

Review

Dependencies of Underwater Noise from Offshore Wind Farms on Distance, Wind Speed, and Turbine Power

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Abstract

The operational phase of offshore wind farms, lasting up to 20–25 years, exceeds the construction phase in duration. The ecological effects of underwater noise demand serious consideration, necessitating urgent research into its acoustic characteristics. This review conducts a systematic analysis of measurements of underwater noise from operational offshore wind farms, considering the correlations between turbine noise and distance, wind speed, turbine power, and foundation type. Propagation distance is the most critical factor influencing the underwater sound pressure level (SPL) of wind turbines, exhibiting a negative correlation with the SPL, with an attenuation of approximately 20.4 dB/decade. In contrast, wind speed and turbine power show a positive correlation with the SPL, with increase rates of 18.5 dB/decade and 12.4 dB/decade, respectively. Further analysis shows that foundation type and drive technology also have a significant impact on underwater SPL. With technological innovation, specifically the upgrade from conventional geared drive to direct-drive technology, the level of underwater noise can be reduced by approximately 9 dB, with the primary peak frequency being shifted to a lower range. Moreover, significant variations in SPLs were noted with the utilization of various types of foundation structures, with monopile foundations exhibiting the highest SPLs of underwater noise. These conclusions have important reference value for the scientific assessment of the health of aquatic organisms and ecosystems.

Keywords: offshore wind farm; underwater noise; turbine power; ecological effect



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1. Introduction

Since the Industrial Revolution, fossil fuels and other sources of energy have contributed to pollution of the global environment. Therefore, it is imperative to develop alternative clean energy. In November 2024, the International Energy Agency (IEA) released its 2024 World Energy Outlook report, pointing out that over the past 10 years, the proportion of fossil fuels in the global energy structure gradually decreased from 82% in 2013 to 80% in 2023, while global energy demand increased by 15% over the same period, with 40% of the growth coming from clean energy [1]. Driven by goals of carbon reduction, the world's energy structure will undergo profound changes. Primary energy demand will peak in 2030 and then begin to decline gradually [2]. The proportion of fossil energy in primary energy is projected to decrease to less than one-third by 2050 [3–5]. China is

also expected to experience a considerable decrease in energy consumption and carbon emissions, along with a sharp increase in demand for renewable energy [2].

As a major form of renewable energy utilization, offshore wind power generation has been widely used around the world. Although the growth rate has been adjusted recently due to economic slowdown, the trend of accelerated development in the future is still clear [6,7]. At the same time, the potential impact of underwater noise generated by the operation of offshore wind turbines on marine life and ecology has also become a focus of research. Studies have shown that the underwater noise generated by offshore wind turbines will have a negative impact on the surrounding ecological environment and fishery resources [8–11]. The noise from pile driving during construction can exceed an SPL of 200 dB re 1 μ Pa (hereafter referred to as dB) [12], which may cause physiological damage to marine mammals and fish in the vicinity of the construction site. Its broadband noise may also have a serious impact on high-frequency-sensitive marine mammals such as dolphins [13–16]. For example, it was found that harbor porpoise (*Phocoena phocoena*) exposed to pile driving noise exhibited increased respiratory rates and obvious avoidance behavior [15,17]. The impact of relatively low noise levels during operation on marine ecosystems has attracted less attention [18–24]. Studies have shown that underwater noise during the operation of offshore wind farms not only causes fish and marine mammals to avoid the noise [25], but may also cause hearing damage and lead to a shift in hearing thresholds [26–32].

The gearbox located in the turbine nacelle is a primary source of underwater noise, with gear meshing within it being the main contributor to underwater noise during operation [32,33]. At the Utgrunden offshore wind farm, it was found that the correlation coefficient between the vibration acceleration of the tower and the sound pressure at 10 m reached 0.98, confirming that the tower serves as the main pathway for noise transmission [34]. When the gearbox vibration is transmitted to the bottom of the tower, due to the sudden change in cross section, reflection and transmission occur, about 60% of the vibration energy continues to be transmitted downward in the form of structural waves, and the remaining energy radiates to the surroundings in the form of bending waves, generating two pathways of underwater noise. One pathway is directly radiated to the surroundings through the submerged tower structure, which is the main source of noise during turbine operation [35]. On the other hand, when the foundation contacts the seabed sediments, the structural vibration induces compression waves. These waves can propagate upward through the seabed and leak into the water, thereby contributing to the overall SPL. Since the seabed typically absorbs sound waves more effectively than water, and not all energy propagating through the seabed leaks into the water, the contribution of seabed propagation to the overall sound level is less than that of direct propagation through the water [36]. The vibration in the nacelle is highly correlated with factors such as rated power and wind speed. Various wind speeds impact gear meshing, consequently altering underwater noise level. As the turbine power increases, the mechanical loads on gears and bearings increase, which also influences the underwater noise level [37]. The propagation distance, water depth, and seabed type will have different degrees of influence on underwater noise [27]. Moreover, different turbine foundation types can lead to variations in noise transmission within the tower and radiation from the foundation into the water. The foundation types of wind turbines include steel monopile foundation, gravity-based foundation, tripile foundation, jacket foundation, and suction bucket foundation. Among them, monopile foundation is the most common, gravity-based foundation is usually used in shallow water, tripile and jacket foundations are dominant in deep water [8,38–40], and floating foundation, which has become more prevalent in recent years, can be used in deeper waters [41].

This review conducts a systematic analysis of the published data on underwater noise during the operation of offshore wind farms. Based on these data, we analyze the correlation between turbine underwater noise and distance, wind speed, turbine power, and foundation type. We also analyze the differences in underwater noise characteristics between turbines with different drive technologies and explore the potential impacts of underwater noise during offshore wind farm operation on marine life.

2. Materials and Methods

We collected underwater noise monitoring results from 39 offshore wind farms in different regions during operation. By integrating our most recent measurements with existing data, we assembled 105 sets of observed and modeled underwater noise data from wind turbines (Table 1).

Table 1. The level of underwater noise and measurement parameters from different offshore wind farms. (The data source of Table 1 is geared turbine. Detailed data can be found in Table S1 of the Supplementary Materials.)

