Length Z [m]</td>
<td>1.9502</td>
<td>1.9256</td>
<td>1.9304</td>
<td>1.9441</td>
<td>1.9502</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>3.7646e-3</td>
<td>9.8386e-2</td>
<td>1.5336e-3</td>
<td>4.8504e-3</td>
<td>0.10853</td>
</tr>
</tbody>
</table>
The following table lists the material properties of each component of the structure. The radome is made of a 3.175mm (0.125in) thick Lustran ABS 752 Resin, capped with a 0.508mm (0.02in) thick Centrex 485, ASA color white. The reflector is a 1.27mm (0.05in) Aluminum 5052-DH34 sheet, while the internal structural foam is simply Expanded Polystyrene Type I. Appendix F shows further details regarding mechanical and electrical specifications of the antenna.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>Lustran ABS 752 Resin</td>
<td>1900</td>
<td>0.4</td>
<td>1050</td>
<td>35.2</td>
<td>38.4</td>
<td>65</td>
</tr>
<tr>
<td>Foam</td>
<td>Expanded Polystyrene Type I</td>
<td>1.241</td>
<td>0.1</td>
<td>14.42</td>
<td>0.11032</td>
<td>n/a</td>
<td>0.1</td>
</tr>
<tr>
<td>Reflector</td>
<td>Alum 5052-H34</td>
<td>70300</td>
<td>0.33</td>
<td>2680</td>
<td>214</td>
<td>262</td>
<td>214</td>
</tr>
<tr>
<td>Back</td>
<td>Lustran ABS 752 Resin</td>
<td>1900</td>
<td>0.4</td>
<td>1050</td>
<td>35.2</td>
<td>38.4</td>
<td>65</td>
</tr>
</tbody>
</table>

3.2 Fluid-Structure Interaction Models

According to several authors such as Parkinson the most important physical parameter of a structure that could be excited due to the flow is the size and shape of its afterbody [74]. As seen in Figure 51 depending on the shape of the structure the flow breaks away at different positions along the surface of the body. For flow-induced vibrations (FIV) the pressure loading occurs
principally on the afterbody surface. Hence, a structure with a short afterbody, which is the case for the antenna under analysis, will only be weakly excited. Therefore, FIV will be ignored in this chapter since their effect on the dynamic behavior of the structure is minimal. Wind gust, ice load and inclined configurations will be considered.

![Figure 51: Representation of flow around a bluff body](image)

The simulation of the flow around the SP304 antenna followed the same principles to that of the SC Series antennas. As Figure 52 shows, five main regions are defined: 1) the inlet, 2) the outlet, 3) the tunnel walls, and 4) the antenna wall. At the left boundary (inlet) a velocity component in the “z” direction is given, while the velocity components in the other directions are zero. The pressure gradient in the flow direction is zero. At the right boundary (outlet) the pressure and the velocity gradients are zero. The tunnel walls and the antenna have a free-slip boundary condition, that is the velocity component and the pressure gradient perpendicular to the boundary are zero.

Only half of the antenna was initially modeled in order to reduce model size, complexity and run time. A symmetry plane was created in order to account for the entire model. However, it was later realized that the full model was necessary to properly account for the aerodynamic forces. A few results from these preliminary models can be seen in Appendix G. The fluid medium for these analyses is air at 25°C and 1 atm, which is represented by a large box enclosing the antenna.
and it was modeled with the 3D fluid element Fluid142 from ANSYS CFX. The fluid domain resulted in 100312 elements and 39724 nodes.

Just as in the previous chapter, the Computational Fluid Dynamics (CFD) problem is described by the Reynolds-Averaged Navier-Stokes equations (RANS) for incompressible fluids and the $k$-$\varepsilon$ turbulence model is used when appropriate.

![Figure 52: Computational domain for the flow field](image)

The fluid unstructured mesh is only refined in the region surrounding the antenna and it is allowed to be coarser in the farther reaches of the computational domain with the purpose of reducing the computational efforts. Similarly, when meshing the structural domain, regions with small details or sharp angles are refined. The surface of the antenna was defined as the interface between the structural solver and the fluid flow solver, just as in the previous chapter.

The FEM models were subjected to loads representing a uniformly distributed flow with constant velocity acting in the $y$-direction as seen in Figure 52. Wind loads were applied gradually to ensure that external work was converted to internal energy without introducing significant kinetic or viscous energy. Only alongwind effects are studied, since they have higher structural...
effects than crosswind for this antenna. The complete simulation ran until a convergence criterion was reached, that is the change in deflection from iteration to iteration is less than a certain value in the case of a steady state simulation [97].

The antenna was first analyzed under constant wind speed conditions ranging from 10m/s to 60m/s ($1.39 \times 10^5 < Re < 8.35 \times 10^5$), which is the maximum rated speed for this antenna. Each run took approximately 50min with an AMD QuadCore (2.4GHz) computer that has a 4Gb RAM and 512Mb Video Card.

