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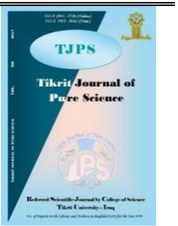

The effect of Flow Speed and Angle of Attack on the Aerodynamic Noise of NACA 0012 Airfoil

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ABSTRACT

Wind energy is one of the main sources of renewable energy in the market today. The influence of the wind speed and the angle of attack on the aerodynamic noise was investigated in this study. Four different samples of airfoils were used. Three speeds (5, 10, 15 m/s) were employed. The results revealed that the aerodynamic noise was associated directly with the flow speed. The data showed that when the velocity increases by (5 m/s), the noise gets louder by an average amount of (10 dB). As the increase of flow velocity increased the velocity shear, this eventually increased the aerodynamic noise. As for the angle of attack, it had an effect on the aerodynamic noise as well. The results showed an increase in the overall sound pressure level between (1-4 dBA) when the angle of attack increased from (5 degrees) to (10 degrees), while there was an increase (1-6 dBA) when the angle of attack increased from (10 degrees) to (15 degrees). This study was conducted under subsonic flow condition and Reynolds number (3.3×10^4).

تأثير سرعة الرياح وزاوية الهجوم على الضوضاء الهوائية لجناح NACA 0012

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الملخص

إن طاقة الرياح هي أحدى المصادر الرئيسية للطاقة المتجددة في السوق اليوم. تم في هذا البحث دراسة تأثير سرعة الرياح وزاوية الهجوم على الضوضاء الديناميكية الهوائية. تم استخدام أربع عينات من جناح (NACA 0012). تم استخدام ثلاث سرع مختلفة (5، 10، 15 م/ث). كشفت النتائج أن الضوضاء الهوائية ترتبط مباشرة بسرعة التدفق. وأظهرت البيانات أنه عندما تزداد السرعة بزيادة قدرها 5 م\ثانية، يرتفع صوت الضوضاء بمتوسط (10 ديسيبل) ويرجع ذلك إلى أن زيادة سرعة التدفق تزيد من سرعة القص التي تزيد في النهاية من الضوضاء الديناميكية الهوائية. وكذلك أظهرت زاوية الهجوم تأثيراً على الضوضاء الهوائية. فقد بينت النتائج زيادة في مستوى ضغط الصوت الإجمالي بين (1-4 ديسيبل) عندما تزداد زاوية الهجوم من (5-10 درجات)، في حين أن هناك زيادة من (1-6 ديسيبل) عندما تزداد زاوية الهجوم من (10-15 درجة). تم إجراء هذه الدراسة في ظل سرعة تدفق تحت الصوتي ورقم رينولدز (3.3×10^4).

الكلمات المفتاحية: توربينات الرياح، الرفع والسحب، القوى الديناميكية الهوائية، طاقة الرياح، جناح NACA 0012.

Introduction

Currently, there is a heavy dependence on fossil fuels and there is a greater need for an alternative energy. Fossil fuels are used for powering nearly all the world's applications, such as producing electricity for residential homes, fueling for vehicle transportation, powering the industry, and other numerous applications. This tremendous usage results in negative impacts on the environment, including an increase in the CO_2 levels that causes Earth's temperature to rise, and the poisonous emissions that are harmful to both the environment and human health. In addition to the poor attributes of fossil fuels, the resources are finite, thus giving it an expiration date for its total depletion [1–4]. In this regard, wind energy provides a renewable and clean power with almost no drawbacks for its usage. However, wind turbines have some disadvantages, including the consequence of the rotating blades that generates aerodynamic noise. A wind turbine has been studied with the endeavor to reduce this aerodynamic noise. Aerodynamic noise hinders the production of wind turbines; accordingly, there are regulations that prevent them from being constructed near residential areas. Katinas et al. [5] investigated the wind turbine noise emissions and their impact on the environment. The study concluded that there was a relation between the drop of the noise at specific wind velocity and the background noise. They found that there was an increase in the wind turbine noise level when the velocity of the wind increased. However, there was a decrease in wind turbine noise level when the distance increased from the wind turbine. The results showed that at more than (100 m) from the tower, when the wind velocity was (12 m/s), the noise emitted from the wind turbine becomes equal to the background noise. Leloudas et al. [6] investigated the reduction of noise from a (2.3 MW) wind turbine. The study showed the influence of the wind speed on the aerodynamic noise experimentally and numerically. Sumesh et al. [7] showed the influence of angle of attack on the sound pressure level of NACA 6412 asymmetric airfoil. The study revealed that the sound pressure level increases when the angle of attack increases. Murugan et al. [8] studied the effect of the wind speed on the aerodynamic noise. The study measured the aerodynamic noise speeds ranging from (2.11 m/s to 6.59 m/s) and showed a linear relation between the aerodynamic noise and wind speed for the entire frequency range, specifically for the low frequencies (100-5000 Hz).

