Bridge Aeroelasticity

Sensitivity Analysis and Optimal Design

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This book is dedicated to...

My parents, Juan and Encarna.

Pilar, Guillermo, Carlos and Dani.

Patricia and Nora.

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Preface

This book is dedicated to the study of an aeroelastic phenomenom of cable supported long span bridges known as flutter and proposes very innovative design methodologies such as sensitivity analysis and optimization techniques utilized successfully in automobile and aerospace industries.

The topic of long span suspension and cable stayed bridges is currently of great importance. These types of bridge pose great technical difficulty due to their slenderness and often great dimensions. Therefore, these structures tend to have problems caused by natural forces such as wind loads, some of which we have witnessed in our history. Besides their intrinsic importance, these constructions are currently of great interest and we are seeing a very high incidence of bridge construction in this historical period for overcoming geographical barriers such as bays, straits, or wide estuaries. The great majority of the obstacles are crossed by suspension or cable stayed bridges commonly called cable supported bridges. Due to their good serviceability, there are a high number of projects underway.

Therefore, it seems very convenient to write a book showing the current capability of analysis and design. Up until now, the information contained in this book could only be found partially in articles of technical journals, which are still useful for learning some specific details of scientific or technological advances, yet not enough for understanding the global panorama. Hence, we thought a text dedicated to this topic would be useful for bridge design engineers as well as researchers working in the field. This book only requires previous knowledge of structural finite element models and dynamics and it is advisable to have some previous background in bridge engineering. Nevertheless, it is very self-contained in such a way that all the information necessary to understand the theoretical developments is presented without the need of additional bibliography.

The book contains twelve chapters. The first one introduces some objectives of the book to readers and presents the most important aspects. It also states the appropriateness of this publication in this historic moment.

Chapter Two describes the collapse of the Tacoma Strait bridge in 1940, the impact caused among bridge designers and to the society at large, and the development and the evolution produced for suspension bridges since then. It narrates in detail great bridges constructed in the last decades and describes various important projects underway in Europe and Asia.

The third describes two existing methodologies for the study of flutter. One of them is based on boundary layer wind tunnel tests of a reduced model of a complete bridge, while the other is a hybrid approach consisting of two phases: the first to test a reduced deck section model in an aerodynamic wind tunnel, and the second a computational phase to process the data obtained in the first phase. Then, advantages and disadvantages of each method are discussed. In the opinion of authors, the second method is more promising for the future due to increasing bridge length and fast evolution of digital computers, and thus the rest of the book is concerned with this method.

The following two chapters are designed to show examples of how to calculate flutter velocity of cable supported bridges. Chapter Four starts with the study of suspension bridges under wind loads during construction. This is a very important and practical problem since a bridge should be able to support adequately not only high wind velocities during its service life, but also during its construction phase because the structural capacity is smaller. Consequently, it is essential to know the maximum wind velocity that an incomplete bridge can withstand in order to take some provisional actions necessary if a storm brings high wind at that moment.

In Chapter Five, various suspension and some cable stayed bridges are the topics of discussion, among which the readers will find the bridge over the Akashi Strait in Japan that holds the world record for span length. For each of them, the calculation to obtain flutter is carried out by multimodal analysis formulation. Then, such velocity is obtained as the number of vibration modes is increased to see the effect of increasing number of modes on such value. We will see that in all cases, using a small number of modes may lead to inaccurate results. We also include a study in which flutter occurs simultaneously for two different vibration modes; in other words, for the same wind velocity, damping cancels out for two different natural vibration modes. Although such situation may seem strange, it can be noted that the calculation of such velocity resulting from resolving an eigenvalue problem does not theoretically prevent repeated eigenvalues producing the same velocity. One might think that this circumstance is somewhat purely theoretical, but one of the practical cases in the book shows this very interesting situation. In fact, the theory supports the previous testing results of a bridge, for which different researchers had obtained similar flutter velocities, yet with different vibration frequencies. Nobody had a good explanation as to why this was happening.

Sensitivity analysis is the topic of Chapter Six. Today the importance of this analysis is widely acknowledged. It employs the derivatives of a structural response with respect to a structural property, which can be obtained by different procedures; one based on a finite difference method, or otherwise totally analytical if the derivative of the state equation is obtained. There are also intermediate approaches, in which after taking derivatives of the state equation, the finite difference method is used to obtain the numerical derivatives in some of the steps of the process.