<table>
<thead>
<tr>
<th>Speed [m/s]</th>
<th>Re</th>
<th>Total drag force [N]</th>
<th>$C_D$</th>
<th>Total lift force [N]</th>
<th>$C_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.39E+05</td>
<td>67.76</td>
<td>1.1778</td>
<td>0.2144</td>
<td>0.0359</td>
</tr>
<tr>
<td>20</td>
<td>2.78E+05</td>
<td>268.00</td>
<td>1.1645</td>
<td>0.9933</td>
<td>0.0416</td>
</tr>
<tr>
<td>30</td>
<td>4.18E+05</td>
<td>602.36</td>
<td>1.1632</td>
<td>2.1395</td>
<td>0.0399</td>
</tr>
<tr>
<td>40</td>
<td>5.57E+05</td>
<td>1086.31</td>
<td>1.1800</td>
<td>1.3344</td>
<td>0.0140</td>
</tr>
<tr>
<td>50</td>
<td>6.96E+05</td>
<td>1695.56</td>
<td>1.1787</td>
<td>2.1975</td>
<td>0.0147</td>
</tr>
<tr>
<td>60</td>
<td>8.35E+05</td>
<td>2442.52</td>
<td>1.1792</td>
<td>3.1908</td>
<td>0.0149</td>
</tr>
</tbody>
</table>

As it can be seen the drag coefficient remained constant over the range of speeds tested at approximately 1.17. This result is in agreement with the experimental work in the literature. According to Schewe the drag coefficient should remain constant as the Reynolds number increases for bluff body similar to a flat plate [105]. If Reynolds number effects occur, they should be very small. On the other hand, the lift coefficient had a sudden decrease around the speed at which the flow became turbulent.

The velocity streamlines shown in Figure 54 illustrate the turbulence formation at the trailing edge. At surfaces with high curvature there are adverse pressure gradients that, together with the drastic change in velocity through the boundary layer, cause the flow to be interrupted entirely and the boundary layer is detached from the wall. This detachment creates the turbulent flow that is seen in the figure. This turbulence creates some dynamic response of the structure; however, large amplitudes of vibrations are not expected since alternating vortex formation is not seen.
The velocity vectors shown in Figure 55 closely correlate with the pressure contour plots shown in Figure 56. As expected, it can be seen how in zones of high pressure, such as the leading edge the velocity magnitude is small. Full stagnation should be found at the center of the cover and as the probe moves towards the side edges the pressure should drop. Conversely, at low pressure zones, such as the sides of the antenna, there is a speed up of the fluid. Only considering the
pressure at front cover, the $C_D$ of the structure would be less than 1; except that there is suction on the back side: a negative pressure (relative to ambient) which is also shown in Figure 56.

![Figure 55: Velocity vectors on two random planes of the SP304 antenna under 60m/s wind](image)

![Figure 56: Pressure contour plot the SP304 antenna under 60m/s wind](image)

The structural analysis of the SP304 antenna is more complex than that of the SC Series antenna. The main reasons are the amount of structural elements, the complex geometry and the unique contact conditions. These contact conditions are required to simulate the interaction between the cover and the back, the cover and the foam, the foam and the reflector and the back and the reflector.
A diagram illustrating the contact types is shown below. If contact regions are bonded, then no sliding or separation between faces or edges is allowed. This type of contact allows for a linear solution since the contact length/area will not change during the application of the load. If contact is determined on the mathematical model, any gaps will be closed and any initial penetration will be ignored [97]. On the other hand, no separation contact allows small amounts of frictionless sliding, while maintaining the separation of faces in contact.

![Diagram of contact types](image)

*Figure 57: Connections between components of the SP304 antenna*

All contacts are flexible to flexible contact because both bodies participating in the interaction are deformable with stiffness in the same order of magnitude. All contacts are also defined as asymmetric. Asymmetric contact has one face as Contact and one face as Target, creating a single contact pair. This contact type is sometimes called "one-pass contact," and is usually the most efficient way to model face-to-face contact for solid bodies [97]. The target surface is always chosen to be the stiffer component of the pair. For example, in the cover-foam connection, the cover is the target and the foam is the contact. Neither interference, nor separation conditions were imposed to the contact elements. The underlying contact formulation method is very important to ensure the model mimics the real life situation and it could also considerably affect run time. Surface to surface 3D elements are used in this analysis with the augmented Lagrangian method to enforce the contact compatibility and check the penetration tolerance.
All parts were meshed and refinement was applied to areas of interest such as the fixed supports at the back cover. Various element types were used in the analysis according to the physical properties and loading conditions. The foam and covers were meshed with SOLID187 (10-Node Tetrahedral Structural Solid with three degrees of freedom at each node), which is very well suited to model irregular shapes. Both covers are thin shell-like structures; therefore, shell elements would have been more appropriate. However, for shell elements to work in fluid structure interaction models there are certain conditions that have to be met. First, the fluids on two sides of shell structures have to be of different ALE multi-material group IDs and remain on their respective sides [106]. This condition can be met since the air inside the antenna was not modeled. Second, the shell thickness should be small enough such that the thickness offset will not affect the overall system response [106]. The cover is only 3.175mm thick, which is very small, compared to the 1.9m length. Last but not least, either shell edges do not come in contact with fluids or that coupling effect can be negligible [106]. This condition is impossible to satisfy since the antenna cover is the interphase between the fluid domain and the solid domain. This could be the explanation as of why the FSI model solution would not converge when shell elements were used. SHELL181 (4-node element with six degrees of freedom at each node) was used for the reflector since it was not in contact with the fluid domain. The contact surface or edge must be built on the shell element side, while the target surface must be built on the solid elements side. CONTA174 was used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element. The element is applicable to 3-D structural and coupled field contact analyses. This element is located on the surfaces of 3-D solid or shell elements with midside nodes. The total amount of the elements and nodes in the FEM are 134,801 and 251,201, respectively.