Piggott studied the ambient sea noise at low frequencies and concluded a relation between the wind speed and the correlated aerodynamic noise. The study revealed a formula for this relation as follows [9]:

$$NL = B + 20n \log (U) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (1)$$

Where: NL and U stand for noise level and wind speed, respectively, B and n are constants.

The overall sound pressure level in all the results is measured by the equation [10]:

$$\text{Overall (dBA)} = 10 * \log[(10)^{\frac{S1}{10}} + (10)^{\frac{S2}{10}} + \ldots\ldots\ldots\ldots\ldots + (10)^{\frac{Sn}{10}}] \quad \ldots\ldots\ldots\ldots\ldots \ (2)$$

Where S1, S2 …… Sn are the sound pressure levels in A-weighting adjustments for one-octave center frequencies starting with (31.5 Hz to 8,000 Hz). Lighthill [11] explained the theory of aerodynamic sound and analyzed the process of generating non-linear aerodynamic sound by turbulence. Lighthill found an increase in the emission of generated sound waves by velocity shear due to the existence of linear terms in the inhomogeneous part of the analogy equations. In this study, the focus of noise reduction will be on the wind turbine blade, more specifically the airfoil. A generic airfoil, NACA 0012, was used to reduce the noise it produces. A customized testing room was first modeled in AutoCAD, and then built with the purpose of reducing exterior and interior background noise during tests. A wind tunnel generator was utilized for the tests to generate the wind [12,13].

1. Experimental Setup and Measurements

2.1 The wind tunnel

The wind tunnel of the fluid dynamic laboratory was utilized to create flow for aerodynamic noise measurements. The specifications of the wind tunnel were circular with diameter (13 cm) and the flow velocity up to (29 m/s). These specifications were used to provide the appropriate environment for measuring acoustics. Therefore, around the wind tunnel, the testing area was built.

2.2 Wind Tunnel Testing Area (Quiet Room)

The Fluid Dynamics Laboratory, Western Michigan University, College of Engineering and Applied Sciences campus, room G-107 was used to build the wind tunnel testing area (the quiet room). As the testing area should be in an insulated environment that negates outside noise and echo from within, the assembly of the quiet room was a fundamental part of the research. Moreover, the laboratory is equipped with a wind tunnel generator. Around the generator's outlet for wind flow, the quiet room was built. The quiet room was built in three stages. AutoCAD version 23.1 in 3D was used to design the room. The quiet room was in the shape of a cube with the following dimensions (3 m × 3 m × 2.7 m). The walls and ceiling of the room were built using plywood. The room was designed to place the wind tunnel generator in the middle opening section. In order to take control of the entrance of the room, a door was also added. Outfitting the quiet room with three layers of foam was performed in the second stage. A white foam (Volara Foam) was used in the first layer that consisted of two layers of (0.63 cm). The whole inside of the room (the walls, ceiling, and floor) was with the foam to negate about 50% of exterior noise and reduce vibrations, as shown in the Figure (1). A black foam (Wedge Foam) was used to cover the first layer. The black foam was to prevent any echo from noise generated within the room. The thickness of the second layer was (10.1 cm) to prevent any echo from noise generated within the room, as shown in Figure (2). These two foams were brought from (Foam N More Company) (For more information open this link: https://foamforyou.com/noise-control).