Windfarm	Depth (m)	Turbine Power (MW)	Distance (m)	Wind Speed (m/s)	SPL (dB)	Dominant Frequency (Hz)	Foundation	References
Svante	2.5–4	0.22	100	6–12	102–113	16	Tripile Gravity-based	Westerberg [42]
Vindeby		0.45	14	13	119–126	25		Tougaard et al. [32], Degn [43]
Bockstigen	4–10	0.55	20–200	92–119	92–111	160–312	Monopile	Tougaard et al. [32], Fristed et al. [44], Degn [43]
Utgrunden	18	1.5	83–463	3.5–17	103–126	63–200	Monopile	Lindell et al. [34], Betke et al. [33]
Middelgrunden	5	2	20–40	6–13	103–114	25–125	Monopile	Tougaard et al. [32]
Horns Reef	13	2	87–100	5.9–15.6	104–118.5	150–176	Monopile	Diederichs et al. [45], Elmer et al. [46]
Model study	2.5	2	14	13	131	25	Gravity-based	Degn [43]
Model study	4	2	20	8	113–118	25–160	Monopile	Koschinski et al. [47]
Scroby Sands	5	2	15	10	130		Monopile	Nedwell et al. [48]
Nysted	4	2.3	100–175	5–10	92–110	135–315	Gravity-based	Diederichs et al. [45], Elmer et al. [46]
Paludans Flak		2.3	100	9–21	116–123	134	Monopile	Elmer et al. [46]
Lillgrund		2.3	160–1000	12	86–102	127	Gravity-based	Andersson et al. [49]
East Sea Bridge	3–13.4	3	15–54	1.5	78–114	25–366	Jacket	Zhang et al. [50], Zhang et al. [25], Niu et al. [51]
Northwind	25	3	40–150	6.4	135	50	Monopile	Thomsen et al. [23]
Barrow	22	3	30	8.9	105	80	Monopile	Cheesman et al. [52]
Southwest coast of Korea	12	3	70	6.3–11	94.6–100	35–198	Jacket	Yoon et al. [53]
Dalian Zhuanghe Phase 1–5	7	3	25–150	4–4.4	109.5–123.3	20–63	Suction bucket	Ge et al. 2024. [unpublished]
Belwind		3	50	8	110	100	Monopile	Norro et al. [54]
Shanghai East Sea Bridge	10	3.6	15–20	3.5–4.5	92–101	11–139	Jacket	Zhang et al. [50]
Sheringham Shoal	14	3.6	50	5–10	123–126	162	Monopile	Pangerc et al. [55]
Gunfleet Sands		3.6	28–42	6.8	110–114	25–125	Monopile	Cheesman et al. [52]
Lynn and Inner Dowsing								
North Seaz one 1 O	21	3.6	100	11	123.7	160	Monopile	Bellmann et al. [56]
North Sea zone 1 NO	18	3.6	100	11	102	50	Monopile	Bellmann et al. [56]
North Sea zone 2 NO	30	3.6	100	11	117	160	Monopile	Bellmann et al. [56]
Baltic Sea	35	3.6	100	11	120	160	Suction bucket	Bellmann et al. [56]
North Seazone 1 SW	20	3.6	100	11	124	160	Monopile	Bellmann et al. [56]

Table 1. Cont.

Windfarm	Depth (m)	Turbine Power (MW)	Distance (m)	Wind Speed (m/s)	SPL (dB)	Dominant Frequency (Hz)	Foundation	References
Yancheng	12	4	20	10	110	100	Monopile	Zhang et al. [35]
Binhai North	15–20	4	10	10	133.3–137	32–160	Monopile	Shashidhar et al. [24]
Formosa 1 wind farm	25	4	100	11	117–121	160	Monopile	Bellmann et al. [56]
North Sea zone 1 NW	10–14.1	5	15–50	2–12	90–117.5	50–125	Jacket	Zhang et al. [50], Niu et al. [51]
East Sea Bridge	30	5	92–100	12–14	110–118	90	Tripile	Van Radecke et al. [57], Betke et al. [58]
Alpha Ventus	39	5	100	11	125	160	Tripile	Bellmann et al. [56]
North Sea zone 2 NW	23–39	5.5	100–1000	4.4–11	87–125	44–160	Jacket	Huo et al. [59]
Three Gorges Yangjiang	25	6.15	40–150	8.3	122–137	50	Jacket	Thomsen et al. [23]
Shapa C-Power	28	6.2	100	11	109	160	Monopile	Bellmann et al. [56]
North Sea zone 1 NW	24	6.2	100	11	115	160	Jacket	Bellmann et al. [56]
North Sea zone 1 O	28	6.3	100	11	110	80	Monopile	Bellmann et al. [56]
North Sea zone 1 NW	28	8	100	11	113	40	Suction bucket	Bellmann et al. [56]

Because the data from different studies were obtained under varying conditions, a general linear normalized model was employed to estimate the overall correlation between the sound pressure level (SPL) and parameters such as distance (horizontal distance from the hydrophone to the foundation), wind speed, and turbine power (quantified by a nominal power output in megawatts, all instances of “Turbine power” in the paper refer to the turbine’s rated power), as follows:

$$SPL = C + \alpha \log_{10}\left(\frac{distance}{100}\right) + \beta \log_{10}\left(\frac{wind\ speed}{10\text{m/s}}\right) + \gamma \log_{10}\left(\frac{turbine\ size}{1\text{MW}}\right)$$

The constant C represents the average SPL of all measurements, normalized to a distance of 100 m, a turbine power of 1 MW, and a wind speed of 10 m/s. The SPL data used for the subsequent summary analysis are all normalized data [37]. α , β , and γ are coefficients corresponding to the independent variables, respectively, reflecting the degree and direction of the impact of each independent variable on the sound pressure level (SPL). For example, α represents the contribution of the logarithmically transformed distance to the change in sound pressure level. The positive or negative sign of the coefficient indicates whether the impact is a positive or negative correlation, and the absolute value indicates the strength of the impact. Measurements were conducted using different methods at varying water depths, and the seafloor topography and sediment types vary across wind farms. These factors can affect the recorded SPLs. Since there is currently no precise method to eliminate this interference, it is considered a source of measurement uncertainty.

