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Rayleigh's Acoustical Research on the Fog Signal

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Abstract

In 1896, Rayleigh was appointed as Scientific Advisor of the Trinity House. Rayleigh applied his knowledge of sound to developing effective fog signals during his 15-year tenure at the maritime organization. Rayleigh's expertise on acoustics met an appropriate field for its application during his improvement of the fog signal for the institution. Rayleigh's activities at the Trinity House were motivated by his desire to make contribution to the public. During his research on the fog signal, Rayleigh effectively employed his expertise acquired through his mathematical and experimental research on sound and vibration since the 1860s. Rayleigh developed effective horns for emitting fog signals and proposed various ways of overcoming the weaknesses of sound signals available at that time. While attempting to solve the problem of the attenuation of sound signals disseminating through the air, Rayleigh put foundations of atmospheric acoustics by developing new scientific theories about it.

Keywords: *Rayleigh, Fog signal, Sound, Trinity House, Diffraction, Attenuation*

I. Introduction

Rayleigh (John William Strutt, 3rd Baron Rayleigh, 1842-1919), one of the most influential scientists in the late 19th and early 20th centuries in Great Britain, earned the Nobel Prize in Physics in 1904[1]. He is also famous for his book, *The Theory of Sound* (1877-78)[2], which is credited with opening up modern acoustics and contributing to the development of mathematical physics[3]. He graduated from Cambridge University in 1865 and was instrumental in developing the Cavendish Laboratory into an established center of experimental physics under his control of it from 1880 to 1884[4]. Following his resignation from the Cavendish Laboratory, his research was conducted chiefly at his own home in Terling Place, Essex.

Rayleigh had a lot of concerns in the application of his acoustical expertise to practical problems. He carried on some experimental research in order to understand and improve church bells and musical instruments. However, his activities at the Trinity House were the climax of his social service with acoustics. This maritime institution needed Rayleigh's knowledge on sound, and Rayleigh willingly complied with the requests to solve practical problems relating to the fog signal.

Although a number of researchers and historians treated various aspects of Rayleigh's acoustical research, none has focused on Rayleigh's research on the fog signal at this maritime institution. Thus the article dealing with Rayleigh's acoustical research on the fog signal provides good examples of how a acoustician in the late 19th and early 20th centuries applied his knowledge of sound to solving practical problems and how he gained insights into the mystery of nature from practical situations.

II. Improving Fog Signaling

In 1896, Rayleigh, succeeding John Tyndall, became

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Scientific Advisor of the Trinity House, where Michael Faraday had played the same role for more than 50 years. The Trinity House had a long history of managing coastal facilities such as lighthouses and buoys. Since the reign of Henry VIII, the Masters of the Trinity House in London had been elected from influential social and military figures including Samuel Pepys, a former president of the Royal Society[5]. Although the institution was not a national organization, it was a famous public association functioning for benefits of society. It helped wretched seafarer's families and supervised the coming and going of ships through the ports in England. Rayleigh believed that the role of Scientific Advisor would provide opportunities to apply his expertise in acoustics and optics to solving practical problems, so he accepted the duty and remained at the post for 15 years.

Rayleigh's work in the institution was related to testing and improving the fog signal which was sent from the coast for the safety of ships navigating in fog. Around 1900 Rayleigh concerned himself with the effect of the double siren involving two separate horns that was being used by the Trinity House[6]. He pointed out that two horns were heard from a distance at the same intensity as one horn. He noted that this phenomenon was evident even when the two horns were arranged in parallel and the observer situated on the axis of symmetry. This finding was in agreement with what Tyndall had experienced in 1874. He set out to measure the longest reach of sound among various combinations of several organ pipes. When a set of two pipes with a period difference of two seconds produced beats, the reach of the sound was much farther than that from a set of two pipes with the same period. Rayleigh could explain this result on a mechanical principle since the loudest part of the beats is 4 times as intense as that of each component with the same intensity. In a subsequent experiment, Rayleigh employed two pipes mistuned to the interval of a third minor. He could not hear, however, the beats because they were too slow. Although he expected that the compound tone would be twice as intense as the component tones, the observers could not pick up the difference of intensity. Rayleigh ascribed the unexpected result to physiological factors because he could not understand the phenomenon on physical principles. His investigation stopped at this step since he did not regard physiological acoustics as his research area. Nevertheless, his investigation was fruitful in that he identified a new and practical method of strengthening the fog signal by using the beats.