Lastly, the third foam was a FOAMULAR® 250 (25 psi) R-15 Extruded Polystyrene Foam Board Insulation (5 cm x 122 cm x 244 cm) - Square Edge, brought from Menards that covered the exterior of the quiet room to add further protection from exterior noises. To link all foams, an adhesive material that was particularly made for foam applications was used. There were some permeable cracks in the third layer that sealed off by utilizing caulk to minimize the noise effect.

(a) (b)

Figure 1. a) The first layer of foam (Volara Foam), b) The second layer of foam (Wedge Foam)

Putting the wind tunnel generator within the quiet room was the third and last stage in the building stages of the quite room. To easy access, the half of the tunnel including control operations were left outside the room. While the other half of the tunnel including the outflow was placed inside the room. To reduce the vibrations and excess noise, the foam was also outfitted the inside of the tunnel. At the opposite end of the wind tunnel, an outflow hole was created in the wall. The diameter of the outflow hole was (35 cm). The purpose of creating the hole was to supply an exit for the wind to prevent the wind to contact with the wall and cause undesired noise. Figure (3) shows the entire room.

Figure 3. the entire quiet room

2.3 The NACA 0012 Airfoil

In this study, the NACA 0012 airfoil was used. SOLIDWORKS version 28 was used to create the samples to study the effect of the noise around the airfoil. The sample was created using a 3D printer. The surface finishing was not smooth enough. These defects might increase eddies that might lead to further disturbances which in turn cause aerodynamic noise generation. Sandpapers were used with 20 different grit sizes (P60, P80, P100, P120, P150, P180, P240, P280, P320, P360, P400, P500, P600, P800, P1000, P1200, P1500, P2000, P2500, and P3000) to avoid this problem. For each sample, three different angles of attacks (5, 10, and 15 degrees) and three different flow speeds (5, 10, and 15 m/s) were applied. Smart office application was used to record the data of noise in the laptop.

2.4 Noise measurements

The microphones set up

Low frequency free field microphone with a frequency range of (0.13 to 20000 Hz) was used to measure the noise around the airfoil. The microphone was set up, as shown in Figure (4). The microphones were located at the distance of 6 inch from the sample. The microphone was connected to the Smart Office application that could read and save the level of noise for all the range of the interested frequencies.

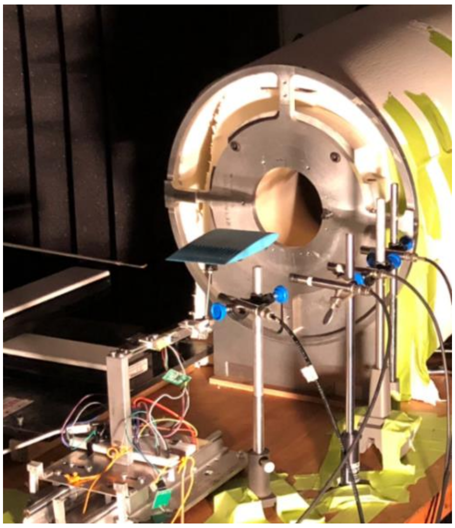

Figure 4. The microphone set up

The microphone system is composed of the microphone (Model: 377A07), preamplifier (Model: 426E01) and a low-frequency filter adapter (Model: 079A43). The complete system allows for the measurement of noise down to (0.1 Hz). Before testing, the microphone was calibrated using a Larson Davis CAL200 Precision Acoustic Calibrator. CAL200 was set to a (94 dB) noise source at 1kHz. The sensitivity is altered during calibration so that the output of the microphone was within (0.025 %) of the (94 dB) source. This output was displayed numerically and graphically on a frequency spectrum within the m+p SmartOffice Dynamic Signal Acquisition and Analysis software. To mitigate this effect in measurement readings, the manufacturer had pre-calibrated the microphone to account for itself. Figure (6) shows ½” Microphone as calibrated by Larson Davis CAL200.