Table 13: Nodes and elements for each component of the SP304 antenna

<table>
<thead>
<tr>
<th>Part</th>
<th>Cover</th>
<th>Foam</th>
<th>Reflector</th>
<th>Back</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>48,420</td>
<td>22,422</td>
<td>52,239</td>
<td>39,368</td>
<td>162449</td>
</tr>
<tr>
<td>Elements</td>
<td>24,317</td>
<td>12,429</td>
<td>25,531</td>
<td>19,612</td>
<td>81889</td>
</tr>
</tbody>
</table>
Only gravity and wind pressure were considered for this initial study; ice loading effects are later presented. The wind pressure is imported from the CDF model results for each wind velocity in the 10m/s to 60m/s range. As illustrated in Figure 59, the two pockets at the back of the radome are fixed at both sides in all degrees of freedom as that is the location of the clamping plates.
Figure 60, Figure 61 and Figure 62 show the results obtained from these models. Maximum deformation and von-Mises stresses of each component are plotted against wind speed. Note that deformation results for the reflector and back are almost identical so the lines superimpose in Figure 60.

![Figure 60: Maximum deformation results for the 10m/s to 60m/s wind speed range](image)

As it can be seen the cover experiences the maximum deformations of all the components. This result is expected since the front cover receives the maximum direct wind pressure and it is only supported against bucking by the polystyrene foam. The reflector experiences the maximum stresses; however, since the aluminum’s yield and ultimate stresses are also the highest of all the antenna components it does not represent the lowest safety factor. The minimum safety factor for
wind speeds of 60m/s occur at the foam component (2.13), which means that the antenna will not fail under the given wind load. The cover, reflector and back have safety factors greater than 7.41, 8.80 and 5.2, respectively.

Figure 62: Deformation contour plots of the SP304 antenna under 60m/s wind
In order to investigate at what point the antenna will yield under high speed winds, the nominal velocity was gradually increased ($V > 60\text{m/s}$) until the safety factor lowered below 1.0 for one of the components, at which point the component is supposed to start yielding. Models were run in 5m/s intervals. Based on the study the maximum wind speed the antenna will be able to withstand, without ice loading in consideration, is 90m/s.

3.2.1 Effect of Ice Load

The communication antennas under study are exposed to environmental conditions all year around. Therefore it is common to have ice build-up on these structures during the winter months. The company has taken data in different sites and concluded that an average ice loading is $12.7\text{mm}$ (0.5in) all around. In order to mimic the loading condition of a $12.7\text{mm}$ (0.5in) thick radial ice build-up a corresponding pressure vector ($P$) was applied on the outside surface of the radome. The pressure vector was calculated to be 114.2Pa in the same direction as gravity by means of the following formula:

$$P = \rho gr \quad (12)$$

where, $\rho$ is the ice density ($0.9167\text{g/cm}^3$), $g$ is the standard earth gravity ($9.81\text{m/s}^2$) and $r$ is the radial thickness ($12.7\text{mm}$) of the ice layer.

*Figure 63: Ice loading representation on the FEA model*
The following table summarizes four cases that represent all the possible combinations of ice and wind loading on the structure. Case 1 is the control, while Case 4 is the worst case scenario (both ice and wind loading simultaneously). Figure 64 shows a comparison between Case 1 and Case 3, where wind load is not considered. Ice loading provokes deformations of the structure and they are the largest at the top surface of the antenna, which buckles in.

**Table 14: Case analysis with 60m/s wind and 1.27mm radial ice load as parameters**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>No</td>
<td>No</td>
<td>0.000866</td>
<td>0.01753</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Case 2</td>
<td>Yes</td>
<td>No</td>
<td>6.35</td>
<td>24.33</td>
<td>2.13</td>
</tr>
<tr>
<td>Case 3</td>
<td>No</td>
<td>Yes</td>
<td>0.0775</td>
<td>1.505</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Case 4</td>
<td>Yes</td>
<td>Yes</td>
<td>6.36</td>
<td>24.91</td>
<td>2.16</td>
</tr>
</tbody>
</table>

![A: Structural Analysis](image1)

![B: Static Structural (ANSYS)](image2)

**Figure 64: Total deformation of the antenna (a) without and (b) with ice loading**

As it can be seen in Table 14, the cover experienced the maximum deflection and the reflector the maximum stresses for all cases. The minimum factor of safety for Case 2 and Case 4 was seen at the foam part, while for Case 1 and Case 3 it was seen at the cover. As it can be seen in Table 14 ice loading has only a small structural effect compared to high velocity winds. The
deformations experienced under wind pressure only are 82 times larger than under ice load only. It is interesting to note that the ice load is actually beneficial to the foam structure. The maximum stresses of the foam come from the cover buckling inwards right at the center of the structure and deforming the rib at the center. However, the vertical pressure due to the ice load has a component acting in the opposite way of the wind velocity, which alleviates the stresses at the ribs of the foam structure.