Multiple linear regression analysis was employed to evaluate the influence of three key factors—distance, power, and wind speed—on the SPL of turbine noise. A multicollinearity diagnostic confirmed the reliability of the regression model, as the calculated Variance Inflation Factors (VIFs) for all variables were well below the common threshold of 10. The overall significance of the regression model was assessed using the F-test, which yielded a p -value of much less than 0.05, demonstrating that the influence of the variables was as expected. The significance of each individual factor was confirmed by t -tests, with all p -values being less than 0.05, indicating that each factor is an important and independent predictor of underwater noise. To compare the average SPL difference between gearbox and direct-drive turbines, an independent samples t -test was conducted. The assumptions of

normality and homogeneity of variances were met ($p > 0.05$ for both tests), and the t -test for equality of means was significant ($p < 0.05$), confirming a statistically significant difference between the two groups. Furthermore, a one-way analysis of variance (ANOVA) was performed to examine variations in underwater noise among the four foundation types. The prerequisites for this analysis, including normality and homogeneity of variances, were satisfied.

The significance of the results was categorized using p -values: $0.01 \leq p \leq 0.05$ was considered statistically significant; $p \leq 0.01$ was considered highly statistically significant; and $p \geq 0.05$ was considered nonsignificant. All statistical analyses were performed using OriginPro 2024 (Origin Lab Corporation, Northampton, MA, USA) and IBM SPSS Statistics 27 (27.0, IBM Corporation, Armonk, NY, USA).

3. Results

3.1. The Impact of Distance, Wind Speed, and Turbine Power

The model applied to analyze the data in Table 1 reveals the impact of distance, wind speed, and turbine power on the noise level, showing good explanatory power ($R^2 = 0.71$). The results show that all three factors are significant, with their respective effects shown in Figure 1.

Based on the fundamental principles of acoustic propagation, underwater noise inevitably attenuates with increasing propagation distance. Furthermore, an increasing propagation distance also influences the noise geometric diffusion. Figure 1a clearly demonstrates a negative correlation between underwater SPL and propagation distance, indicating that the noise level decreases rapidly with increasing distance. This corresponds to a calculated attenuation rate of 20.4 ± 1.8 dB/decade [$t = -11.8$, $p < 0.001$].

Although wind speed is a secondary factor in noise impact, it is highly correlated with turbine noise. Figure 1b clearly shows a positive correlation between the SPLs and wind speed, indicating that noise levels increase with wind speed, with a calculated increase rate of 18.5 ± 5.8 dB/decade [$t = 3.2$, $p = 0.002$].

Greater turbine power leads to higher unit capacities, imposing greater mechanical loads on essential components such as gearboxes, bearings, and generators. This results in elevated friction and impact levels during mechanical operation, subsequently increasing the noise energy emitted into the water. Figure 1c shows a positive correlation between the SPLs and turbine power, indicating that the noise levels increase with turbine power, with a calculated increase in turbine power of 12.4 ± 3.3 dB/decade [$t = 3.8$, $p < 0.001$].

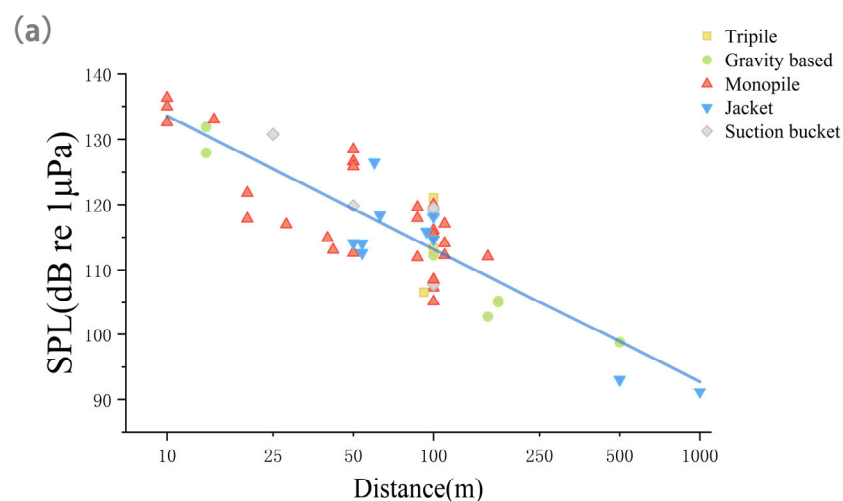


Figure 1. Cont.

