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厦门大学

博 士 学 位 论 文

海上降雨的噪声特性研究

Study of Sound Characteristics of RainNoise at Sea

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摘要

海上降雨引起的噪声信号（简称降雨噪声）是海洋环境噪声背景场的一个重要干扰源，会极大地降低声呐的检测能力，影响水声通信的应用频段和降低水声设备的性能。考虑未来的海战极可能是在恶劣天气（往往伴随疾风暴雨）下进行，充分掌握降雨噪声的特性，不仅在军事上有利于检测海洋环境噪声背景中的干扰源，提升水声设备的作战效能，而且在民用上可拓展应用声学方法监测海上降雨的技术。近几十年来，美国等发达国家为了解释降雨噪声的产生机制，对自然界的降雨噪声开展了大量观测。前期的研究成果表明，降雨噪声的功率谱分布与空中降雨强度大小息息相关。但是，由于受限于降雨噪声的观测和数据获取的诸多困难与不确定性，现有的工作仍以揭示降雨噪声现象、解释水滴在水中辐射噪声信号的机理为主，尚未从量化角度系统地建立降雨噪声功率谱与降雨强度的内在联系。国内对降雨噪声特性的研究亦鲜有报道。因此，为深入掌握降雨噪声的特性，本文从以下多个角度开展研究：（1）在收集和综合各种文献资料基础上首次系统分析了水滴落至水面在水中辐射噪声信号的机理；（2）开展了降雨噪声的多次现场测量；（3）详细分析了降雨噪声的功率谱特征；（4）结合水声传播理论，创新性推导了降雨噪声源强度的提取方法。通过这些研究，初步掌握了降雨噪声的基本特性，为将来的应用研究奠定了基础。

论文的主要内容包括：

1. 首次深入、系统地分析了水滴落在水面时在水中辐射噪声信号的内在机制。在综合分析国内外降雨噪声相关文献的基础上，阐述了室内水滴实验与自然界实际降雨过程中辐射噪声信号的异同，提出了降雨中影响噪声信号辐射的三个主要因素：雨滴的粒径分布、雨滴的终端速度和雨滴的入射角度。采用可控法在实验室水池中开展了人工水滴观测和水滴撞击水面时产生的噪声波形与功率谱分析；

2. 从理论上推导了降雨噪声观测过程中水面有效测量面积的估计方法，设计了岸基和潜标两种形式的降雨噪声观测方案。开展了 12 次的野外降雨噪声的观测，获取了约 2000 min 的降雨噪声数据，涵盖了毛毛雨、中雨、大雨等不同

类型的降雨条件（0-72 mm/hr）。阐述了降雨噪声信号的提取方法、降雨噪声的功率谱计算方法。研究了干扰噪声的剔除方法、尤其是风成噪声功率谱的剔除方法。

3. 开展了降雨噪声功率谱的定量分析。通过采用“时间一致”的原则，同步匹配了空中降雨强度与水下噪声，提取了不同降雨强度下的典型的水下噪声功率谱，建立起噪声功率谱曲线类型与降雨强度的联系。根据功率谱在频带 1-30 kHz 的形状，创新性地将降雨噪声功率谱曲线分成三类：一是降雨强度为 0.1-4.0 mm/hr 的噪声功率谱，在频段 13-25 kHz 时出现较高幅度的谱峰；二是降雨强度在 4.0-18.0 mm/hr 的噪声功率谱，除了存在频段 13-25 kHz 宽谱峰外，频段 2-10 kHz 的功率谱级迅速增加；三是降雨强度在 18.0 mm/hr 以上（大雨或暴雨期间）的噪声功率谱，频段 1-30 kHz 上的谱级都较高，比无雨时的背景噪声增加了约 20-30 dB，且谱级具有负斜率趋势。此外，通过各频率点噪声功率谱与降雨强度的相关性分析，表明，在 1-30 kHz 的频率分析带宽内，频段 1-10 kHz 上各频率对应的功率谱与空中降雨强度的相关性最好。

4. 首次结合水声传播理论提出了海面降雨噪声源强度的计算方法。在降雨噪声研究文献中，通常把水听器接收到的降雨噪声信号直接当成水面降雨噪声源信号，而极少考虑水面降雨噪声源在水声信道传输过程的声能损耗，导致利用降雨噪声功率谱反演的降雨强度公式的系数不能普遍适用。因此，针对不同海洋环境和不同接收深度下的降雨噪声源强度归一化问题，本文在综合分析海面噪声源模型、降雨噪声源强度提取的研究背景和影响海面噪声源强度提取的因素之后，结合水声传播理论，创新性地建立了基于接收器降雨噪声信号提取海面降雨噪声源强度的方法，考虑了声波在水体传输中引起的声能损耗，提取了与测量水域环境不再相关的降雨噪声源强度。最后，通过传播模型的数值仿真给出海面降雨噪声源强度的校正系数，结合深海和淡水湖两个典型水域环境和实际测量的降雨噪声数据进行检验。结果表明，这种利用水听器获取的降雨噪声信号提取海面降雨噪声源强度的方法是可行的。

