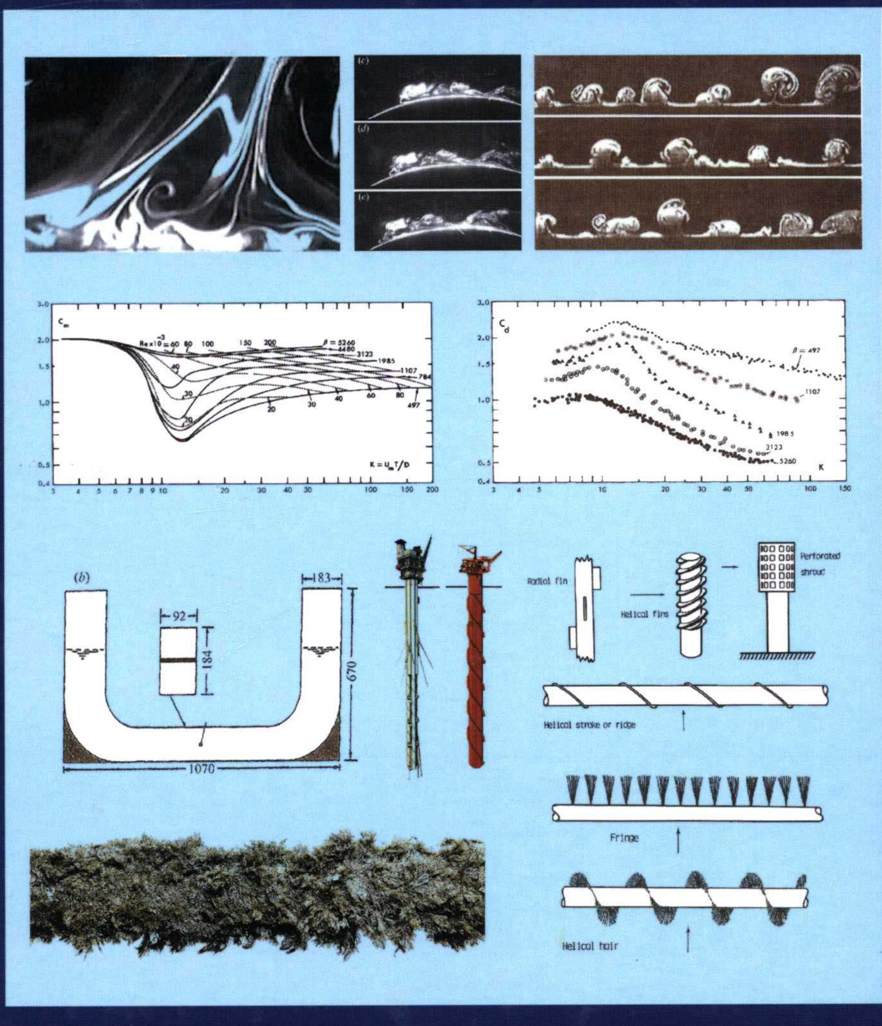
Turgut "Sarp" Sarpkaya

Wave Forces on Offshore Structures



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WAVE FORCES ON OFFSHORE STRUCTURES

A thorough understanding of the interaction of waves and currents with offshore structures has now become a vital factor in the safe and economical design of various offshore technologies. There has been a significant increase in the research efforts to meet this need. Although considerable progress has been made in the offshore industry and in the understanding of the interaction of waves, currents, and wind with ocean structures, most of the available books concentrate only on practical applications without a grounding in the physics. This text strives to integrate an understanding of the physics of ocean–structure interactions with numerous applications. This more complete understanding will allow the engineer and designer to solve problems heretofore not encountered and to design new and innovative structures. The intent of this book is to serve the needs of future generations of engineers designing more sophisticated structures at ever-increasing depths.