3.2.2 Effect of Inclination Angle

With the purpose of optimizing the electromagnetic properties of the antenna, the company mounts these antennas in inclined positions as well. As Figure 65 shows, the mounting hardware allows for a range of inclinations of 30 degrees: 15deg towards the downtilt position and 15deg towards the up tilt position.

(a) Downtilt configuration  (b) Uptilt configuration

Figure 65: Inclined configurations of the SP304 antenna (courtesy of Sinclair Technologies)
In order to investigate the effect of inclination angle on the aerodynamic properties and structural response of the antenna, FSI models were developed for six different configurations. The inclination angle was swept in five degree intervals from negative 15deg to positive 15deg, but the velocity was maintained at 60m/s. Figure 67 shows the sign convention that is used for this study. Procedures and setup are similar to the vertical configuration, the only difference is that the angle with which the wind reaches the structure changes with each model. Each run took approximately 95min with an AMD QuadCore (2.4GHz) computer that has a 4Gb RAM and 512Mb Video Card.

![Figure 66: Definition of sign convention](image)

Table 15 summarizes the most relevant results from each configuration. As it can be seen the vertical configuration was included as well as for comparison purposes. Maximum deformation of 6.98mm occurs when the antenna is 10deg downtilt. That configuration also experiences the
lowest safety factor (0.93). Since the safety factor is below 1 the antenna is likely to fail at this configuration under 60m/s wind.

Table 15: Results for the SP304 antenna for angle of inclination -15deg to +15deg

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>3.3026</td>
<td>2560.6</td>
<td>123.67</td>
<td>1.24</td>
<td>6.5291</td>
<td>29.174</td>
<td>1.1853</td>
</tr>
<tr>
<td>10</td>
<td>21.343</td>
<td>2735.4</td>
<td>70.277</td>
<td>1.32</td>
<td>6.983</td>
<td>39.378</td>
<td>0.93</td>
</tr>
<tr>
<td>5</td>
<td>50.68</td>
<td>2623.1</td>
<td>50.162</td>
<td>1.27</td>
<td>6.9287</td>
<td>37.859</td>
<td>1.58</td>
</tr>
<tr>
<td>0</td>
<td>2.656</td>
<td>2442.5</td>
<td>3.1903</td>
<td>1.18</td>
<td>6.35</td>
<td>24.33</td>
<td>2.13</td>
</tr>
<tr>
<td>-5</td>
<td>24.76</td>
<td>2520.8</td>
<td>56.717</td>
<td>1.22</td>
<td>6.4235</td>
<td>25.673</td>
<td>1.95</td>
</tr>
<tr>
<td>-10</td>
<td>8.3724</td>
<td>2661.0</td>
<td>100.59</td>
<td>1.28</td>
<td>6.569</td>
<td>29.002</td>
<td>1.26</td>
</tr>
<tr>
<td>-15</td>
<td>53.516</td>
<td>2680.7</td>
<td>139.13</td>
<td>1.29</td>
<td>6.677</td>
<td>30.841</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Variations of drag coefficient, maximum deformation and minimum safety factor can be seen in the following graph. As it can be seen the drag coefficient increases as the antenna moves away from the vertical position. It is interesting to note that 5deg in the downtilt direction are more damaging to the structure than 5deg in the uptilt direction.

Figure 68: Drag coefficient, maximum deformation and safety factor with varying inclination angles
Figure 69 shows deformation contour plots of the antenna front cover, since the cover is the component that deformed the most all cases analyzed. It is interesting to notice that the contour plots are very expressive in identifying the position of the antenna, as the maximum location of deformations varies with each configuration. For negative angles of inclinations (uptilt configuration), the regions of maximum deformation are larger at the top half of the antenna. As the antenna moves towards positive angles of inclinations, these maximum deformation regions move towards the bottom of the antenna.

Figure 69: Deformation contour plots of the SP304 antenna front cover
As Figure 70 shows, the concentration of stresses at the side edges of the reflector vary significantly with each configuration. However, the reflector can hold higher stresses without yield. Therefore, a more interesting area to pay attention is the surrounding area of the supporting plates. Figure 71 shows the equivalent stresses at the supporting plates. The corners experience very high stresses due to the tight angles. To minimize hot spots in this region, the designer should perform a shape optimization analysis having the corner diameter as the main parameter.

(a)-15deg  
(b) +15deg

Figure 70: Equivalent (von-Mises) stress contour plots for the reflector at maximum inclinations

Figure 71: Equivalent (von-Mises) stress contour plot at the supports for -15deg inclination
The streamlines around the inclined antenna are shown below and the vorticity contour plot is shown in Figure 73. As it can be seen the wake behind the structure is turbulent and vortex formation is seen. However, as it was previously discussed organized vortex formation does not occur for bluff bodies with short afterbodies.