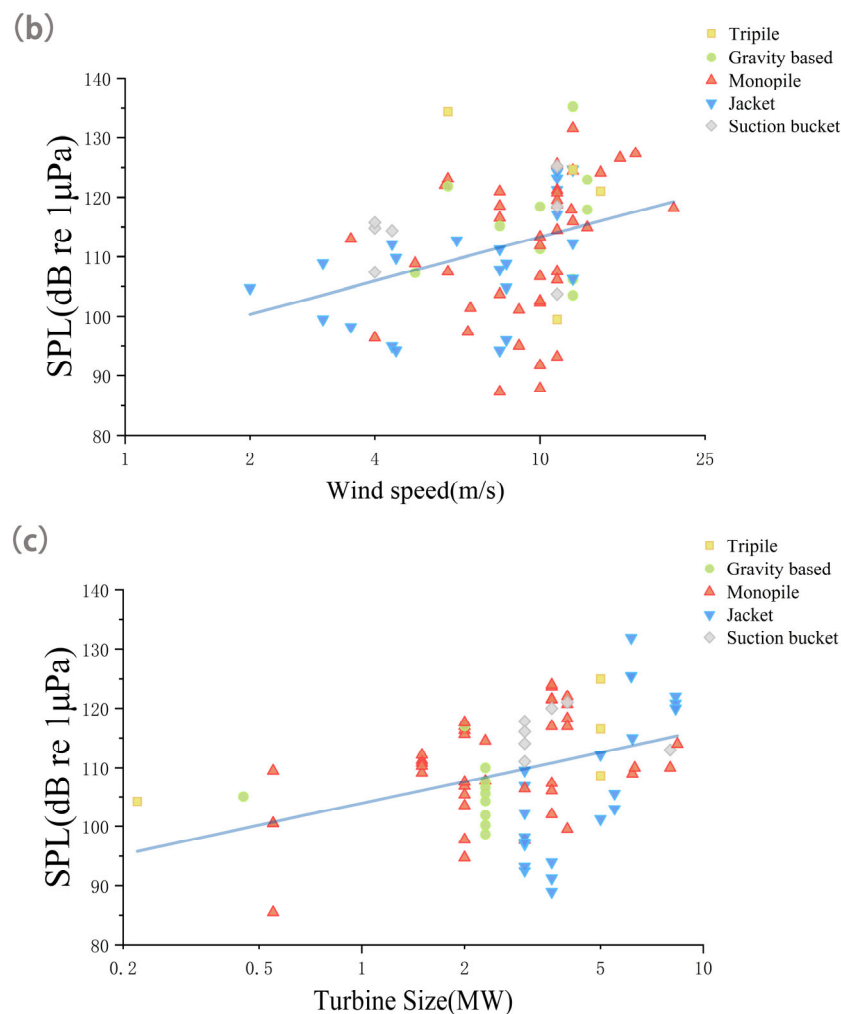


Figure 1. Variation in sound pressure level as a function of three influencing parameters. (a) SPL vs. Distance Diagram; (b) Wind speed variation with distance diagram; (c) Turbine size with distance diagram.

3.2. The Impact of Turbines with Different Drive Modes

The noise from a geared turbine is mainly due to the mechanical vibrations of core components, such as gear meshing, and vibrations from bearings and shafts. Direct-drive wind turbines utilize a permanent magnet synchronous generator directly connected to the rotor, completely eliminating the gearbox and gear meshing noise. The fundamental differences in their mechanical structures lead to significant differences in the noise generated. Table 2 shows data on the SPL and dominant frequency of direct-drive turbines. The corresponding data for geared turbines are shown in Table 1.

Figure 2 shows a histogram of the dominant frequency distribution for geared and direct-drive turbines in different offshore wind farms. Data for the dominant frequencies of 29 turbines with power from 4 MW to 8.3 MW were summarized, including 17 geared turbines (Table 1) and 12 direct-drive turbines (Table 2). Figure 2 clearly shows that the dominant frequencies of underwater noise generated by the turbines are generally distributed below 200 Hz, with three prominent frequencies at 12.5 Hz, 80 Hz, and 160 Hz, with 160 Hz being the dominant frequency. Overall, the dominant frequency distribution of direct-drive turbine noise is relatively concentrated at lower frequencies, with six groups of turbines having a dominant frequency at 12.5 Hz, the most prominent frequency. The dominant frequency distribution of geared turbines, on the other hand, is more dispersed, with varying degrees of contribution across multiple frequencies. However, compared

to direct-drive turbines, the dominant frequencies of geared turbines are distributed at relatively higher frequencies.

Table 2. Dominant frequency and sound pressure level of direct-drive turbines. The frequency corresponds to the peak frequency, and the measurement distances of the cited SPLs are all derived from the original literature.

Windfarm	Turbine Power (MW)	Distance (m)	Wind Speed (m/s)	SPL (dB)	Dominant Frequency (Hz)	Reference
North Sea zone 2 SO	4	100	11	111	160	Bellmann et al. [56] Elliott et al. [60]
Block Island	6	50	4	113.1	14	
Block Island	6	50	6	114	14	Bellmann et al. [56]
Block Island	6	50	8	115.1	14	
Block Island	6	50	10	116.7	14	
Block Island	6	50	12	119.5	14	
Block Island	6	50	15	120.6	14	
Baltic Sea	6	100	11	108	25	
North Sea zone 1 NW	6	100	11	110	25	Holme et al. [61]
North Sea zone 1 NW	6	100	11	110	80	
North Sea zone 2 W	6	100	11	109	80	Bellmann et al. [56]
Gode wind 1	6.3	70	12	117.4		
Gode wind 2	6.3	75	12	116.6		
Gode wind 3	6.3	150	12	115		Bellmann et al. [56]
North Sea zone 2 NW	7	100	11	116.0		
North Sea zone 2 NW	7	100	11	120.0	80	

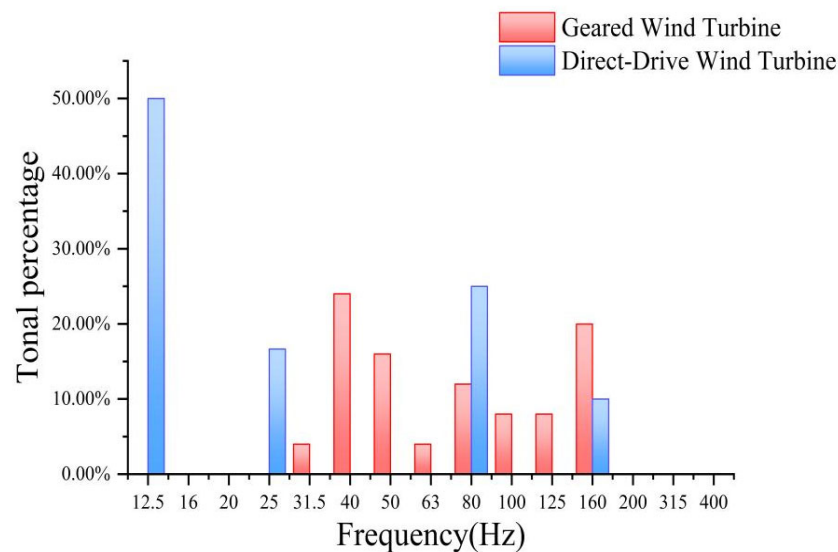


Figure 2. Dominant frequencies histogram of geared wind turbines and direct-drive wind turbines.