Dr. Turgut "Sarp" Sarpkaya is an internationally recognized authority in fluid mechanics research and was named by Cambridge University as one of the world's one thousand greatest scientists. "Sarp," as he is known to friends and colleagues, is the recipient of the Turning Goals into Reality Award by NASA, and he was selected Freeman Scholar by the American Society of Mechanical Engineers (ASME). Sarpkaya received his Ph.D. from The University of Iowa, followed by postdoctoral work at the Massachusetts Institute of Technology. He was the Thomas L. Fawick Distinguished Professor at the University of Nebraska and taught at the University of Manchester. He was named Professor and Chairman of Mechanical Engineering at the Naval Postgraduate School in 1967 and Distinguished Professor in 1975. His research over the past 50 years has covered the spectrum of hydrodynamics. His oscillating flow tunnel and the vortex-breakdown apparatus are two among several unique research facilities he has designed. Sarpkaya has published more than 200 papers and has explored for the Defense Advanced Research Projects Agency (DARPA) numerous classified projects dealing with the hydrodynamics and hydroacoustics of submarines.

He served as chairman of the Executive Committee of the Fluids Engineering Division of ASME and the Heat Transfer and Fluid Mechanics Institute. He is a Fellow of the Royal Society of Naval Architects and Marine Engineers, Fellow of the ASME, and Associate Fellow of the American Institute of Aeronautics and Astronautics.

*The book is dedicated to the memory of Herman Schlichting,
who shared with me his time and inspiration for an unforgettable year at
AVA/Göttingen in 1972.*

Preface

In 1857, William Thomson (Lord Kelvin) wrote to Sir George Gabriel Stokes, "Now I think hydrodynamics is to be the root of all physical science, and is at present second to none in the beauty of its mathematics." However, 117 years later, Sir Geoffrey Ingram Taylor had a thoughtful reminder (1974): "Though the fundamental laws of the mechanics of the simplest fluids, which possess Newtonian viscosity, are known and understood, to apply them to give a complete description of any industrially significant process is often far beyond our power."

The ultimate requirement for the understanding and quantification of the ocean–structure interaction is the understanding of the physics of turbulence, separation, and computational fluid dynamics. This is particularly true for the extraction of oil and gas. Computers (virtual simulations) and experiments (i.e., what can be calculated and what can be measured) have and will continue to have unsurpassable limitations. Even if one were able to calculate a given fluid–structure interaction, with sufficient time and resources, one will not be able to cover the entire parameter space. Thus, approximations, experiments, experience, successes and failures, empirical equations, and virtual modeling will continue to define the limits of our power to design structures that serve the intended purposes. Experience, physical insights, computers, past regrets, and future failures will continue to define the form and the substance of ocean–structure interactions. Developing the technology and carrying out the physical processes to discover and extract oil and gas, particularly from greater depths at increased risks and cost, have become one of the major challenges facing the industrialized countries, notwithstanding the efforts to develop alternate sources of energy.

The impetus for the offshore industry came from the tragic failure of the Texas Tower No. 4 (a U.S. Air Force radar platform) in January 1961, which was quite recent, considering the fact that humans have occupied this planet for millions of years. Such tragedies have precipitated the need to understand wave–structure interaction, tower dynamics in random seas, and gusts at ever-increasing depths in friendly as well as hostile environments. The pre-computer era and unsophisticated electronic age had to go through their own evolutions to alleviate the frustrations of the offshore engineer. Now the attention of the offshore engineer is engaged with the problems of how to study, measure, and observe the ocean environment and how to exploit its riches. These tasks require not only a periodic assessment of the state-of-the-art and definition of research goals for the foreseeable future, but also the understanding and use of *virtual modeling*, because the fundamental and physical research and numerical simulations are cheaper than regret and unknown conservatism.

The principal difficulties stem from the problems associated with the determination of the state of the sea, the three-dimensional and random nature of the ocean–structure interactions, quantification of the forces exerted on structures, and the lack of fluid-mechanically satisfying closure model(s) for turbulence. The collective creative imagination of many paved the way to physics-based laws, approximate models, and enlightening explanations of infinitely complex (but beautiful) phenomena.

Considerable progress has been made during the past few decades. The seminal experimental studies of Keulegan and Carpenter in 1956 inspired much experimental work and led, in the mid-1970s, to a better understanding of the vortex trajectories about bluff bodies, evolution of the transverse vortex street, three-dimensional instabilities and damping at very low K values, effects of the aspect ratio and three-dimensionality of flow along a cylinder, flow about tube bundles, vortex-induced oscillations, dynamic response, separation-point excursions, and to the demonstration (by this writer) of the dependence of the force coefficients not only on K (the Keulegan–Carpenter number) but also on $\beta = Re/K = D^2/\nu T$ (first conceived and used by Sarpkaya in 1976). This brought a new age of experiments in the laboratories and in the field, reliable data analysis, model tests, new journals, and ever-increasing practical and engineering research with the help of computers (starting with memories as large as 264 bytes in 1956 with an IBM 650). This writer is fortunate to have been an active part of this evolution.