Chapter Seven is dedicated to show how to obtain the sensitivity analysis of a particular problem -free vibration of a structure- or in other words, to obtain the sensitivity analysis of frequencies and natural vibration modes. We describe in detail the mathematical development to obtain these structural responses all analytically, which has two great advantages. On the one hand, it is very accurate for avoiding numerical errors of finite difference and its uncertainty with respect to the value used for the perturbation of the variable. Another aspect is that the analytical approach accelerates the process of obtaining sensitivities since it is programmable in computer codes.

One of the most important objectives of this publication is to demonstrate how to carry out sensitivity analysis of flutter velocity for cable supported bridges. This is shown in Chapter Eight. We start by differentiating the aeroelastic equilibrium equation for an incipient flutter and carry out all the mathematical process to obtain the analytical derivatives of the flutter velocity and reduced frequency of vibration. A step necessary to take prior to this is to know the sensitivity of vibration modes and frequencies, which we learnt in the previous chapter.

In Chapter Nine, a method to obtain sensitivity of flutter velocity of suspension bridges under construction is developed theoretically. The same examples in Chapter Four are used to show how to obtain flutter velocity for partially constructed bridges.

The book takes it further in the following chapter to show how to obtain flutter sensitivity analysis of complete bridges. The same examples as in the previous chapter are used. The sensitivity analysis is repeatedly performed with different number of vibration modes in order to demonstrate the importance of the number of modes included in the analysis. As we will see, the value of sensitivities, i.e., the derivatives, is even more sensitive to the number of modes used than to the flutter speed itself. Therefore, it is very important to include sufficient number of modes in the calculation to obtain adequate results. At the end of the chapter, we give some orientations in this respect.

The sensitivity analysis is a wonderful design tool in itself since it allows bridge designers to know beforehand how the modification of structural properties will affect the flutter velocity. They will know if the changes bring about some positive or undesirable consequences and how much they affect quantitatively. Such sensitivity analysis is even more useful when combined with optimization algorithms to carry out the procedure of optimal design of a structure. As mentioned in the book, the optimization methods are presently utilized in aerospace and automobile engineering, yet they have been completely absent in large bridge projects. This is somewhat surprising knowing the complexity of these constructions, their high cost and social implications.

Another important aspect of this book is to collect some work of its authors in this field as found in Chapter Eleven in which the formulation of optimum design of structures is developed considering flutter velocity as a constraint besides the common elastic type constraints. This approach is unique and innovative since it is not found in any existing book up till today.

After the theoretical approach of optimum design including aeroelastic constraints, the book concludes with Chapter Twelve in which we apply this methodology to the project of the future suspension bridge over the Messina Strait. With its main span of 3300 meters, it will hold the world record for a long while. Because of the deck configuration of this bridge consists of three independent box sections, three variations of optimization process are presented, which demonstrate the flexibility of the methodology and its capability to help bridge designers.

As has been mentioned previously, we can conclude that this book is very complete in the procedures for obtaining flutter speed of cable supported bridges, sensitivity analysis, and optimization techniques. The topic of sensitivity analysis is not treated with sufficient detail in existing bibliography, and the optimization aspects have not been considered at all up until today, so the book provides significant amplification of the topic.

This book contains a good portion of the work done by the authors for more than a decade on those topics and their experiences in various branches –not only academic- that have produced several doctoral theses and papers in scientific journals and a continuous experimental work of testing reduced bridge deck models in the wind tunnel of the University of La Coruña. It should also be mentioned the creation of software for aeroelastic, sensitivity, and optimization analysis of bridges as well as their participation as advisers for important bridge projects in different continents. We tried to convey our diverse activities and abilities, from purely research to practical application, so that it will be useful in the society when needed, and we hope to have achieved it.

During these years regarding bridge aeroelasticity, the authors have discussed topics and interchanged experiences and ideas with several people. Among them, A. Davenport and P. King of the University of Western Ontario, R. Scanlan and N. Jones of the Johns Hopkins University, P. Mendes from the IST of Lisbon and the team in the Politecnico de Milano, especially G. Diana and A. Zasso.

The book also deals with optimization techniques and in that scientific field the authors have enjoyed over a long period of time the wise advice and friendship of G. Vanderplaats, CEO of Vanderplaats R&D. Also, J. Arora of the University of Iowa, R. Haftka of the University of Florida and A. Belegundu of Pennsylvania State University have been instrumental in discussing many subjects and initiatives. Therefore, the authors are grateful for the hospitality and support provided on many occasions by all of them.

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