This study also compared the SPL characteristics of geared turbines and direct-drive turbines during operation, as shown in Figure 3. We selected a portion of noise data with the same power range (4–8.3 MW) from the two types of data. The average SPL for geared turbine noise was 120 dB, with a median of 119 dB. In contrast, the direct-drive turbine had an average SPL of 111 dB, with a median of 111 dB. This reveals that the average SPL of the gearbox turbine was approximately 9 dB higher than that of the direct-drive turbine [$t = 5.4$, $p < 0.00001$]. Overall, the underwater noise SPL of the gearbox turbine was higher than that of the direct-drive turbine, indicating that the geared turbine could lead to a greater impact on marine life during operation.

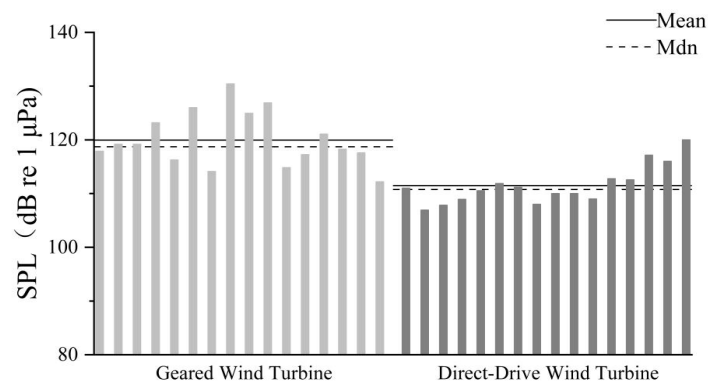


Figure 3. Comparison of sound pressure level between geared wind turbines and direct-drive wind turbines. In the diagram, the solid line represents the average value, and the dashed line represents the median. Light gray represents the noise data of Geared Wind Turbines, and dark gray represents the noise data of Direct-drive Wind Turbines. The data in the figure have all been normalized with respect to distance, wind speed, and turbine power.

3.3. The Impact of Different Foundation Types

This study also conducted a systematic statistical analysis of the SPLs of turbines with four different foundation types. Due to the small number of operational offshore wind farms using gravity-based and tripod foundations, our paper contains a limited amount of data for these two types. However, we believe it is necessary to analyze and compare them because these wind farms are built and operating, generating underwater noise that could potentially affect marine life. Furthermore, our study took this issue into consideration. To reduce the influence of other variables, we filtered the turbine power data for the jacket and monopile foundations when selecting the data, and we also standardized the parameters for distance and wind speed. Figure 4 shows a boxplot comparison of the SPLs of different foundation types. The comparison results are expressed as mean $\pm$ standard error (Mean $\pm$ SE). It can be observed from the boxplot in Figure 4 that the SPLs of monopile foundations are generally higher, with an average value of 117.0 ± 1.2 dB, which is significantly higher than the average values of gravity-based (106.0 ± 1.1 dB), jacket (104.0 ± 2.2 dB), and tripile foundations (111.0 ± 3.6 dB) [$f = 10.2$, $p < 0.01$]. The SPL data distribution for gravity-based foundations shows a relatively tight concentration, exhibiting minimal variations and high stability. Jacket foundation SPLs demonstrate a high level of dispersion, indicating significant variability in the noise levels measured under different conditions.

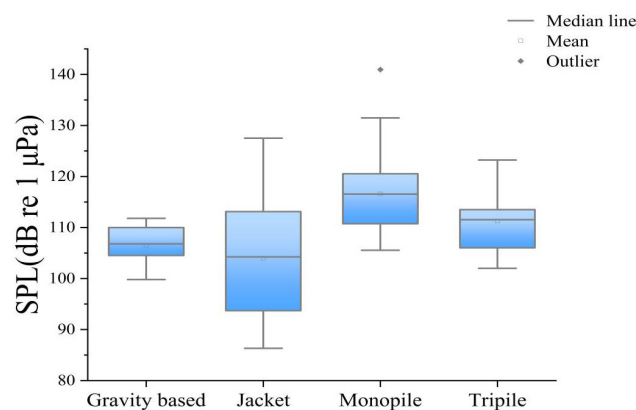


Figure 4. The sound pressure levels for different foundation types. The distance, wind speed, and turbine power of the data in the figure have all been normalized. The figure shows the minimum and maximum values of different types of fan noise.

3.4. The Impact of Noise on Fish

To systematically evaluate potential ecological impacts, this study contrasts the underwater acoustic signatures of direct-drive and geared offshore wind turbines using a threshold-overlay analysis. We quantified their sound pressure level (SPL, unit: dB re 1 μ Pa) distributions and compared them against established hierarchical response thresholds for marine fish, as follows: perception (>62 dB), physiological (>80 dB), behavioral (>100 dB), and injury (>120 dB). Each threshold marks a distinct stage in the graduated response of fish to acoustic stimuli.

As is clearly observed in Figure 5, the underwater SPL of the direct-drive turbine is concentrated within the 105–120 dB range, exhibiting a relatively narrow-band concentration of acoustic energy. In contrast, the noise SPL from the geared turbine covers a broader range of approximately 115–130 dB, a difference that stems from additional vibration and cavitation effects during the gearbox’s mechanical transmission. We classify fish responses to noise into a hierarchical progression, as follows: perception (>62 dB), physiological (>80 dB), behavioral (>100 dB), and injury (>120 dB), with the SPL threshold for each level showing distinct, staged characteristics. As shown in Figure 5, the noise at a 100 m distance from a direct-drive turbine fully covers the perception, physiological, and escape thresholds, which could trigger basic perception, physiological stress, and active avoidance behavior in fish. Furthermore, its high-SPL range approaches the injury threshold, where long-term exposure may lead to a Temporary Threshold Shift (TTS). The underwater noise produced by the geared turbine, however, not only covers the first three thresholds, but also overlaps with the injury threshold. Exposure to noise in this band is more likely to breach the critical injury threshold of the fish’s auditory organs, leading to the permanent destruction of structures such as inner ear hair cells. This, in turn, may cause a Permanent Threshold Shift (PTS), resulting in irreversible impacts on the fish’s long-term survival (e.g., foraging, predator avoidance, and reproductive behaviors) [62].