Since the 1970s, the dependence of the force coefficients on K, k/D, and β has led to a better understanding of the vortex trajectories about bluff bodies, evolution of the transverse vortex street, separation–point excursion, three-dimensional instabilities, flow separation and damping at very low K values, effects of aspect ratio and three-dimensionality of flow along a cylinder, coherent and quasi-coherent structures, flow about multi-tube bodies, vortex-induced vibrations, numerical simulations, large-eddy simulation (LES) (an ingenious compromise based on "multilayer" filtering), Reynolds-averaged Navier–Stokes (RANS) equations, and detached eddy simulation (DES), which emerged to alleviate the difficulties that are inherent in both LES and RANS solutions; see, e.g., Mittal and Moin

(1997) and Breuer (1998). Other models, such as DESIDER (detached eddy simulation for industrial aerodynamics), UFAST (unsteady effects in shock-wave-induced separation), POD (proper orthogonal decomposition), unsteady-RANS, and others are relatively more recent entries into the art of modeling.

The friendly and enlightening input of many of my colleagues (Drs. C. Dalton, G. E. Karniadakis, C. C. Mei, D. J. Newman, O. H. Oakley, B. M. Sumer, J. K. Vandiver, M. M. Zdravkovich, and many others) is sincerely appreciated. I have had the privilege to be assisted by several colleagues with specific talents and information. Professor Charles Dalton (a longtime friend) read each chapter and provided valuable input and encouragement. Many graduate students have worked with me: Dr. Gerardo Hiriart Le Bert, Dr. Farhad Rajabi, Dr. Ray L. Shoaff, Dr. Frank Novak, and others working toward their M.S. or Ph.D. degrees. Mr. Jack McKay's ingenuity permeated the design and construction of numerous research facilities. I express my sincere appreciation for the extensive research support and willing cooperation extended to me through the years by the Office of Naval Research and the National Science Foundation. Finally, I am truly grateful to Mrs. Irma Fink, Ms. Greta Marlatt, and Mr. Jeff Rothal, who have found and delivered with incredible speed hundreds of references. For all of these I express to them and the Naval Postgraduate School my special gratitude. I owe my special thanks to Peter C. Gordon, Senior Editor of Cambridge University Press, for his friendly advice and encouragement during the past two years.

I am deeply indebted to Professor Günther F. Clauss for his gracious permission to use the drawings and photographs of his fixed platforms and guyed and compliant towers.

This book is dedicated to the designers and builders of offshore structures and to the researchers in this field. Their concern for the advancement of the state of the art motivated my work. I sincerely hope that my efforts, modest relative to their monumental achievements, will meet their approval.

T. "Sarp" Sarpkaya, California

www.omae2006.com

A video is presented by Sarpkaya in the above Web site in black and white. It depicts the motion of vortices for about two minutes and may be played over and over again.

In addition, there is a PowerPoint presentation by Sarpkaya on fluid damping (Chapter 7). It is provided *as a courtesy of Dr.-Ing. Walter L. Kuehnlein (advice@sea2ice.com), and Sarah@seatoskymeetings.com and ian@seatoskymeetings.com. To them, I express my gratitude.*

Contents

1

Introduction

It is appropriate to begin this introduction with a thoughtful reminder by Sir Geoffrey Ingram Taylor (1974): "Though the fundamental laws of the mechanics of the simplest fluids, which possess Newtonian viscosity, are known and understood, to apply them to give a complete description of any industrially significant process is often far beyond our power." This is particularly true for oil-hungry mankind's desire for hydrocarbons, with pollution as a bonus. The principal difficulties stem from the problems associated with the determination of the state of the sea, the three-dimensional and random nature of the ocean–structure interaction, quantification of the forces exerted on structures, and the lack of a fluid-mechanically satisfying closure model for turbulence. The past hundred years have shown that "almost-randomness" is the law of the physics of turbulence. One can quantify the consequences of turbulence and probe into its behavior for a given event only through approximate models and physical and numerical experiments (provided that the wideband of relevant scales is fully resolved). Even if the direct numerical simulations (DNSs) at Reynolds numbers as high as 10^7 were possible in the centuries to come, the large parameter space in any application precludes a purely numerical solution.