Figure 72: Different views of the flow around the inclined antenna

Figure 73: Vorticity contour plot for the antenna at 15deg inclination angle
3.3 Modal Simulation

This section presents the mode shapes and natural frequencies resulting from a free-vibration modal analysis of the SP304 communication antenna. The antenna was given the maximum displacement that a 60m/s wind gust would result on and then it was released, and the free vibration was investigated afterwards. The first seven natural frequencies of the antenna assembly are 2.84Hz, 4.64Hz, 14.84Hz, 28.43Hz, 40.89Hz, 45.97Hz, and 52.48Hz. The corresponding mode shapes for the SC281 are seen in Figure 74. Maximum deflections obtained from the mode shapes are small in magnitude, which proves that this antenna will only be weakly excited. Furthermore, most of these modes of vibrations would never be excited since a very particular forcing input would be needed to excite them.

a) First mode

b) Second mode
c) Third mode

d) Fourth mode

e) Fifth mode
f) Sixth mode

Figure 74: Mode shapes for the first seven natural frequencies of the SP304 antenna

g) Seventh mode
3.4 Summary

This chapter presented a fluid-structure interaction study of the Sinclair Technologies SP Series communication antennas. These antennas are under similar service loading condition as of the SC Series, but now ice build-up and inclination angles are considered. Since a structure with a short afterbody, which is the case for this antenna, will only be weakly excited, flow induced vibrations were ignored in this chapter. The most relevant results are summarized below:

- For the initial analysis, the SP304 antenna was subjected to loads representing a uniformly distributed flow with constant velocity ranging from 10m/s to 60m/s ($1.39 \times 10^5 < Re < 8.35 \times 10^5$).

- It was found that the drag coefficient remained constant over the range of velocities at approximately 1.17. This result was in agreement with the experimental work in the literature. On the other hand, the lift coefficient had a sudden decrease at 30m/s, which is approximately the velocity at which the flow becomes turbulent.

- Alternating vortex formation was not seen, so large amplitudes of vibrations are not expected for this antenna.

- It was concluded that the cover experiences the maximum deformations (6.35mm), the reflector experiences the maximum stresses (24.33MPa) and the foam the minimum safety factor (2.13) of all the components at 60m/s wind. These results confirm that the antenna will not fail under the given wind load.

- The study was extended to higher wind speeds and it was concluded that the maximum wind speed the antenna will be able to withstand, without ice loading in consideration, is 90m/s.

- The effect of ice loading was also explored. It was concluded that ice loading has only a small structural effect compared to the effect of the 60m/s wind. The deformations experienced under wind pressure only are 82 times larger than under ice loading only.

- In order to investigate the effect of inclination angle on the aerodynamic properties and structural response of the antenna, FSI models were developed for six different
configurations. The inclination angle was swept in five degree intervals from negative 15deg to positive 15deg.

- It was found that the cover is the component that deformed the most in all cases analyzed. Maximum deformation of 6.98mm occurred when the antenna was 10 degrees downtilt. This configuration also experienced the lowest safety factor (0.93). Since resultant maximum stress is greater than the material’s yield stress, the antenna is likely to fail at this configuration under 60 m/s winds.

- It was also found that the drag coefficient increased as the antenna moved away from the vertical position.

- For all models, the corner regions around the supports experienced very high stresses due to the tight angles; therefore, these regions of high stress concentration are areas that could be optimized.

- Mode shapes and natural frequencies were also found using a FE modal analysis. The first seven natural frequencies of the antenna assembly were found to be 2.84Hz, 4.64Hz, 14.84Hz, 28.43Hz, 40.89Hz, 45.97Hz, and 52.48Hz. Maximum deflections obtained from the mode shapes are small in magnitude, which proves that this antenna will only be weakly excited.

The above summarized results should serve designers as a guide to understand the structural behavior of these antennas under service loads and thus design and/or optimize them accordingly. Several measures could be applied to minimize undesired deformations. Different material could be selected for critical components such as the polystyrene foam. The structure could be strengthened or stiffened with metal ribs. Furthermore, changing the aerodynamic characteristics by adjusting the aspect ratio, adopting a more aerodynamic radome or by adding aerodynamic spoilers could also minimize aerodynamic forces.
Chapter 5
Conclusions and Future Work

This chapter summarizes the results obtained from this investigation and highlights the areas for improvement. It restates the objectives and contributions and provides a framework for future research and development.