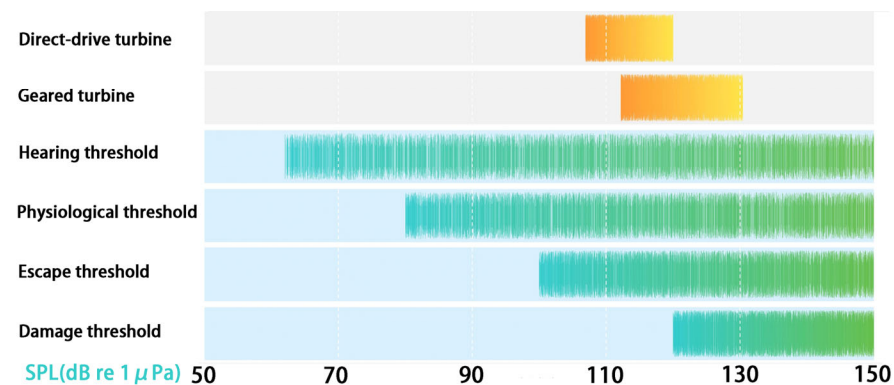


Figure 5. Comparison between the auditory thresholds of marine fish and wind turbine noise. Data for the direct-drive and geared turbines are taken from Table 1 and have been standardized to a distance of 100 m and a rated power of 6 MW. Yellow represents the range of wind turbine noise, and green represents the range of noise affecting fish.

4. Discussion

Among the many factors affecting underwater noise during the operation of offshore wind farms, the effect of propagation distance on noise attenuation is the most important. The attenuation of noise with distance shows a complex environmental dependence and has been extensively studied in previous studies [37]. When sound waves propagate in seawater, they spread outward in the form of spherical waves or cylindrical waves. Ideally, for spherical waves, the sound intensity is inversely proportional to the square of the

propagation distance; for cylindrical waves, the sound intensity is inversely proportional to the propagation distance. Due to the short distance, attenuation may initially resemble that of cylindrical waves at short distances but approach that of spherical waves with increasing distance [36]. Figure 1a shows that the turbine noise level during operation decreases rapidly with increasing distance, reaching 20.4 dB/decade, which is higher than the 20 dB/decade predicted by the simple spherical diffusion model. Similarly, Tougaard et al.'s research indicates that the noise level decreases with distance at nearly 24 dB/decade [37], which is also higher than the prediction of the spherical diffusion model. When Lindell et al. measured the underwater noise of a 1.5 MW turbine at the Utgrunden wind farm, they found that the average attenuation was about 4 dB per two-fold distance in the range of 83–463 m [34]. According to Betke et al., at a water depth of 10 m, the underwater noise of a 1.5 MW turbine was attenuated by about 4.5 dB per two-fold distance in the range of 110–1000 m [33]. Existing studies have clearly shown that the impact on marine life varies significantly with the distance from offshore wind farms. In their 2021 study, Puig-Pons et al. found that at a distance of 50 m from the turbine, the operating noise SPL was 120–142 dB, which would cause the tuna (*Thunnus*) in the cage to form a denser school and a decrease in swimming radius, thereby affecting fish migration or spawning behavior [63]. At a distance of 300 m from the foundation, Nabe-Nielsen et al. observed a notable influence of operational wind farm noise on harbor porpoises. This influence includes both a 10.4% decline in population size and the evident local avoidance responses [64]. This study suggests that the propagation distance will also interact with other environmental factors to jointly affect noise attenuation [44]. Factors such as water depth, temperature, salinity, and currents at the location of the wind farm will affect the speed of sound [65], thereby changing the propagation path of sound waves. It was observed that an increase in tidal current speed can lead to a shift or disappearance of the spectral peak in the noise generated by the 3 MW turbine, suggesting interference by the current in the propagation process [53]. This also suggests that turbine noise frequencies may overlap with ambient tidal noise. However, whether this current-masked signal affects marine life requires further study. The seabed topography and sediment characteristics can also affect the noise propagated over long distances. When the noise propagates near the seabed, the reflection and absorption effects of the seabed cannot be ignored [66,67]. Since the existing models are based on data from multiple independent offshore wind farms with inconsistent measurement conditions, it is difficult to accurately isolate the individual effects of various environmental factors. Therefore, this study concludes that more systematic in situ measurements are necessary to further clarify and refine propagation loss models.

The second factor affecting the noise level is wind speed, which is directly related to rotor speed. The influence of wind speed or rotor speed on underwater noise during the operation of offshore wind farms involves a complex and closely coupled mechanism. From the perspective of energy input, wind speed, as the initial energy source of the wind turbine, directly regulates rotor speed [68]. When the wind speed increases, the aerodynamic force acting on the blades increases, thereby driving the rotor to rotate at a higher speed [69]. For example, Yoon et al. (2023) [53] monitored a 3 MW turbine situated on the southwest coast of Republic of Korea. It was observed that as the wind speed increased from the cut-in wind speed to the rated wind speed, the rotor speed demonstrated a corresponding gradual increase. However, this change was not a simple linear relationship, but was governed by a complex control system inside the wind turbine. According to the research of Niu et al., an increase in wind speed causes the blades to rotate faster, thereby increasing the structural excitation force and increasing the intensity of radiated underwater noise [51]. Elliott et al. (2019) [60] found that when the wind speed increased from 2 m/s to 4 m/s, the SPL of a 6 MW turbine increased from 112.2 dB to 113.1 dB, and further increasing the wind speed