The past four decades have seen an explosion of interest in the broad subject of ocean hydrodynamics. This interest led to an improved and more realistic understanding of the physical characteristics of some time-dependent flows about bluff bodies and their mathematical formulation and experimental exploration. On the one hand, attention has been focused on controlled laboratory experiments, which allow for the understanding of the separate effects of the governing and influencing parameters, and, on the other hand, on mathematical and numerical methods, which allow for the nearly exact solution of some wave-loading situations (large bodies, whose volumes are as large as 10 times that of the great pyramid of Khufu). For many practically significant fluid–structure interactions involving flow separation, vortex motion, turbulence, dynamic response, and structural and fluid-dynamical damping, however, direct observations and measurements are continuing to provide the needed information, whereas theory has not yet played an important role.

The hydrodynamic loading situations that are well understood are those that do not involve flow separation. Thus they are amenable to nearly exact analytical treatment. These concern primarily the determination of the fluid forces on large objects in the diffraction regime where the characteristic dimension of the body relative to the wavelength is larger than about 0.2. The use of various numerical techniques is sufficient to predict accurately the forces and moments acting on the body, provided that the viscous effects and the effects of separation for bodies with sharp edges are ignored as secondary.

The understanding of the fluid–structure interactions that involve extensive separation and dependence on numerous parameters, such as the Reynolds number and the Keulegan–Carpenter number $K = 2\pi(A/D)$, a parameter that does not depend on time (it is a simple length ratio). There are several reasons for this. First, although the physical laws governing motion (the Navier–Stokes equations) are well known, valid approximations necessary for numerical and physical model studies are still unknown. Even the unidirectional steady flow about a bluff body remains theoretically unresolved. Fage and Johansen's (1928) pioneering work and Gerrard's (1965) vortex-formation model, followed by a large number of important experiments, have provided extremely useful insights into the mechanism of vortex shedding. It became clear that a two-dimensional ambient flow about a two-dimensional body does not give rise to a two-dimensional wake, and only a fraction (about 60% for a circular cylinder) of the original circulation survives the vortex formation.

Offshore technology has experienced a remarkable growth since the 1940s, when offshore drilling platforms were first used in the Gulf of Mexico. At the present time, a wide variety of offshore structures are being used, even under severe environmental conditions. These are predominantly related to oil and gas recovery, but they are also used in other applications such as harbor engineering and ocean energy extraction. Difficulties in design and construction are considerable, particularly as structures are being located at ever-increasing depths and are subjected to extremely hostile environmental conditions. The discovery of major oil reserves in the North Sea has accelerated such advances, with fixed platforms in the North Sea, now located in water depths up to about 185 m and designed to withstand waves as high as 30 m. In more recent years the depths to be reached for more hydrocarbon resources have increased to 1600 m or more. In fact, the depths reached during the past 55 years increased as $h \approx (1/540)N^{3.5}$, where h is the depth and N is the number of years, starting with $N = 0$ in 1949.

The potential of major catastrophic failures, in terms of both human safety and economic loss, underlines the critical importance of efficient and reliable design. In January 1961, the collapse of Texas Tower No. 4 off the New Jersey coast involved the loss of 28 lives. In March 1980, the structural failure and capsizing of the mobile rig *Alexander Keilland* in the Ekofisk field in the North Sea involved the loss of over 100 lives. The *Piper Alpha* oil and gas platform caught fire in 1988, leading to the loss of 167 lives. The *Petrobras* (a floating production system) sank in the Campos Basin in 2001 and cost 10 lives.

1.1 Classes of offshore structures

It is appropriate at the outset to provide some perspective to what follows by classifying briefly the wide variety of offshore structures that are in current use or that have been seriously proposed. The major offshore structures used in the various stages of oil recovery include both mobile and fixed drilling platforms, as well as a variety of supply, work, and support vessels.

The various offshore structures currently in use have been described in detail in the trade and technical literature. Mention is made of Bruun (1976), who summarized the offshore rigs used in the North Sea, and Watt (1978), who reviewed the design and analysis requirements of fixed offshore structures used in the oil industry. Ships and moored shiplike marine vessels are also used extensively, but they are treated within the field of naval architecture and are not of primary consideration in this book.