Figure 6. ½" Microphones as calibrated by Larson Davis CAL200

Wind tunnel testing procedure

Before the wind tunnel testing can begin, the wind tunnel does not provide actual wind velocity values. Therefore, a method was needed to measure the velocity output. A digital manometer, shown in Figure (7), was used to measure the pressure of the wind when the tunnel was in operation. The measured pressure was then converted into velocity. Density of air was assumed to be (1.225 kg/m³). With a valid method to calculate the wind flow speed, then it could easily be controlled to operate at designated speeds of (5, 10, and 15 m/s).

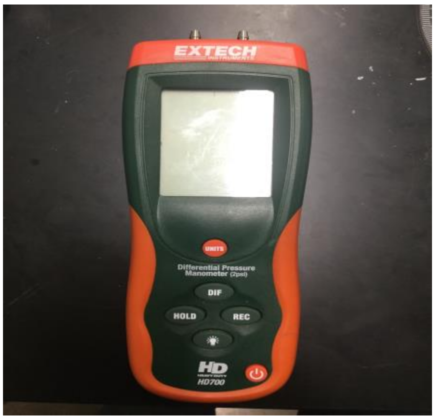

Figure 71. Digital Manometer

2. The Results

Acoustic equipment, including the microphone and smart office, was used to calculate the noise around the airfoils. This section presented all the factors that affect the noise, such as the flow velocity and angle of attack. From the preliminary results, the range of frequencies measured from the airfoil section was (20 Hz to 12 kHz). The results indicated that the noise of interest will be within (0-500 Hz) range.

3.1 Velocity influence

Figures (8, 9, 10, 11) show the relation between sound pressure level and flow velocity. It is very clear that when the wind velocity gets larger, the noise gets higher. Generally, when the velocity increases by (5 m/s), the noise gets larger by an average amount of (10 dB), as shown in Table (3). The increase of flow velocity increases the velocity shear that eventually increases the aerodynamic noise [11]. These results match the results found in the previous studies [5,6,9].

