

现代声学科学与技术丛书

水下矢量声场理论与应用

Underwater Vector Sound Field Theory and
Its Applications

杨德森 B. A. Гордиенко 洪连进 著



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内 容 简 介

本书系统介绍了水下矢量声场特征和结构等方面的理论与应用,主要包括流体介质中声波的基本方程、海洋中确定性声源信号场的矢量特征、海洋噪声场的矢量-相位结构、水下声矢量信号的获取、矢量水听器的校准、矢量水听器的应用。

本书可作为理工科高等院校水声工程专业高年级本科生和研究生的教材,也可作为相关专业研究人员和技术人员的参考书。

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序

水声科学与水声技术是国家实施海洋战略和建立先进水下体系的重要研究领域。自第二次世界大战以来,特别是随着近代科学技术的进步,在世界范围内水声科学都取得了迅速发展。20 世纪末出现的水下矢量信号接收技术就是这些进步之一,该技术的出现改变了传统水下感知的声学物理量只有声压标量的局面,而矢量信号的接收不仅具有良好的抑制各向同性噪声的能力,提高探测信噪比,而且获取的信息量大,这些优势使这项技术在各海军大国都得到了迅速发展和使用。《水下矢量声场理论与应用》一书作者从声场能量的概念入手,介绍了水下信号的获取由标量向矢量进步的过程,对海洋环境中噪声场的相关性、声场中的矢量特征、矢量传感器的设计、校准及矢量信号接收和处理模式,特别在水声工程中的应用方面做了较为详尽的描述和介绍。该书是由中国和俄罗斯两国的水声工作者集多年研究成果共同完成的力作,两国作者们在各自国家的矢量声场及信号处理方面都做了大量的研究工作,他们之间的密切合作给我们展现出这种新型水下矢量信息获取与处理技术的优势和本领域最新研究成果。相信这本书会对水声工作者大有裨益,也一定会受到高校学子们的欢迎。

杨士莪

2013 年 5 月

前 言

人类一直在想方设法地了解神秘海洋中的各种信息。当人们知道声波可以较好地作为水下信息的载体以后,各种用途的水下声学系统相继诞生。如何让这些系统更有效地工作,使声学系统性能的提高与声信号有效的传播和信噪比的改善联系起来,这一切导致了水声工程学科的诞生。为了更全面地了解和利用声场中所包含的信息,借助于具有一定体积和密度并且合为一体的水下声压信号接收器——声压水听器是基本的手段之一。但是,在声信号的接收实践中,为了了解除声压以外更多的物理信息,人们探索研制了一维、二维和三维的声压梯度水听器。这种具有同一相位中心、多分量的声压梯度水听器就是矢量水听器。矢量水听器出现以后,立即得到了广泛应用。矢量水听器与传统的声压水听器相比,其优势是多方面的,特别是体积、重量、能耗、低频性能和获取信息量等方面。最引起人们关注的是矢量信号在海洋中对各向同性背景噪声的抑制能力,这种情况下对矢量信号的接收使信噪比得到改善。

这项工作可以追溯到 1877 年 Mr. Rayleigh 出版的著名的 *Theory of Sound* 一书阐述的基本声学概念。1882 年,应该也是 Mr. Rayleigh 设计了空气中质点振速的测量装置。1920 年,科学家 C. V. Drysdale 发表了论文 *The mechanical properties of fluids*,描述了利用中性浮力接收器获取水介质中声压梯度的过程,可惜这篇文章未能引起重视。1929 年,法国人 M. Carrier 也研究了质点振速的测量。通常认为,德国人 Conrad Tamp 和 Ervin Mayer 首先进行了声压梯度的测量研究。然而直到 1931 年,具有一定频带宽度的传声器出现,声压梯度的测量才成为现实,随后这方面的工作方兴未艾。

这时遇到的困难主要是缺少性能稳定、尺寸小(与波长相比)、灵敏度高的传感器,因此,常常使用两只相同水听器反接的办法实现声压梯度的接收,这种方法一直沿用到今天。显然,这种情况极大地阻碍了矢量接收技术的发展。