5.1 Conclusions

Large structures exposed to the environment such as the antennas in this research generally suffer damage from cyclic wind, rain, hail, ice load and impacts from birds and stones. Stresses from self-weight, ice loading and wind gusts will produce deformations of the structure that will lead to performance deterioration of the antenna. In order to avoid such a case, it is important to understand the static, dynamic and aerodynamic behavior of the structure and thus optimization can be achieved. The two main possibilities for the behaviour of the antenna under service loads were studied in this research:

1. The wind load and ice build-up on the structure causes a steady deformation state.
2. The fluid flow leads to a time-dependent movement of the structure, which is caused by one of the following effects:
   (a) A transient wind field exists even far away from the structure (e.g., change in wind direction or in strength, sudden gust of wind).
   (b) Due to the shape of the structure, the flow becomes time-dependent in the wake of the structure (e.g., generation of a von Kármán vortex street past bluff bodies impinged with a constant wind).
Therefore, the main contribution of this thesis is the application of the current fluid-structure interaction methods to the simulation and analysis of communication antennas, specifically, to collinear omni and large panel antennas. A methodology to understand the static and dynamic behavior of communication antennas under service loads was developed and verified. Different configurations of the SC Series of collinear omni antennas and the SP Series of UHF panel antennas were modeled, simulated and analyzed taking into account technical constraints and environmental factors. The different antenna configurations within the series were compared based on their capacity to minimize vibration effects, stress-induced deformations and aerodynamic loading effects. Conclusions regarding the effect of different parameters such as aspect ratio and inclination angle on structural response of the antenna were reached. Regions of stress concentration and maximum deformations were identified and the likelihood of structural failure due to those regions was assessed.

The following list enumerates the most relevant results obtained from this research:

- FEA models analyzing the aerodynamic and structural behavior of the antennas subject to loads representing a uniformly distributed flow with constant velocity were developed. The analysis of the SC281 antenna for the range 10m/s to 80m/s ($8.74 \times 10^4 < Re < 6.44 \times 10^5$) concluded that the drag force increased linearly as the velocity increased. Furthermore, the drag coefficient remained constant at approximately 0.84 until the fluid velocity reached somewhere between 40-50m/s. From that point on there was a drop in the drag coefficient to about 0.5 and the drag force followed. On the other hand, the analysis of the SP304 antenna for the range 10m/s to 60m/s ($1.39 \times 10^5 < Re < 8.35 \times 10^5$) concluded that the drag coefficient remained constant over the range of velocities at approximately 1.17. The lift coefficient had a sudden decrease at 30m/s, which is approximately the velocity at which the flow becomes turbulent. The difference in results from these two sets of test is due to the physical properties difference of the two series of antennas. The SC series is a circular cylinder, which the SP Series is a bluff body similar to a plate.

- Both series of antennas were tested at the maximum rated wind speed given by Sinclair Technologies. The SC series antennas should be able to withstand wind gusts of up to
76m/s since their minimum safety factor against yielding was found to be 1.6. The SP series of antennas could also be rated to withstand wind gusts of up to 60m/s with a factor of safety of 2.13. However, when the SP304 antenna was positioned at 10 degree inclination angle, its factor of safety dropped to 0.93. Both analyses were extended to obtain the maximum possible wind gust speed under which the antennas would yield. It was concluded that a 95m/s wind would plastically deform the SC281 antenna, while 90m/s wind would do the same for the SP304 antenna, as long as ice loading is not considered or the antennas are not positioned at an angle.

- The natural frequencies and mode shapes for all antenna configurations were found with a FEA model. Maximum amplitudes of vibration were seen during the first mode, but they were still much smaller than deformations from external forces. Flow induced vibrations were explored for the SC series of antennas; however, alternating vortex formation was not seen for the SP304 antenna and maximum deflections obtained from the mode shapes were small in magnitude. Since large amplitudes of vibrations are not expected for this antenna, no flow induced vibration analysis was performed.

- The effect of ice loading was also explored for the SP series since their large surface area makes them prone to ice build-up. It was concluded that ice loading has only a small structural effect compared to the effect of the 60m/s wind. The deformations experienced under wind pressure only are 82 times larger than under ice loading only.

### 5.2 Future Work

While this research has accomplished several key goals, there are still some studies that due to lack of time or resources were not possible. Therefore, those studies represent opportunities for future work. The following list enumerates possibilities for future work:

- Wind tunnel tests for the antennas could be performed in order to further validate the FEA models. There are only a handful of high speed tunnels in the country that could accommodate structures of such magnitudes; therefore, scaled prototypes would have to be developed.
• Methods for reducing vibration amplitudes could be explored. For example, the effect of strengthening or stiffening different components and thus increasing the structural damping could be explored. Perhaps increasing their mass or using visco-elastic materials or special dynamic absorbers to break down the wake pattern could be explored as vibration control methods.

• A fatigue analysis due to flow-induced vibrations would extend the overall structural analysis of the antenna. This study was not possible at this time since service data to determine S-N curves for each material were not available. As large vibrations may occur at moderate and frequent wind velocities, structures may undergo a great number of stress cycles that lead to damage accumulation and may determine structural failure without exceeding the ultimate limit stress. Therefore, fatigue analysis of the structure is also important if a through structural analysis is desired. The communication antennas under analysis experience wind gusts repeatedly and flow induced vibrations; therefore, it is wise to explore its effect on the structure. The fatigue damage of any component of the antenna depends on the complete stress history during the antenna’s service life. The calculation of this stress history and its effects on the structure is complex; however, simplified FEA models could be developed. The equivalent static pressure range to be used for fatigue design of vortex shedding-induced loads can be found by [107],

\[ P_{vs} = \frac{0.613V_{cr}^2C_D\beta I_F}{2\beta} \]  \hspace{1cm} (13)

where, \( V_{cr} \) is the critical speed, \( C_D \) is the drag coefficient, \( I_F \) is the fatigue importance factor (accounts for the degree of hazard and damage to property) and \( \beta \) is the damping ratio.