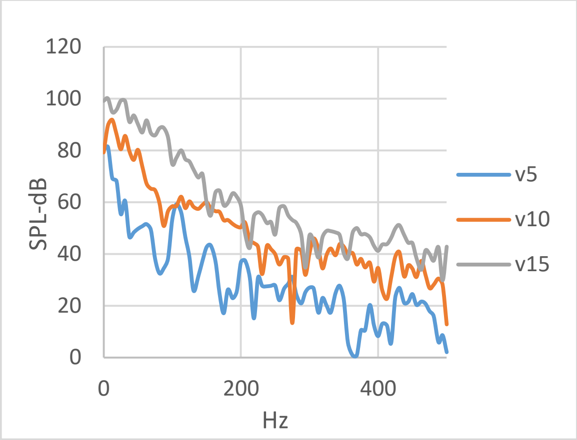

Figure 82. SPL vs. Freq. for sample1 for Velocities 5,10, 15 m/s

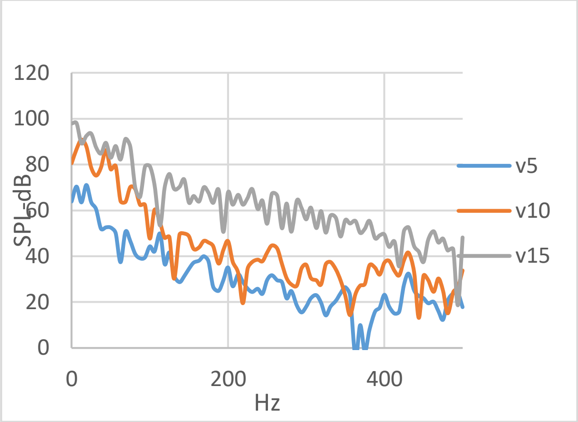

Figure 9. SPL vs. Freq. for sample 2 for Velocities 5,10, 15 m/s

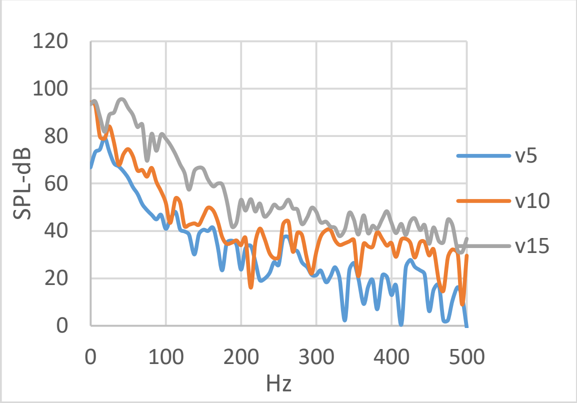

Figure 10. SPL vs. Freq. for sample 3 for Velocities 5,10, 15 m/s

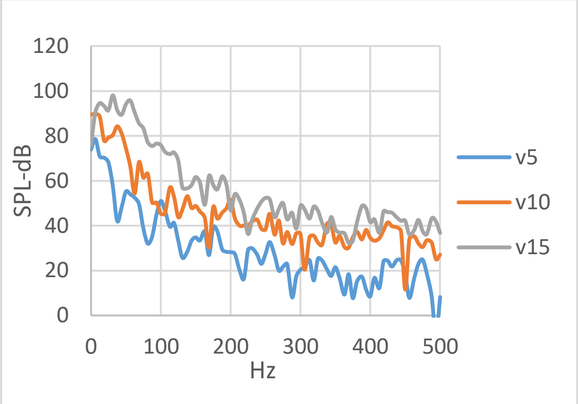

Figure 11. SPL vs. Freq. for sample 4 for Velocities 5,10, 15 m/s

Tables (1) to (3) show the sound pressure level in (dBA) for the velocities (5, 10, 15 m/s) in order. Table (1) shows A-weighting adjustments for one octave center frequencies for all the samples in flow velocity 15 m/s. The overall sound pressure level is measured by the equation (2).

Table 1. A-weighting adjustments for one octave center frequencies for all the samples in flow velocity 15 m/s

X [Hz]	SPL (dBA) Sample 1	SPL (dBA) Sample 2	SPL (dBA) Sample 3	SPL (dBA) Sample 4
31.5	43.89	42.59	44.13	44.67
63	49.56	47.60	46.03	44.32
125	45.81	43.30	47.84	42.91
250	28.43	35.04	45.57	37.80
500	27.93	33.52	38.97	33.64
1000	29.80	46.46	37.56	37.41
2000	15.59	37.99	27.36	35.33
4000	11.99	24.37	28.12	26.48
8000	0.85	12.67	11.01	9.22
Overall SPL (dBA)	**51.91**	**51.86**	**52.49**	**49.71**

Tables (2) and (3) show the A-weighting adjustments for one-octave center frequencies for all the samples in flow velocities (10 and 5 m/s) in order and AOA (10^o). The overall (dBA) was measured in the same way. While table (4) shows the overall SPL for all samples in flow velocities (15, 10, 5 m/s) AOA (10^o).

Table 2. A-weighting adjustments for one octave center frequencies for all the samples in flow velocity 10 m/s AOA 10°

X [Hz]	SPL (dBA) Sample 1	SPL(dBA) Sample 2	SPL (dBA) Sample 3	SPL (dBA) Sample 4
31.5	38.19	37.68	35.83	38.03
63	34.03	35.74	37.94	35.39
125	31.49	26.45	32.83	27.68
250	31.34	28.40	34.28	29.85
500	19.65	23.35	30.55	23.95
1000	28.02	23.46	29.38	17.41
2000	26.43	7.71	17.74	19.19
4000	13.37	5.38	-7.12	12.23
8000	-2.20	-4.42	-2.91	9.25
Overall SPL (dBA)	**41.2**	**40.5**	**42.2**	**40.7**

Table3. A-weighting adjustments for one octave center frequencies for all the samples in flow velocity 5 m/s