与此同时,对具有同一相位中心的声压梯度接收器的研究从未中止,各个国家的水声工作者均在此领域投入了大量的力量进行探索研究。20 世纪 50 年代中期,美国海军就曾研究了声压梯度接收器,尽管也是在不断地改进之中,但研究结果使用到了声呐浮标中。60 年代,法国人利用压电陶瓷研制了声压梯度传感器,日本人利用双叠片式的压电传感器设计了双通道的声压梯度接收器。从 70 年代开始,出于研制无线电声呐浮标的需要,美国海军开始研究组合式接收器,后来被称之为矢量接收器。显然,无线电声呐浮标使用的高要求直接促进了声压梯度水

听器及后来的组合式接收器(矢量水听器)的出现。

在这个发展过程中,俄罗斯水声工作者的研究一直令人瞩目。俄罗斯莱蒙诺索夫莫斯科国立大学的 С. Н. Ржевкин 教授和以他为首的声学系于 1944~1951 年就在声压梯度接收器方面做了大量研究工作。后来,苏联许多科学家和研究机构也被吸纳参加了这方面的研究工作,其中包括列宁格勒水声仪器研究所、列宁格勒船舶学院、远东国立大学、远东工业学院、远东海洋技术研究所、乌克兰基辅的“风暴”工程设计院、全俄物理与无线电技术研究院,到 1975 年已研制出多种型号的低频和低频矢量水听器。70 年代末期,声压梯度接收器在声呐的固定基阵和拖曳阵上的使用技术就申请了专利。随后,根据水声使用的特点和技术需求,声压水听器和质点振速水听器完美结合的结果——组合接收器或矢量水听器,已成为水声工程设计中的优先选择,其工作频带可以从零点零几赫兹到高频超过十千赫兹甚至更高。有人说“矢量水听器的出现是水声技术领域的一场革命”。为了防止传感器在水中的旋转振动,性能更为优良的同振型接收器随之产生。

早在 1985~1989 年,苏联就把这项技术应用到包括拖曳阵和声呐浮标的各种声呐之中。美国人于 1996 年成立了专门机构对这种新型信号接收方式进行海上目标(包括潜艇噪声特性测量方面)的计量和技术保障方法的研究工作。

20 世纪 70~80 年代,中国的水声工作者就开展了声压梯度接收器的研究。90 年代,在与俄罗斯相邻的哈尔滨市,哈尔滨工程大学水声工作者研制成功了我国第一只矢量水听器。本书中介绍的工作表明他们的研究脚步从未停止。当前中国在实施海洋强国战略,对水声技术的需求将不断增强。

本书作者均亲身参与了这项技术的研究工作,经历了各自国家矢量水听器诞生的全过程。基于研究工作的经历,本书介绍了水下矢量声场的基本理论及在这一理论上诞生的水下矢量传感器,有趣的是,尽管各国水声工作者互相有着学术间的交流与联系,但在研究中,却对这种新型传感器有着不同的称谓。俄罗斯的研究者认为,由于这种水下传感器是由多种基本传感器组合而成,故称之为组合接收器(Комбинированный приемник)。美国的研究者则多称之为矢量换能器(vector transducer)。中国的水声工作者鉴于水听器的称呼已经历史形成且使用广泛,故称之为矢量水听器(vector hydrophone)(本书统一用矢量水听器描述)。显然,称谓上的不同没有阻碍研究工作的进展,各国的水声工作者在此领域均取得了进步与成功。2005 年春季,著名的俄罗斯矢量声学专家乌·阿·休洛夫教授来哈尔滨工程大学实验室时感到惊讶,称在这里“看到了世界上性能最好的矢量水听器”。

本书的俄方作者 В. А. Гордиенко 是莫斯科国立大学物理系声学教研室教授,在著名的 С. Н. Ржевкин 教授带领下,长期开展矢量水听器方面的研究工作,是一位杰出的水声科学家。中方作者杨德森教授和洪连进教授在著名的杨士莪院士

带领下一一直开展矢量水听器方面的研究工作。在长期合作交流和研究基础上,本书汇集了作者们在矢量水听器领域的研究进展和成果,但也仅是声学界前辈肩膀上的一个小台阶,而对此的研究无疑是永无止境的。在此,中方作者特别感谢老师杨士莪院士的远见卓识和悉心教诲。此外,借本书出版之际,对这一项新技术给予支持的各方面人士表示衷心感谢。同时,感谢刘伯胜教授对全书进行了审校。