In earlier years the development and production activities at an offshore site were primarily carried out with fixed platforms. The jacket or template structures, and extensions to them, were the most common platforms in use. A jacket platform comprises a space frame structure, with piles driven through its legs. An extension to this concept includes the space frame structures that employ skirt piles or pile clusters. Some platforms contain enlarged legs to provide for self-buoyancy during installation. Jacket platforms are located throughout the world, including the North Sea, where they may be exposed to waves with heights approaching 100 ft.

Figure 1.1 shows numerous structures with a variety of names [fixed platforms: gravity-based structures (GBSs) and the jacket]. These are followed by guyed and compliant towers. Under the general title of floating structures, there are tension leg platforms (TLPs), SPAR-buoys, and floating production systems (FPSs). The largest platform until 1980 was one installed in the Cognac field off the Louisiana coast in a water depth of just over

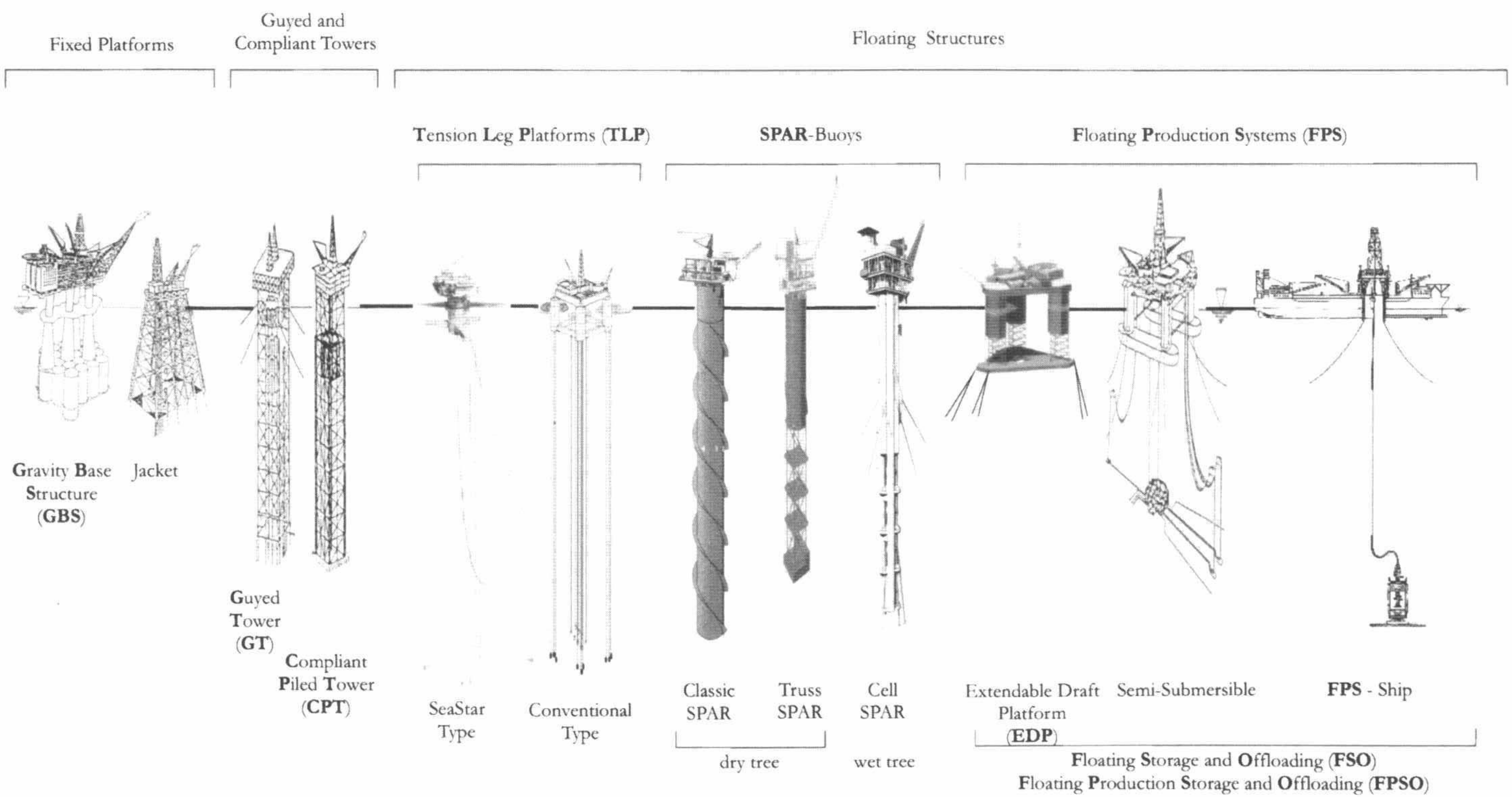

Figure 1.1. Representative offshore platforms (after Günther F. Clauss 2007).