关键词： 降雨噪声；降雨强度；噪声功率谱；海洋环境噪声；声能损耗系数

Abstract

When precipitation falls on the water surface, an acoustic signal with broadband frequency and strong intensity will be radiated in oscillogram pattern. It is now known as rain noise. As one of loudest sources, the intermittent rain noise can decrease the detection ability of sonar, affect the application frequency bands of underwater acoustic communication and reduce using performance of part of underwater sound equipments. Knowledge of the characteristics of rain noise is important not only to identify interference sources in ambient noise spectrum, but also to measure the rainfall at sea with passive acoustic detection method. Yet, while decades of field measurements abroad have shown the part of spectrogram of rain noise and revealed the mechanism of raindrops making underwatersound, very few studies have tried to describe the characteristics of rain noise versus rainfall rates or establish a similar relationship between field parameters of rain noise and rainfall intensity. The few studies that have attempted to do so show that there is some uncertainty for rain noise spectral levels. Unfortunately, very few domestic research of rain noise also leads to be not familiar with the characteristics in detail. This work attempted to investigate the mechanism of sound radiation of droplets, have conducted experiments measuring ambient noise, rain and wind. Then, anacoustic discrimination process is developed to retrieve the oscillogram, sonogram and source levels of rain noise. The results showed as follow:

Firstly, based on knowledge of research foundation on rain noise at home and abroad, the underwater sound radiation mechanism of water drops impacting on the water surface is deeply and systematically analyzed. Further, the major differences of sound features between artificial water-drop experiments and outdoor actual rainfall is inducted and the three main impact factors for rain noise such as raindrop size distribution, terminal velocity and incidence angle are introduced. Then, a controlled observation experiment for sound radiation of water drops impacting on the surface of a pool in lab is conducted in order to describe acoustic signal patterns.

Secondly, a shore-based and submerged-buoy observation scheme for measuring rain noise are designed respectively and two typical observation sites are chosencarefully. As a result, 12 timesobservation experiments have conducted in total and about 2000 min spectrum data generated by rainfall have collected in an open lake or coastal shallow sea. The observed maximum rainfall rate is up to 72 mm/hr consisting of drizzle, moderate rain and heavy rain. Based on the raw data, a series of subsequent investigations have established including the quality control of sound data, signal waveforms extraction, elimination of noise, power spectral analysis, measured meteorological data processing, matching of sound feature and meteorological information and so on.

Thirdly, a matching method between power spectrum of rain noise and the synchronous rainfall intensities is studied and their relationship is established. The results show that: with rainfall rate increases, the sound levels above 10 kHz begin to increase. For example, when rainfall rate is up to 0.3 mm/hr, the sound levels increase at least 10 dB in the frequency band of 10-20 kHz. When the rate continue to increase beyond 18 mm/hr, the sound levels below 10 kHz increase sharply while the sound levels above 10 kHz increase slowly, which suggest that there is different spectral shapes generated by drizzle and heavy rainfall. According to the shape of spectral curve, the sound spectrum can be divided into three groups: (1) there is a higher –level spectral peak in the frequency band of 10-25 kHz, which generally occurs during the period of drizzle that rainfall rates are 0.1-4.0 mm/hr. (2) the sound spectral level increase quickly frequency band of 2-10 kHz as well as the spectral peak in frequency band of 10-25 kHz, which generally occurs during the period of rainfall ratesbeing 4.0-18.0 mm/hr. (3) the sound spectrum curve is seen as negative trend on the slope in the frequency band of 1-30 kHz during the period of rainfall rates beyond 18 mm/hr. It is worth noting that thevalue increases at least 20-30 dB than the one during the period of no rain.Furthermore, correlation analysis is carried out for sound power spectrum in the frequency band of 1-30 kHz and the result shows that there is stronger correlation between rain noise spectrum in frequency band of 1-10 kHz and rainfall intensities.

Lastly, a theoretical model of ambient noise for surface sources and influence factors of retrieving sound level between surface sources and underwater receivers are discussed. The sources of rain noie are assumed to be statistically independent directional acoustic sources situated on the surface, and the effects of ocean environment on ambient noise are studied. Then, based on the underwater sound pressure from receiving hydrophones away from some depth or distance, a method of sound intensity extraction is present. Then, combined with numerical propagation model simulation, the corrected sound levelsare computed and compared by measured sound spectrum. Thecorresponding comparison results with two examples show that the sound intensity extraction method is reasonable feasible.

Key Words: Rain noise; rainfall intensity; power spectrum; oceanic ambient noise; attenuation coefficient of sound energy

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