由于作者水平有限,不足之处在所难免,敬请读者批评指正。

Preface

Humans have been trying to understand the mysteries of marine information. When people learn that sound waves can function as a carrier of underwater information, a wide range of underwater acoustic systems with different applications have been born. To increase efficiency, performance improvement of acoustic systems is linked closely to the effective transmission of acoustic signals and increase in signal to noise ratio, which leads to the emergence of the discipline of underwater acoustic engineering. To better understand and utilize the information contained in the sound field, underwater sound pressure signal receiver, i. e. , sound pressure hydrophone with a given size and density has become one of the basic means. However, in the practice of acoustic signal reception, in order to understand more physical information besides the sound pressure, the development of one-dimensional, two-dimensional, and three-dimensional sound pressure gradient hydrophone have been explored. The sound pressure gradient hydrophone with the same phase center and multi-component is called vector hydrophone which has been widely used ever since its occurrence. The size, weight, energy consumption, low-frequency performance and access to information represent substantial advantages of vector hydrophone over traditional sound pressure hydrophone. Considerable attention has been focused on the suppression of isotropic background noise in the ocean by vector signals for the reception of vector signals leads to the improvement of signal-to-noise ratio.

This work can be traced back to the basic acoustic concepts put forward by Mr. Rayleigh in his famous book *Theory of Sound* published in 1877. A device was designed to measure the particle vibration velocity in the air also by Mr. Rayleigh in 1882. In 1920, scientist C. V. Drysdale published a paper entitled "The mechanical properties of fluids" in which he described the process of obtaining the sound pressure gradient in water media by means of neutral buoyancy receiver, but this article failed to attract much attention. In 1929, a Frenchman M. Carrier also studied particle vibration velocity measurements. It is generally believed that two Germans Conrad Tamp and Ervin Mayer first conducted studies on the measurement of sound pressure gradient. However, until the occurrence of microphone with a given bandwidth in 1931, the measurement of the sound pressure gradient was realized, and extensive research work continued afterwards.

The difficulty encountered at that time was the lack of a sensor with stable

performance, compact size (compared with the wavelength), and high sensitivity, therefore two identical hydrophones were reversely connected to realize the reception of acoustic pressure gradient and this approach has been used to this day, which obviously hindered the development of vector reception technology.

Meanwhile, research on the acoustic pressure gradient receiver with the same phase center never stops. Intensive research has been carried out in various countries. In the mid 1950s, the sound pressure gradient receiver was studied by the United States Navy, though in constant improvement, it was used in the sonobuoy. In the sixties of last century, a Frenchman developed a sound pressure gradient sensor by using piezoelectric ceramics. In Japan, a dual-channel sound pressure gradient receiver was designed with double chip piezoelectric sensor. From the 1970s, in order to develop radio sonobuoy, United States Navy started a combined receiver, later known as vector receiver. Obviously, higher requirements for radio sonobuoy facilitated the development of sound pressure gradient hydrophone and later the combined receiver (vector hydrophone) occurs.

In the course of this development, Russian underwater acoustic research has been remarkable. The department of Acoustics in Russia Lomonosov Moscow State University chaired by Professor Ржевкин studied acoustic sound pressure gradient receivers extensively during the period from 1944 to 1951. Later, many scientists and research institutes in Soviet Union was also involved including "Gidropribor" Research Institute (Leningrad), Leningrad Shipbuilding Institute, Far Eastern State University (FESU), Far East Polytechnic Institute (FEPI), "Storm" Design-Engineering Department (Kiev, Ukraine), All-Russian Research Institute of Physicotechnical and Radiotechnical Measurements (Mendeleevo, Moscow), "Kvant" SPA (Research Institute of Current, Moscow) and some other institutions. In 1975 various models of vector hydrophones with low and high frequencies have been developed. In the late 1970s, the sound pressure gradient receiver based on fixed arrays and towed array sonar technology was patented. Later, to meet the needs of acoustic applications, modular receiver i. e., vector hydrophone, the perfect combination of particle vibration velocity hydrophone and sound pressure hydrophone has become a preferred option in underwater acoustic engineering with operating frequency ranging from a few hundredths of a hertz to 10,000 hertz or higher. Some people believe that the occurrence of vector hydrophone revolutionized underwater acoustic technology. The prevention of rotational vibration in the water resulted in the occurrence of co-oscillating receiver with better performance.

Earlier on from 1985 to 1989, vector hydrophone technology has been applied to sonar equipment including towed array sonar and buoy in the Soviet Union.