from 4 m/s to 8 m/s raised the SPL from 113.1 dB to 115.1 dB. These data were measured at a distance of 50 m from the turbine. The SPL continued to increase with wind speed up to the rated power. Taking Yoon et al.'s monitoring of a 3 MW turbine as an example, when the rotor speed increased from 6.4 rpm to 10.7 rpm, the vibration acceleration amplitude of components such as the gearbox and generator increased by 2–3 times. The vibration of these components was transmitted to the foundation through the tower and radiated into the water, eventually causing a significant increase in the underwater noise SPL [53]. Monitoring data reveal a two-phase relationship between wind speed and underwater noise levels. Initially, the SPL increases with wind speed in the range from the cut-in speed (4 m/s) to the rated speed (10–14 m/s). Subsequently, once the wind speed exceeds the rated value, the SPL enters a plateau phase, and may even decrease slightly [55,57,70]. The change in SPL with wind speed can also have different effects on organisms with different activity ranges. Abbott et al. found that during operation, when the wind speed reached 13 m/s or above, some fish such as Chinook salmon (*Oncorhynchus tshawytscha*), northern anchovies (*Engraulis mordax*), and shiner perch (*Cymatogaster aggregata*) within 4 m of the wind turbine were observed to permanently avoid the area [70]. As with the effect of propagation distance, wind speed will also interact with other factors. The most obvious factor is the difference in mechanical design between geared and direct-drive turbines [56]. The difference in wind conditions (stable wind and wind with rapid changes in wind speed) is also an important influencing factor. In addition to a change in the SPL, an increase in wind speed can also lead to a change in the dominant frequency. The gear meshing frequency of the gearbox is closely related to the rotor speed and can be calculated by the following formula: $f = n * z$ (where n is the rotor speed and z is the number of gear teeth). In a study of a 3 MW wind turbine on the southwest coast of South Korea by Yoon et al., it was found that when the rotor speed was 6.4 rpm, assuming that the number of teeth on a specific gear stage was 500, the meshing frequency was approximately 53.3 Hz (6.4 rpm $\times$ 500 gear teeth/60 s). However, when the speed was increased to 10.7 rpm, the frequency jumped to 89.2 Hz (10.7 rpm $\times$ 500 gear teeth/60 s). It was also observed that when the speed was greater than 10.5 rpm, the peak frequency shifted to 198 Hz [53].

The third influencing factor is turbine power. As shown in Figure 1c, the SPL shows a positive correlation with turbine power, increasing at a rate of approximately 12.4 dB/decade. The power dependence emerges from the fact that the vibration energy of mechanical components, such as gearboxes, increases in tandem with the power output. The increased vibration energy enhances the radiated sound at the gear meshing frequency and its harmonics. Therefore, the effect of turbine power on noise level is closely related to mechanical components. Based on available turbine monitoring data, Stober et al. predicted that the source level of a wind turbine with a rated power of 10 MW could reach 170 dB, which could cause behavioral disruption in marine mammals within a range of 6.3 km, while the avoidance range of a 5 MW wind turbine was only 540 m [71].

All the noise levels discussed above are generated by geared turbines, but many modern turbines operate using direct-drive technology. Since the gearbox is one of the main noise sources, it is expected that a direct-drive turbine will produce lower noise levels. According to the monitoring results of 6 MW direct-drive wind turbines at Block Island Wind Farm by Elliott et al., the gearless design significantly reduces high-frequency noise [60], and the SPL is 10–15 dB lower than that of geared turbines with the same power. Stöber et al. compared a 6 MW direct-drive turbine with a 6.15 MW geared turbine and found that the average SPL of the direct-drive turbine was about 10 dB lower than that of the geared turbine [71]. The data comparison in this paper is shown in Figure 3, and it is found that the average SPL of a geared turbine is about 9 dB higher than that of a direct-drive turbine, which is generally consistent with expectations. In evaluating the

impact of offshore wind farms on the marine environment, it appears that further noise reduction measures may be required for geared turbines to mitigate potential disturbances to marine life.

In addition, this study also examined the main frequency distribution of direct-drive turbines and geared turbines within offshore wind farms. Direct-drive turbines exhibit more low-frequency components, which is consistent with their operating characteristics [72]. Since the speed of the direct-drive generator is relatively low, the low-frequency components are relatively rich. In contrast, the geared turbine converts the low-speed rotation of the rotor into the high-speed rotation of the generator through the speed-increasing gearbox, so less energy is distributed in the low-frequency range [73,74]. As the frequency increases, the frequency distribution of the two turbine types changes significantly. In Figure 2, it is evident that the dominant frequency of the geared turbine noise falls within a relatively high-frequency range, displaying a relatively dispersed distribution. This indicates that the energy distribution of the geared turbine is more concentrated in the high-frequency band, which is closely related to its characteristic of achieving high-speed operation through the speed-increasing gearbox.

Since the noise is generated in the turbine nacelle and radiated into the water through the foundation, it is expected that radiated noise differs among turbines based on foundation type [75]. As shown in Figure 4, the average SPL of the monopile foundation is the highest, reaching 117 dB, which is about 13 dB higher than that of the jacket foundation and about 6 dB higher than that of the tripile foundation. This suggests that structural stiffness and radiation area are important influencing factors [41]. The cylindrical radiation area of the monopile foundation is much larger than that of the jacket foundation, making it an efficient sound radiation interface. The acoustic impedance mismatch between the steel and water interface causes about 30% of the vibration energy to be directly radiated into the water [38]. When comparing monopile foundations and jacket foundations of equal capacity, it was observed that the SPL of the monopile foundation at 162 Hz exceeded that of the jacket foundation by approximately 3 dB [55]. Within Belgian North Sea offshore wind farms, the noise level (below 100 Hz) of monopile foundations is also 5–8 dB higher than that of jacket foundations [54]. This difference was attributed to the direct contact between the steel piles of monopiles and the seawater [54]. The multi-pile design (e.g., four piles) of jacket foundations and the three-pile design of tripile foundations reduce the radiation intensity in a single direction by spatially dispersing the vibration energy [76]. Taking the 5 MW tripile foundation of the Alpha Ventus offshore wind farm as an example, the distribution of three 2.6 m diameter piles at 120° was identified [57]. When the gearbox vibration was transmitted to the top of the foundation, the vibration energy was decomposed into three directional components. The vibration phase difference in each pile was about 120°, forming interference cancelation in the far field (>100 m), making the noise peak at 90 Hz about 5 dB lower than that of monopile foundations [57]. In addition, the supporting legs and horizontal struts of the jacket foundation form a truss structure, and its natural frequency (e.g., 85 Hz) is not harmonically related to the gear meshing frequency (162 Hz), which reduces the resonance amplification effect. This also indirectly suggests that structural stiffness and radiation area may be key influencing factors. Gravity-based foundations, with their significant mass and stiffness, are likely to filter out high-frequency vibrations (>100 Hz). Zhang et al. (2016) [50] investigated the 5 MW gravity-based foundations at the Shanghai Donghai Bridge offshore wind farm. They observed that the SPL at 162 Hz was 90 dB, which was 15 dB lower than that of equivalent monopile foundations. Furthermore, the SPL in the low-frequency range (<50 Hz) showed an increase of 3–5 dB. The attenuation coefficient of concrete for high-frequency vibrations exceeds that of steel, while it exhibits higher transmission for low-frequency vibrations [77,78]. However, some