300 m. This platform contained 60000 metric tons of steel and was fabricated in three sections, which were joined under water on site.

Gravity platforms depend on excessive weight, rather than on piles, for their stability. They are thus suited to sites with overconsolidated soils and have been used primarily in the North Sea. The most usual gravity platforms comprise a large base, which has the capacity for significant oil storage. In addition to their being located in depths of several hundred feet, gravity platforms are characterized by large horizontal dimensions. For example, a typical platform may be 180 m high, its base may have a diameter of 90 to 120 m, and it may have the capacity to store one million barrels of oil.

In more recent times, exploratory drilling is usually carried out with mobile drilling rigs. These include submersible platforms, rendered stationary with chain and wire mooring systems (Barltrop, 1998). They are limited to relatively shallow water, jackup platforms, drill ships or drill barges, and semisubmersible (SS) drilling platforms. The sketches of representative SS platforms are shown in Fig. 1.1 (GBS, jacket, guyed tower, and compliant structures). Such platforms are capable of operating at large depths. The major buoyancy members are placed well below the mean water level under operating conditions to minimize the wave action and to withstand severe weather conditions. They have a relatively low metacentric height (GM) that tends to reduce their pitch and roll motions. With careful design, counteracting inertial forces on surface-piercing columns and on submerged hulls may be made to cancel each other at a certain wave frequency. However, one must be beware of the fact that their high GM limits their variable load. In recent years, their primary station keeping by chain and wire has been augmented by azimuthing thrusters to assist the mooring system and the SS when in transit. The advances in dynamic positioning systems enabled them to operate and to transit at deeper waters without mooring.

What may be called a cousin of SS's is the tension leg platform (TLP). They are similar to SSs in a number of ways. TLPs have a greater water plane area, typically three to six surface-piercing columns, taut vertical mooring tethers, and a complete set of pontoons. All this is made possible because they are stationary.

Spar platforms (Halkyard, 1996) are essentially vertical, almost submerged, circular cylinders kept on station by lateral catenary anchor lines. Their center of gravity is below the center of buoyancy because of the fixed ballast concentrated at their bottom. This gives rise to a relatively large GM, i.e., enhances stability. However, as Barltrop (1998) noted, even though the large draft of a spar significantly reduces heave, its vertical length gives rise to a number of ocean–structure interaction problems: overturning moments that are due to wind, offloading forces, and current-induced forces. The spars are often fitted with spiral strakes to suppress vortex-induced vibrations. If the effect of the strakes is not experimentally optimized, they may give rise to massive separation at sufficiently high Reynolds numbers and enhance fluid loading and instability.

It should be noted in passing that the center of gravity of a spar may be lowered further (relative to that of a circular cylinder), and giving it a conical shape may further reduce the wave- and current-induced forces: round or hemispherical at the bottom and narrowing toward the free surface (resembling a pear). Above the free surface it may be reduced to a cylinder of constant radius. Such a "pear"-shaped spar has never been used.

The sequence of calculation procedures needed to establish the structural loading generally involves (a) establishing the wave climate in the vicinity of a structure, either on the basis of recorded wave data or by hindcasting from available meteorological data; (b) estimating design wave conditions for the structure; (c) selecting and applying a wave theory to determine the corresponding fluid particle kinematics; (d) using a wave-force formulation to determine the hydrodynamic forces on the structure (often very difficult near the mean water level where wave motion, currents, and strong gusts cannot be quantified); (e) calculating the structural response; and (f) calculating the structural loading, which includes base shear and moment, stresses, and bending moments. These steps may serve only as a rough indicator. The most important fact is that the design of a structure is based on computational fluid dynamics and virtual modeling, as pointed out earlier.