Another problem which Rayleigh solved using his professional knowledge of sound was related to the concept of diffraction[7]. At that time, sirens were often being used for fog signals. Diffraction of the sound from the horns of a siren frequently caused a failure in the transmission of the signal to some points within the estimated effective range. In particular, when the diameter of the mouth of the horn was greater than half wavelength of the sound, the effect of diffraction was critical. Rayleigh could provide a full explanation of the reason why diffraction caused a failure of the transmission of the signal to some areas. At some points off the axial line of the horn, where the phase difference between the sound ray from the nearest point of the mouth and that from the farthest point were exactly half wavelength of the sound, the siren was not heard. From this reasoning it could be explained that the signal observed at the sea far from the coast was lost even at 20 degrees from the axis, and the loss increased to 40 or 60 degrees. This was a very important problem that needed to be solved when it came to designing more efficient fog signaling horns at the Trinity House. In 1902, Rayleigh solved the difficulty by designing and making a new form of horns, which had an elliptical or elongated section with the long diameter placed vertical. This made the sound spread horizontally over the sea and reduced the loss of sound energy in an upward direction. A horn constructed on this principle was tested in his laboratory and proved to effectively cover the horizontal range of 150 to 160 degrees. Then a set of two horns was constructed and tested off St. Catherine's Point. The results were safisfactory, though some difficulties prevented exhaustive examination.

The result of Rayleigh's research on the perception of the direction of the sound source was also applied to the reception of the fog signal. Rayleigh's pioneering experimental work on the perception of sound direction arrived at the modern view that the perception of the sound direction depends upon the difference of intensity in case of high frequencies and the difference of phase in case of low frequencies. He also recognized that there could be no distinction between the two sound rays coming from the positions in symmetry in regard to the line connecting both ears of a person[8]. In 1907, he noted that the knowledge of the perception of sound direction was necessary in order to identify the source of a fog signal. Rayleigh suggested that the duration of a fog signal should be longer than 5 or 6 seconds so that the sailor could accurately find the direction of the sound source while changing the positions of ears by turning his head to and fro[9]. Rayleigh further suggested that several sailors' cooperation would enhance the accuracy of the localization by sharing their perceptions.

III. Obstacles to the Fog Signal

Unfortunately Rayleigh's efforts were not always productive. At times his attempts to solve problems were hampered by obstacles whose resolution was not to be achieved. 'The silent sea' observed by Tyndall was such an example. Tyndall had noticed that on the sea, fog signals were sometimes lost in the range of 1 to 2 miles but were again detected at greater distances. In 1902, the Committee of the Elder Brethren of the Trinity House was summoned to examine and solve the problem and Rayleigh took part in the investigation. At that time, most of experts believed that this phenomenon was caused by interference between the direct sound and its reflection from the sea surface as Lloyd's bands in optics occur. Lloyd's bands are bright and dark bands alternately formed by the interference of direct light ray with its very oblique reflection from a mirror as if there were two light sources emitting coherent light rays. Rayleigh could make similar bands of interference acoustically in his laboratory.

After the field investigation, Rayleigh rejected the conventional interpretation that 'the silent sea' was part of acoustical Lloyd's bands. If the phenomenon had been similar to Lloyd's bands, there should have been a regularly alternate pattern of constructive and destructive interference. But the observation did not match the expectation. And, according to the analogy to Lloyd's bands, the points of silence should be at specific heights above a point of the sea and should be confined to those heights. But in the area of 'the silent sea', the sound was not detected at any height. Nevertheless, Rayleigh could not explain why 'the silent sea' displayed the features. In this case Rayleigh could nullify the established view using his expertise, but he could not provide any better explanation and could not help to solve the problem. A number of factors causing irregular propagation patterns of sound through the atmosphere were to be found later.

Rayleigh's concern with how to lengthen the reach of the fog signal led him to pioneer a new field of atmospheric acoustics by reflecting on the cause of the loss of sound transmitted through the air. In 1899, Rayleigh noted Wilmar Duff's observation, which showed that the processes of absorption of sound described by G. G. Stokes and G. Kirchhoff were not enough to account the attenuation of sound. Duff attributed the great part of the falling off to radiation. Stimulated by Duff's observation, Rayleigh derived an expression for the energy dissipation by radiation. But he realized that the absorption due to radiation was much too small to account for the difference, and attributed another cause of the attenuation to "a delay in the equalization of the different sorts of energy in a gas undergoing compression, not wholly insensible in comparison with the time of vibration of sound."[10] Rayleigh realized that extra absorption was caused by the slowness of exchange of the energy between the sound wave and the internal degree of freedom of the molecules. Since this idea was picked up by James Jeans in 1904, relaxation theory of sound absorption in fluid was widely explored in the 20th century[11].