• The effect of inclination angle for the SC series is yet to be explored. Furthermore, a shape optimization study of the different antenna components could give more insight into the relationship between physical properties and maximum stresses.
References


1979.


B1/2.


[63] V.C. Strouhal, "on a particular way of tone generation (German)," *Annalen der Physik und Chemie*, vol. 5, pp. 216-251, 1878.


[80] G. Morgenthal, "Fluid-structure interaction in bluff-body aerodynamics and long-span bridge design: phenomena and methods," University of Cambridge, Department of


[94] G. Schewe, "On the force fluctuations acting on a circular cylinder in cross-flow from


[97] Ansys Help, Release 12.0 Documentation for ANSYS.


Appendix A: SC412 Product Specifications
Appendix B: SP323 Product Specifications
Appendix C: SP281 Product Specifications
Appendix D: Sample Calculations for the Cantilever Experiment on SC281 Antenna

Thin tube cross-section

\[ d_0 = 4.5825\text{in} \]
\[ d_i = 4.0755\text{in} \]

Moment of Inertia

\[ I_0 = \frac{\pi}{64} (d_0^4 - d_i^4) = 8.1in^4 \approx 3.37 \times 10^6 mm^4 \]
\[ = 3.37 \times 10^{-6} m^4 \]

\[ L = 112.5\text{in} \]
\[ \delta_{max} = 20\text{in} \]

Utilizing the results from \{1\}:

Maximum Stress at Fracture

\[ \sigma_{max} = \frac{M}{I_0} = \frac{PL_0}{I} = 41.752 psi \]
\[ \approx 287.87 MPa \]

\[ \{2\} \]

Modulus of Elasticity at Failure

\[ E = \frac{PL^3}{3\delta I_0} = 3843,750 psi \]
\[ \approx 26502 MPa \]

\[ \{3\} \]
Appendix E: Deflection Prediction for Steady Deformation State of SC281 Antenna

The maximum deflection of a cantilever beam under a distributed load can be calculated by:

\[ \delta_{\text{max}} = \frac{q(L_{\text{overhang}})^4}{8EI_0} \quad \{1\} \]

The wind pressure over the structure is:
\[ \text{Pressure} = \frac{F_D}{A} \quad \{2\} \]

The distributed load is:
\[ q = \text{Pressure} \times D \quad \{3\} \]

Equating the \{2\} and \{3\}:
\[ \frac{F_D}{A} = \frac{q}{D} \quad \{4\} \]

Projected area of the cylinder is:
\[ A = DL_{\text{Total}} \quad \{5\} \]

Substituting \{5\} into \{4\} and simplifying:
\[ q = \frac{F_D}{L_{\text{Total}}} \quad \{6\} \]

Substituting \{6\} into \{1\}
\[ \delta_{\text{max}} = \frac{F_D(L_{\text{overhang}})^4}{8EI_0L_{\text{Total}}} \quad \{7\} \]
Appendix F: SP304 Product Specifications

Sinclair's new UHF panel antenna SP304 series is designed for mission critical applications where reliability and durability are the most important. It is configured with a light weight UHF protected radome, covering 300-312 MHz frequency range by two frequency splits, 300-420 MHz and 450-512 MHz. Electrical downtilt is available in 0, 10, and 15 degrees. Other electrical downtilt are available upon request. The antenna can be pole mounted or wall mounted using Sinclair #170 clamps. Mechanical lift for up to 15 degrees down or 10 degrees up is available using Sinclair clamps #191. #170 and #191 must be ordered separately.

SP304 series has different polarization options including dual cross polarization, vertical polarization or circular polarization. The horizontal beamwidth is available with 65 degrees, 90 degrees, or 120 degrees. For vertical polarization, Sinclair also provides a wideband model which covers full 380-512 MHz frequency range with 90 or 120 degrees beamwidth.

The dual cross polarized option can be used for polarization diversity to reduce the multiple path effect. It can also be used as one Tx antenna and one Rx antenna to save the lower space.

Please use the full model name SP304V-SF1P70LDF given in the application notes to order the proper polarization, frequency band and beamwidth for your application.