In 1996 US has set up a special research agency to study noise characteristics measurement of marine target including submarines by this new signal reception technology and the corresponding technical protection measures.

In the 1970s and 1980s, Chinese researchers also studied sound pressure gradient receiver. Professors in Harbin Engineering University in the 1990s have successfully developed China's first vector hydrophone. Their research work described in this book will continue, especially amidst strong demands for underwater acoustic technologies in the process of implementing China's maritime power strategy.

The authors of this book are personally involved in the development of vector hydrophone in their own country and have years of research experience in this field. This book introduces the basic theories in the vector acoustic field and vector hydrophones developed accordingly. Interestingly enough, this new receiver is named differently even with scholarly exchange and communication in this field. In Russia, scholars believe that this receiver is composed of a variety of basic sensors, it is called “Комбинированный приемник”; in the US, it is named “vector transducer”, while vector hydrophone is widely used by Chinese scholars due to historical traditions. In this book, we adopt the name “vector hydrophone”. Despite the different names, progress in this field is remarkable world wide. In the spring of 2005, a famous Russian vector acoustics expert В. А. Щупов was surprised when he visited the lab of Harbin Engineering University saying he has seen “the best vector hydrophone in the world”.

Russian author В. А. Гордиенко is a Professor of Acoustics Department at Moscow State University. He, together with Professor Ржевкин, has been studying vector hydrophone for years and is a distinguished acoustic scientist. Chinese authors Prof. Yang Desen and Prof. Hong Lianjin are pioneer researchers in this field under the guidance of famous Prof. Yang Shie, a member of Chinese Academy of Engineering. Based on long-term cooperation and academic exchange, this book is a product of the advances and achievements in the field of vector hydrophone. A small step forward by standing on the shoulders of our predecessors, our research work is endless. The Chinese authors feel grateful to Academician Yang Shie for his guidance and vision throughout the research process. We would like thank all the people who have supported the development of vector hydrophone technology. Special thanks goes to Prof. Liu Bosheng for the review of this book.

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第 1 章 流体介质中声波的基本方程

广义地说,一种物质存在于另一种物质内部时,后一种物质就可称为是前一种物质的介质。某些波状运动,如声波、电磁波等,其借以传播的物质称为这种波状运动的介质,也可称为媒质,如机械波介质、电介质等。波动能量的传递需要物质中基本粒子的弹性或准弹性碰撞来实现,这种物质的成分、形状、密度及运动状态等性质决定了波动能量的传递状态,对波的传播起决定作用的物质称为波的介质。

声波是一种机械振动状态在介质中传播的现象,它可以在一切弹性介质中传播,其传播与介质本身的性质有关。介质弹性力的作用使得发射器附近的介质由近及远依次振动。介质具有质量,因而有惯性,惯性的作用使得介质的振动依次落后一定时间。通过介质的弹性和惯性作用,介质中相应局部的振动状态或形变就传到另一处去,这就是声波的传播过程。当振动在流体中传播时,形成介质的压缩和伸张交替运动,声波表现为压缩波的形式传播,即纵波。固体中由于有切应力,所以还有横波的传播形式。介质中振动的传播过程会有时间滞后,即声波在介质中传播有一定速度,称之为声波的传播速度,简称声速。在介质中,声波所涉及的区域统称为声场。

除特殊说明外,本章假设介质的切面弹性模量为零,不具有声吸收现象,并且除了声波引起介质本身的振动外,介质自身不作整体的运动,即在理想流体介质的假设下,介绍声波的基本方程、声场的基本性质和能量关系等。

1.1 声学基本方程

声波在流体中的传播过程是流体运动的特殊形式。当流体中某体积元受到外力的扰动而压缩和膨胀时,流体的连续性与压缩性使得与该体积元相邻的体积元作相应的运动。以此类推,体积元受到的扰动就以波动的形式向远处传播,形成了流体中声波的传播。建立声波的基本方程,就是研究流体元的状态,如密度、速度或位移等物理量随时间和空间的变化规律,通常有以下两种具体的描述方法^[1~5]。

(1) Lagrange 方法。在无限大连续流体空间中,取微体积元在某个初始时刻所在空间坐标为 $\mathbf{r}_0(A, B, C)$,随着时间变化,体积元运动到不同的空间位置,其瞬时位置为