In 1916, Rayleigh noticed that the sound from even a powerful siren reached merely 1 or 2 miles. Rayleigh remembered that his calculation in 1896 had indicated that a 60 horsepower siren giving off sound in all directions should be audible to 2,700 km in favorable conditions. On the other hand, Sir G. I. Taylor suggested that the loss of sound transmitted through the lower atmosphere was chiefly caused by the eddying motion in it. Stimulated by Taylor's suggestion, Rayleigh began to reconsider the causes of the attenuation of sound. He believed that the loss originating from the radiation and conduction of heat was not enough to explain the degree of attenuation observed over the distance.

Rayleigh added the reflection from obstacles as another cause of attenuation of sound through the air. He came up with the concept of invisible surfaces of reflection in the air[12]. He hit upon his observation at St. Catherine's Point in 1901, where he heard echoes for at least 12 seconds after the siren had stopped, though the sky was clear and the waves were still. Rayleigh thought that this reflection would be caused by irregular layers somewhat sharply defined in the medium. He guessed that the rising flux of heated air might produce these reflective surfaces. Rayleigh criticized Taylor's eddying motion theory in that Taylor considered neither dissipation nor reflection and pointed out if there were the eddying motion disturbing the sound transmission, the velocity of the sound wave would be decreased at some points in the vortex and be increased at other points, so that the total effect would be the same as if no vortex existed.

In 1918, Taylor answered Rayleigh that if the turbulence was a maximum in any particular direction then more sound energy will be dispersed from the wavefront as they proceed in that direction than will be received from the less turbulent regions. He clarified that as Rayleigh suggested, the effect of give and take of energy in eddies occurred, but the effect was limited to uniformly distributed turbulence.

Just after World War II, L. V. King performed extensive measurements of the sound detected from a fog horn under various conditions. His results were highly variable and depended on the atmospheric conditions. King accepted Taylor's ideas and suggested larger vortices whose diameters exceeded 40 meters could account for much of the variability in air-borne sound signals[13].

Therefore Rayleigh's ideas on the attenuation of sound in the air prompted a lot of discussions and were extensively influential on subjects of atmospheric acoustics in the 20th century. He performed pioneering research in atmospheric acoustics, which were inspired by his consulting job at the Trinity House.

Although Rayleigh had worked hard to improve the sound signal in fog, he made a major contribution to ending up the fog signaling by sound. In 1916, Rayleigh proposed to the Trinity House that the combined use of an underwater sound signal and a radio signal in the air would overcome the weakness of the sound signal through the air[14]. Rayleigh believed that if the underwater signal were effective within 4 to 5 miles, it could be used together with a radio signal. As an expert on sound, he was well aware of the weakness of the sound fog signal. Although he had tried to overcome the difficulties and to increase the effectiveness of the sound signal, he now began to think that a radio signal would be better than a sound signal, and seriously suggested the adoption of the radio signaling. Rayleigh pointed out that although both the sound signal and the radio signal are transmitted through the air, the radio signal is impervious to atmospheric conditions such as temperature and wind unlike the sound signal. He believed that radio technology at the time would allow a radio signal to be transmitted through 10 to 20 miles without fail. Rayleigh suggested detailed methods of radio signaling so that he anticipated a new era of fog signaling by wireless. His suggestions, which were to be adopted after World War I, marked the decline of the fog signaling by sound.

IV. Conclusions

As an established scientist, Rayleigh accepted the consulting job with the Trinity House because he cherished his cause of social responsibility and he intended to employ his scientific knowledge for the betterment of society. Rayleigh's research on the fog signal focused mostly on how to transmit sound farther and more clearly in fog. He investigated various ways of sending sound farther and made efforts to remove obstacles to the transmission of the sound signal. He devised new and effective sound sources for the fog signal and proposed effective ways of picking up fog signals. Furthermore he suggested new mechanisms to replace the sound signal. In this regard, Rayleigh's expertise which was developed during his mathematical and experimental research since the 1860s was crucial to his successful consultation with the Trinity House. Rayleigh identified new research topics during the course of his consulting with the institution and formulated new theories to explain the loss of transmitted sound. In the course, He pioneered atmospheric acoustics which were to become an established area in acoustics in the later 20th century. Thus Rayleigh's consultation work with the Trinity House provided him with a number of opportunities to apply his acoustical expertise to practical problems in one hand and to find new research subjects which were to be influential in acoustics in the other.

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[Profile]

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