**Application Notes**
- **Model name**: SP304V-SF1P70LDF
  - H, cross polarization
  - V, vertical polarization
  - C, circular polarization
- **Model name**: SP304V-SF1P50LDF
  - M1, frequency band 380-450MHz
  - M2, frequency band 450-512MHz
  - Fe-WB, wideband 380-512 MHz
- **Model name**: SP304V-SF1P50LDF
  - A5, horizontal beam width 65 degrees
  - A90, horizontal beam width 90 degrees
  - A120, horizontal beam width 120 degrees

**Electrical Specifications**

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>MHz</th>
<th>Gain (normal)</th>
<th>dB (dBd)</th>
<th>Input VSWR (max)</th>
<th>1.5:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 to 450</td>
<td></td>
<td>13.6 (11.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Polarization**
- Vertical
- Impedance: 50

**Pattern**
- Directional

**Horizontal beamwidth (typ)**: 70 degrees

**Vertical beamwidth (typ)**: 18 degrees

**Passive intermod.**: -110 dBc

**Lightning protection**: DC ground

**Bandwidth**: 70 MHz

**Electrical tilt**: 0, 10, 15 degrees

**Front-to-back ratio**: dB 22

**Mechanical Specifications**

<table>
<thead>
<tr>
<th>Connector</th>
<th>7/16 DIN (female)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length/Height</td>
<td>mm (in)</td>
</tr>
<tr>
<td>Width</td>
<td>483 (19)</td>
</tr>
<tr>
<td>Depth</td>
<td>216 (8.5)</td>
</tr>
<tr>
<td>Base pipe diameter</td>
<td>mm (in)</td>
</tr>
<tr>
<td>Weight</td>
<td>kg (lbs)</td>
</tr>
<tr>
<td>Weight (packed)</td>
<td>30.87 (68)</td>
</tr>
<tr>
<td>Shipping weight</td>
<td>27.05 (61)</td>
</tr>
<tr>
<td>Shipping dimensions</td>
<td>mm (in)</td>
</tr>
</tbody>
</table>

**Environmental Specifications**

- **Temperature range**: -40 to 70°C (-40 to 158°F)
- **Rated wind velocity (1/2 radial ice)**: km/h (mph) 217 (153)
- **Rated wind velocity (100 mph)**: km/h (mph) 177 (110)
- **Lateral thrust (100 mph)**: N (lbs) 978.6 (220)
- **Toroidal moment**: Nm (ft-lbs) 189 (160)
Appendix G: Sample Results from SP304 Initial Study
10m/s wind speed

70m/s wind speed
Appendix H: Modal Analysis Procedure for the SC Series Antennas

Procedure from [108]

Equation of motion:
\[
c^2 \frac{\partial^4 w}{\partial x^4}(x, t) + \frac{\partial^2 w}{\partial t^2}(x, t) = 0
\]

where:
\[
c = \sqrt{\frac{EI}{\rho A}}
\]

Free vibration solution:
\[
T(t) = A \cos \omega t + B \sin \omega t
\]

For fixed-free end conditions:
\[
\omega = (\beta l) \sqrt{\frac{EI}{\rho Al^4}}
\]

Frequency equation:
\[
\cos \beta_n l \cdot \cosh \beta_n l = -1
\]

Values of \( \beta_n l \):
\[
\beta_1 l = 1.875104
\]
\[
\beta_2 l = 4.694091
\]
\[
\beta_3 l = 7.854757
\]
\[
\beta_4 l = 10.995541
\]

<table>
<thead>
<tr>
<th>fn</th>
<th>w</th>
<th>bl</th>
<th>E</th>
<th>I</th>
<th>\rho</th>
<th>A</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC323</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.84</td>
<td>112.0907</td>
<td>1.875104</td>
<td>270000000000</td>
<td>2.2865E-07</td>
<td>1688</td>
<td>0.000903</td>
<td>1.413</td>
</tr>
<tr>
<td>111.80</td>
<td>702.4603</td>
<td>4.694091</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>313.04</td>
<td>1966.909</td>
<td>7.854758</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>613.44</td>
<td>3854.357</td>
<td>10.995541</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1014.06</td>
<td>6371.528</td>
<td>14.137168</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| SC281  |          |        |         |          |          |           |           |
| 3.21   | 20.15487 | 1.875104 | 270000000000 | 0.000003566 | 1688 | 0.002338 | 5.22 |
| 20.10  | 126.3084 | 4.694091 |              |          |          |           |           |
| 56.29  | 353.6672 | 7.854758 |              |          |          |           |           |
| 110.30 | 693.0465 | 10.995541 |             |          |          |           |           |
| 182.34 | 1145.656 | 14.137168 |            |          |          |           |           |

| SC412  |          |        |         |          |          |           |           |
| 2.76   | 17.34974 | 1.875104 | 270000000000 | 3.56553E-06 | 1688 | 0.002338 | 5.626 |
| 17.30  | 108.729  | 4.694091 |              |          |          |           |           |
| 48.45  | 304.4443 | 7.854758 |              |          |          |           |           |
| 94.95  | 596.5893 | 10.995541 |             |          |          |           |           |
| 156.96 | 986.2048 | 14.137168 |            |          |          |           |           |

| SC279  |          |        |         |          |          |           |           |
| 4.12   | 25.89179 | 1.875104 | 270000000000 | 7.66526E-07 | 1688 | 0.001157 | 3.739 |
| 25.82  | 162.2611 | 4.694091 |              |          |          |           |           |
| 72.31  | 454.3358 | 7.854758 |              |          |          |           |           |
| 141.70 | 890.3167 | 10.995541 |             |          |          |           |           |
| 234.24 | 1471.757 | 14.13716839 |            |          |          |           |           |