X [Hz]	SPL (dBA) Sample 1	SPL(dBA) Sample 2	SPL (dBA) Sample 3	SPL (dBA) Sample 4
31.5	25.10	26.10	25.10	23.20
63	30.30	29.40	21.20	30.30
125	25.70	23.70	25.50	23.20
250	22.20	17.10	21.00	18.90
500	-1.14	-3.88	14.60	5.03
1,000	5.57	18.60	16.80	15.70
2,000	1.04	11.70	14.90	4.73
4,000	-12.30	-1.37	-10.60	2.52
8,000	5.32	10.10	8.12	9.10
Overall SPL (dBA)	**32.88**	**32.21**	**30.21**	**32.10**

Table 4. The overall SPL (dBA) for all samples in the flow velocities 5, 10, 15 m/s

Flow velocity	SPL (dBA) Sample 1	SPL(dBA) Sample 2	SPL (dBA) Sample 3	SPL (dBA) Sample 4
15 m/s	51.91	51.86	52.49	49.71
10 m/s	41.2	40.5	42.2	40.7
5 m/s	32.88	32.21	30.21	32.10

3.2 The Influence of Angle of attack

The results of noise showed a direct relation between aerodynamic noise results and the angle of attack of the samples. Figures (12)-(15) show this relation between Sound Pressure Level (SPL) and Angle of Attack (AOA). The figures show an increase in the sound pressure level when the angle of attack increases. This increase in sound pressure level is due to: the increased low frequency from the suction side of the airflow because of its thicker boundary layer thickness and large turbulence scales; and the increased higher frequency from the pressure side because of its thinner boundary layer thickness and small turbulence scales [14].