articles hold different views. Bellmann et al. suggest that the average radiated noise of monopile foundations may be slightly lower than that of other types of foundation structures [56]. Monitoring data indicates that monopile foundations are 4 dB lower than suction bucket foundations of a comparable rated power. However, the existing data is not sufficient to support a more in-depth analysis. The primary factor is the varying environmental conditions to which different types of foundations are subjected. For example, most gravity-based foundations are utilized in shallow waters, thereby presenting potential constraints such as cutoff frequency propagation [25]. In addition, differences also exist in the matching of turbines of different powers with foundation types. For example, most high-power turbines currently use jacket foundations.

In addition, the data are collected from different wind farms, and the water depth, seabed type, sediment properties, temperature, and salinity of the location may affect the measurement results. In summary, the impact of foundation type on underwater noise SPL currently lacks a consensus or standardized approach. The specific mechanism of action requires additional analysis and verification, considering factors such as the marine environment, construction technology, and structural dynamic characteristics.

This review examines the propagation characteristics of underwater noise generated by offshore wind farms during operation. These acoustic characteristics serve as the primary stimuli by which marine organisms perceive their environment and elicit behavioral and physiological responses. Noise of varying intensities and frequencies, when transmitted through the water and perceived by marine organisms, can interfere with key life activities such as navigation, communication, predation, and reproduction [15,24,79–86]. The main negative impact during the construction period comes from the high-intensity, transient underwater noise generated by pile driving operations. This noise can trigger large-scale avoidance behavior in marine mammals: for example, the abundance of harbor porpoises can drop sharply within tens of kilometers [30,87,88], and the avoidance radius of harbor seals (*Phoca vitulina*) can even reach 40 km [89]. At the same time, strong noise also causes direct physical damage and severe physiological stress to fish [8,90]. The impacts of turbine noise on marine organisms during operation are intricate. Its persistent low-frequency noise may interfere with the low-frequency communication of species such as cod (*Gadus*), herring (*Clupea*), and rabbitfish (*Siganus*) through the “acoustic masking” effect [81,89–93]. In addition, noise during operation not only causes a significant decrease in the abundance of some fish species [18,94], but also interferes with the early development of marine life like crabs [95].

However, some studies suggest that offshore wind farms have a dual impact on organisms, with the positive effects potentially outweighing the negative ones. The most significant positive effect is the ecological role of the “artificial reefs” created by their foundation structures. The hard substrate introduced by the wind turbine foundations provides a stable substrate for attachment and habitat for various marine organisms. This establishes the turbine foundation as an aggregation site for marine organisms, thereby enriching marine biodiversity over a wider area [96–100]. Overall, whether the positive ecological consequences of offshore wind farms outweigh their negative effects requires further in-depth research.

In summary, although the present study provides a systematic analysis of the associations between underwater noise from offshore turbines and key variables—including propagation distance, wind speed, power rating, drive technology, and foundation type—through the integration of empirical and simulated data, it is subject to certain limitations. In a similar vein, Jakob Tougaard et al. argue that the cumulative acoustic effect of multiple turbines transforms an entire wind farm into a powerful and extensive regional source of noise, underscoring the scale of the issue [37]. This persistent acoustic

environment can severely mask the acoustic communication of marine organisms, thereby interfering with their critical life activities and potentially leading to long-term avoidance of the area. A key limitation is that the data originate from wind farms in disparate regions and under varying monitoring conditions, which prevents the precise isolation of the independent effects of single environmental factors—such as seabed sediments and current velocity—on underwater noise propagation. Moreover, the majority of existing data are from short-term monitoring, which does not cover the long-term impacts of seasonal or climatic changes, thus failing to effectively quantify the temporal dynamics of the noise. Concurrently, assessments of ecological impact have predominantly remained at the behavioral level, such as avoidance by marine mammals and aggregation of fish, with a lack of quantitative analysis at the physiological and population levels.

Based on these limitations, future research should focus on several key areas, as follows: conducting long-term, multi-parameter monitoring that controls for single variables and optimizing existing prediction models by incorporating parameters such as the acoustic properties of the seabed and the speed of sound in seawater.

5. Conclusions

The SPL data from offshore wind turbines discussed previously indicate that propagation distance is the most significant factor, with the SPL showing a negative correlation with increasing distance, exhibiting an attenuation rate of 20.4 dB/decade. Wind speed and turbine power, on the other hand, show a positive correlation with the SPL. Furthermore, based on data from multiple wind farms, this study found that the technological transition from geared turbines to direct-drive turbines will not only shift the dominant noise frequency to a lower frequency band, but also reduce the SPL generated by turbines by approximately 9 dB. From a noise control perspective, it is recommended to prioritize direct-drive turbines and low-noise foundation types such as jackets and tripile and to optimize wind farm layout based on distance attenuation. For monopile foundations and geared turbines, targeted noise reduction measures are needed to minimize potential disturbance to marine life. Future research can focus on in the following areas: First, long-term continuous monitoring is needed under multiple environmental conditions to systematically explore the coupling mechanisms between water depth, temperature, seafloor topography, and sediment type and noise propagation; secondly, noise prediction models should be further refined to accurately clarify the effects of various influencing factors on noise characteristics. Beyond this, there is a need to integrate bioacoustics monitoring with our synthetic noise data to more closely link acoustic metrics to biological responses. Such research will provide scientific support for more targeted efforts to reduce the potential impacts of noise pollution on marine life and ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/acoustics7040071/s1>, Table S1: The level of underwater noise and measurement parameters from different offshore wind farms.

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