Preface

This is the first and only book on the HELS (Helmholtz equation least-squares) method. While the original contract with Springer to write this book was signed in 2003, it took 10 years for me to actually sit down and complete the writing. This is because during the past decade I have been heavily involved in research projects and teaching, which has constantly distracted me from fulfilling my obligation with the publisher. On the other hand, we have seen tremendous growth and expansion in the HELS theory. Its applications have been extended to many areas that have not been explored such as hybrid near-field acoustical holography (NAH), transient NAH, and NAH-based panel acoustic contributions analyses. Hence, in this sense it was good that I did not write this book 10 years ago. Of course, the HELS method is being further developed and expanded to new frontiers, including reconstruction of the aerodynamically generated sound field generated by an aircraft jet engine and realization of super resolution in discerning acoustic sources by taking input data in space at a rate less than the Nyquist sampling requirement. These new developments will be included in the second edition of this book.

What makes the HELS method unique is its simplicity in mathematical form, efficiency in numerical computation, and flexibility in engineering applications. The idea of using an expansion of certain basis functions to approximate the acoustic field can be traced back to the beginning of the last century. The most famous example was given by Lord Rayleigh to depict the acoustic field scattered from a corrugated surface. The differences and interrelationships between the Rayleigh series and the HELS method are explained in great detail in this book.

The underlying principles of the HELS method are strikingly different from the traditional Fourier acoustics and boundary element method (BEM)-based NAH. The Fourier acoustics-based NAH relies on the Fourier transforms and requires the source surface to contain a level of constant coordinate such as an infinite plate, an infinite cylinder, and a sphere. Moreover, the source must be in free space without the presence of any other source or boundary surface. Although the BEM-based NAH is suitable for arbitrarily shaped surfaces, it also requires the source to be in a source-free region. In addition, both of them require that the hologram surface enclose the entire source surface. If these conditions are not met, then they are invalid theoretically. This makes it difficult for these methods to be adopted in engineering applications because a source-free region is nonexistent and oftentimes a source surface cannot be enclosed by a measurement surface in reality.

In contrast to the traditional NAH implementations, the HELS method does not seek an analytic solution to the acoustic field produced by an arbitrarily shaped structure that cannot be found anyway. Rather, it attempts to obtain the best approximation of an acoustic field through the expansion of certain basis functions. Therefore it significantly simplifies the complexities of the reconstruction process, yet still enables one to acquire a good understanding of the root causes of different noise and vibration problems that involve arbitrarily shaped surfaces in non-free space using much fewer measurement points than both Fourier acoustics and BEM-based NAH do. The examples given in this book illustrate that the HELS method may potentially become a practical and versatile tool for engineers to tackle a variety of complex noise and vibration issues in engineering applications.

Since 2001, I have developed a new course on ME7460 Advanced Acoustic Radiation for graduate students in the Department of Mechanical Engineering at Wayne State University. The main objective of this course is for students to learn the state-of-the-art technology, namely, NAH to diagnose various noise and vibration problems encountered in practice. The major parts of this book are based on my class notes plus new developments in the HELS method accumulated over the past decade. While attending various acoustics conferences sponsored by professional societies such as the Acoustical Society of America, American Society for Mechanical Engineers, and Society for Automobile Engineering, I often have people asking me questions about the HELS method and its implementation. I am happy to report that finally there is a formal textbook on this subject that outlines in great detail this methodology, its implementation steps, and guidelines in practice. In particular, I have provided many examples on how to reconstruct and predict the acoustic fields emitted from different types of sources, and illustrated the intermediate steps in the derivations of various formulations. I sincerely hope that this textbook can serve as a resourceful reference, helpful guidance, and valuable tool for students, engineers, practitioners, and users to understand the HELS-based NAH, how it can be implemented in practice, and why.

This book is structured as follows. Chapter 1 gives a brief history of the major evolution of NAH since its inception in the early 1980s. For a comprehensive review of the development of this technology including its various implementations and extensions over the past three decades, the readers are referred to a review paper by the present author, which was published in the *Journal of the Acoustical Society of America* in 2008.

Chapter 2 reviews the expansion theory using the spherical Hankel functions and spherical harmonics, which form the basis of the HELS method. In particular, many examples are presented that use the expansion theory to reconstruct the acoustic field based on the input data measured on a hologram surface, or to predict the acoustic field based on the boundary condition specified on the source surface.