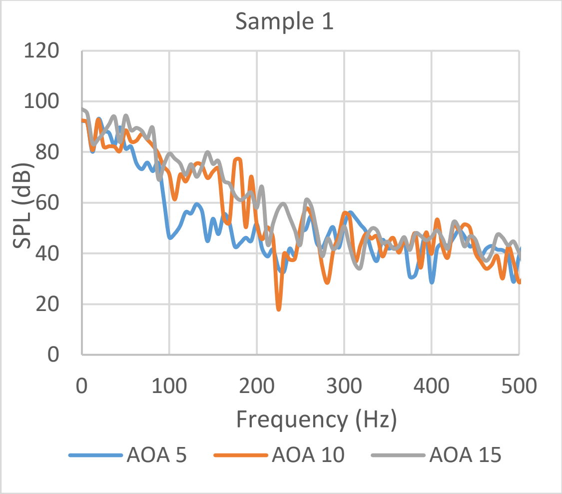

Figure 12. SPL vs. Freq. for sample1 for AOA 5,10, 15

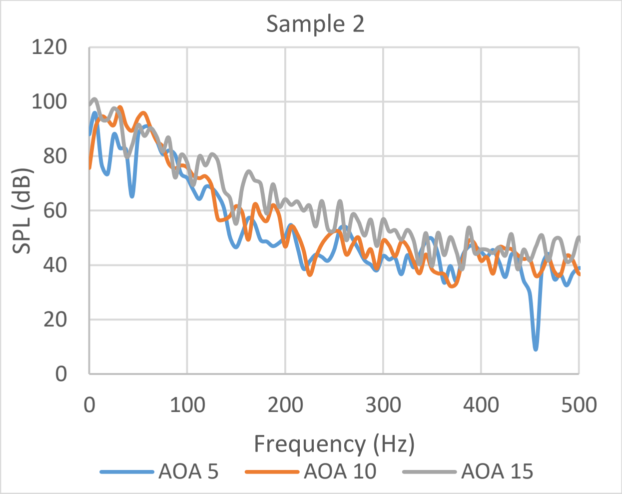

Figure13. SPL vs. Freq. for sample2 for AOA 5,10, 15

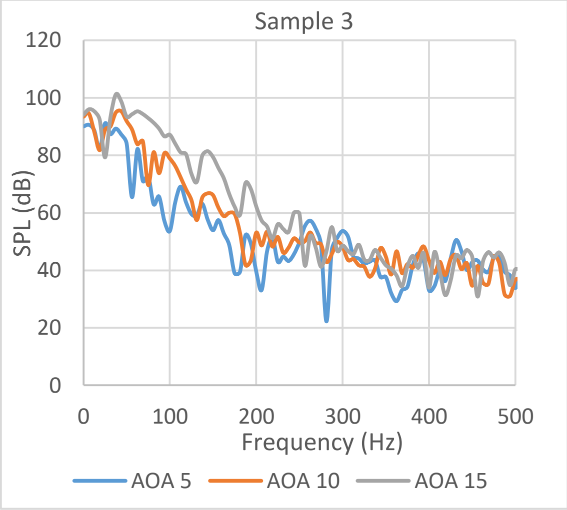

Figure 14. SPL vs. Freq. for sample3 for AOA 5,10, 15

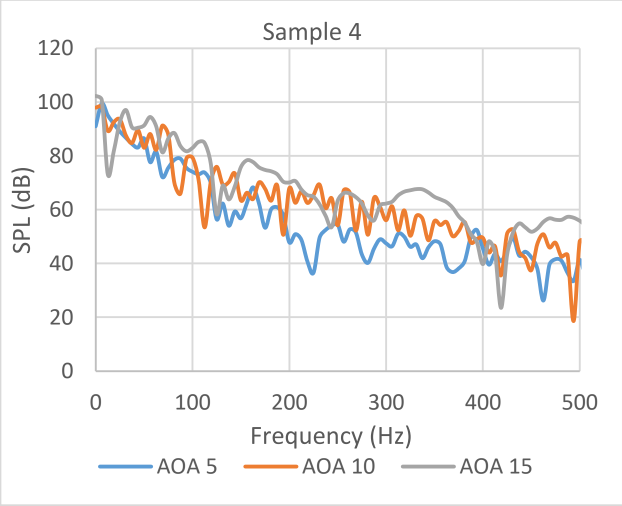

Figure 15. SPL vs. Freq. for sample4 for AOA 5,10, 15

The overall SPL increases between (1-4 dBA) when the angle of attack increases from (5-10 degrees), while there is an increase from (1-6 dBA) when the angle of attack increases from (10-15 degrees). Figure (16) shows the overall sound pressure level for different angles of attack for all samples.

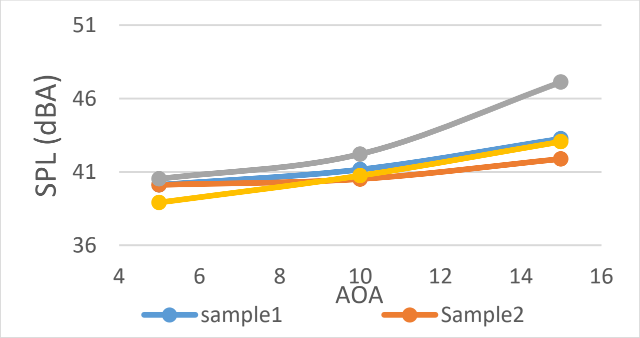

Figure 16. The overall sound level for all samples vs. AOA

3. Conclusion

Wind speed and angle of attack have a direct effect on the quantity of noise emitted from wind turbines. Wind tunnel and sound level measurement equipment are used in this study to investigate this effect. The effect of wind speed and angle of attack on the aerodynamic noise is investigated in this study. Four different samples of NACA 0012 airfoil are used. Three speeds (5, 10, 15 m/s) are employed. The study shows that the aerodynamic noise is associated directly with the flow speed and the increase of flow velocity increases the velocity shear that increases the aerodynamic noise. The data shows that when the velocity increases by (5 m/s), the noise gets louder by an average amount of (10 dB). The angle of attack shows a direct influence on the aerodynamic noise as well. The results reveal that there is an increase in the overall sound pressure level between (1-4 dBA) when the angle of attack increases from (5-10 degrees), while there is an increase from (1-6 dBA) when the angle of attack increases from (10-15 degrees). This study is carried out under subsonic flow conditions.

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