Chapter 3 discusses the underlying principle of the HELS method and its implementation. In particular, various types of regularization techniques are discussed, including the simplest one that is based on the least-squares minimization and that is very simple to program yet very effective to reconstruct the acoustic pressure field to the most comprehensive hybrid technique that can yield accurate reconstruction for all vibro-acoustic quantities in a nonideal environment. Experimental validations of using the HELS method together with hybrid regularization to reconstruct the vibro-acoustic quantities on the surface of highly non-spherical source geometry are demonstrated. And satisfactory agreements with respect to the benchmark data obtained through direct measurement using a scanning laser probe are obtained.

On the surface the HELS method is very similar to the Rayleigh series or expansion theory. Naturally, people would ask the question whether the HELS method would be subject to the same difficulty as the Rayleigh series did when reconstruction was attempted inside the minimum sphere circumscribing the source for an exterior problem, or beyond the maximum sphere inscribing the source for an interior problem. This question is answered in Chap. 4. In addition, the interrelationships between the HELS method and the Rayleigh series are revealed, and the reasons why the HELS method can be extended beyond the so-called region of validity for the Rayleigh series are presented. Most importantly, rigorous mathematical justifications for the HELS method are provided and its significance is discussed.

Once a solid mathematical foundation for the HELS method has been established, Chap. 5 proceeds to outline the guidelines for implementing this methodology to reconstruct the acoustic fields produced by non-spherical source geometry typically encountered in practice. In particular, detailed steps and formulations to determine the microphone spacing, aperture size, measurement distance, measurement points, etc. are illustrated and explained. In addition, special considerations together with various illustrations and schematic are given to the real-world test configuration and environment for noise and vibration diagnosis.

Chapters 6–10 deal with the extensions of the HELS method to a variety of scenarios that have posed serious challenges to the traditional NAH implementations. Needless to say, there are lots of room for further improvement and new challenges to meet. This is a never-ending process.

This book ends with some of the true stories I have personally experienced in addressing various vehicle-related noise and vibration issues. These stories stress the importance of understanding the physics of sound generation and propagation and how they may help us solve various complex noise and vibration problems in the most cost-effective manner.

I would like to take this opportunity to express my deep gratitudes to my former students, without whom it would not have been possible for me to complete this book. In particular, I would like to thank Dr. Zhaoxi Wang, who was the first student who conducted numerical simulations and validations of the early version of the HELS method; Dr. Nassif Rayess, who was the first one to demonstrate experimentally that the HELS method could indeed be utilized to reconstruct the

acoustic field generated by a vehicle buck; Dr. Tatiana Semenova, who revealed the interrelationships between the HELS method and the Rayleigh series and experimented the HELS via various expansions such as localized spherical waves, distributed spherical waves, and distributed point sources; Dr. Manjit Bajwa, who was the first to successfully conduct experiments using transient HELS-based NAH; Dr. Huancai Lu, who was the first to extend the HELS method to reconstruct the normal surface velocity distribution on highly non-spherical source geometry; Dr. Logesh Kumar Natarajan, who was the first to use hybrid regularization and proved experimentally that the HELS method can be used to provide satisfactory reconstruction of the acoustic pressure and the normal surface velocity distribution on highly non-spherical vibrating structures, and to conduct the panel acoustic contributions analyses; Dr. Richard Dziklinski, who was the first to show experimentally that one can violate the Nyquist sampling criterion, namely, take less than two measurement points per wavelength in space, yet still be able to discern two point sources separated by a distance less than one wavelength of the sound emitted by these sources, realizing the so-called super resolution via the HELS method; Dr. Mamohan Singh, who was the first to use the HELS method to visualize the acoustic field generated by an aircraft jet engine and who was instrumental in making HELS codes user-friendly; Mr. Ravi Beniwal, who has made significant contributions toward the graphic user interface of the HELS codes and its real-world applications for diagnosing vehicle noise and vibration problems; and last but not least, my postdoctoral fellow, Dr. Xiang Zhao, who was the first to conduct the numerical simulations using the combined HELS method and hybrid NAH to solve challenging inverse acoustics problems that cannot be done by using other methods.

Finally, I acknowledge that it was Dr. Earl G. Williams who challenged me the validity of using HELS to reconstruct the acoustic quantities on an arbitrarily shaped surface, thus forcing me to look deeper into reasons why the HELS method can be extended beyond the region of validity that the Rayleigh series cannot. However, it was beyond me to prove this validity mathematically. Fortunately, Dr. Victor Isakov came to the rescue and gave a rigorous mathematical justification, for which I am eternally grateful to him for his very important contributions toward the ultimate establishment of the HELS theory.

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