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Research paper

Study the Effect of Blade Angles on the Performance of Axial Six Blades Wind Turbine

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Abstract

In this paper, the performance of a six blades axial type wind turbine has been studied experimentally to estimate the wind power, the electrical generated power and-the modified power-coefficient of the wind-turbine. This study was conducted under different operating conditions assuming steady-state, incompressible and isothermal air flow through the wind-turbine. The range of operating condition was (2 to 5.6 m/s wind speed), (10% to 100% of electrical load that is applied on the terminals of the electrical generator) and (10° to 80° blades angle of the wind-turbine). A good agreement was obtained when comparing the results of the present work with those of a previously published article. The predicted results showed that increasing the wind speed and-the blades angle of the wind-turbine will increase the generated power from the wind-turbine. The maximum-value of the modified power-coefficient was (0.57) at a wind velocity value of (5.6 m/s) and at a blades angle value of (80°). It is found that it's not recommended to operate the wind-turbine at (80°) blades angle associated with a wind speed range that is above (3.8 m/s) due to a high level of wind-turbine vibration.

Keywords: *Axial wind turbine, Renewable energy, Blade angle, Wind velocity, Power coefficient.*

1. Introduction

The new technology of power-generation from wind energy is growing rapidly and it has technical and financial challenges including the issues of low performance and high capital costs. These technical challenges are mainly to overcome the operation of the power unit at frequent change of wind direction and at extremely low wind velocity. In general, a wind-turbine is defined as a mechanical device that converts the kinetic-energy of wind into mechanical-energy and then to electrical-power to be utilized to drive water pumps, wind mills or other applications.
In 2009, few countries have achieved high levels of wind power generation, such as the 20% of power production in Denmark, 14% in Ireland and Portugal, the 11% in Spain, and 8% in Germany. In May 2009, all countries around the world was using wind energy on a commercial basis. At the end of 2009, the overall capacity of wind-power generators was 159.2 GW (Gigawatts). In 2014, the global capacity of wind energy increased up to 369,553 GW. The production of wind power is growing rapidly and has reached approximately 4% of the overall electrical power usage in the last years. Few regions in Iraq have a wind velocity range of (3.5- 5 m/s) which is useful for the wind-energy application. These local areas are more suited for this application, due to being remote and generally small and scattered population.
(Medici, 2005) Investigated experimentally the effect of a wake behind a wind-turbine model with one, two and three blades to calculate the output power from the turbines. The yaw-angle of the blade was varied from 0 to 30 degrees. Three velocity-components were measured for the flow field. It was found that a yawed-turbine deflects the wake to the side. The output power of the turbine depends on the rotational-speed of the wind-turbine rotor.(Khalil, 2007) Investigated the performance analysis of a wind-turbine on the basis of a different modelling approach of wind-turbine. The dynamics of wind-turbine has been investigated to avoid unpredictable outputs and to ensure that continuous and efficient power is supplied according to the load requirements. The work was the initial step of the control of wind-turbine. The performance and transfer function of wind-turbine were derived by using the commercial software MATLAB. The research showed different approach of wind-turbine modelling.
The design of a position control system for the blade pitch angle of a variable speed wind-turbine generators were studied by (Ahmed, 2009)**.** The quality of power has been enhanced by using suitable control technique in the system. The fluctuating output of wind power generator has been controlled to study the dynamic characteristics of the wind-turbine. Blade pitch control has been discussed by using rotary potentiometers for position control and some experimental tests as a simulation of the position control.
(Jasim, 2010) Investigated theoretically the dynamics of a small wind-turbine**.** The aerodynamic forces were predicted at any variable speed wind-turbine blade. The results were presented by using a code of FORTRAN 90. In this code, the torque and the output power were both estimated at any wind-speed. The results were compared with those predicted using Betz theorem. Additionally, the numbers of revolutions of the small turbine were evaluated for any wind-speed. The suiting tip speed ratio and wind-speed have been determined from this model.
(Toshimitsu et al., 2012) Predicted the performance of a compact type flanged diffuser shroud wind-turbine in a sinusoidal oscillating and fluctuating velocity for both stable and un-stable wind flow. The results show that the efficiency of compact type wind-turbine is high when compared with that having only rotor.
The performance of both wind-turbines for unsteady flow were studied numerically and experimentally. Predicted results were

visualized. The accuracy of the predict results of the power-coefficient in the oscillating flows was (94 – 102 %).

Experimental studies of a shrouded, horizontal axis micro-wind-turbine with diffuser augmented were investigated by (Kosasih, 2012) to enhance the wind-turbine performance. The enhancement of performance depends on many parameters including diffuser geometry, blade aerfoil, and-the wind-speed. Three different shapes of diffusers were selected. It was found that the performance enhancement ratio with diffuser was only 60% when compared with that of the bare turbine while it was 63% for nozzle-diffuser enhancement.

(Rachman, 2014) **S**imulated the yearly-energy-production of a wind-turbine. This simulation was developed using a mathematical model of blade momentum.

(Abdin *et al.*, 2012) Manufactured a three blade PVC wind turbine and tested its efficiency at three values of wind speed (4.0, 5.1 and 6.1 m/s) and at five values of turbine blade pitch angles (10^o, 15^o, 20^o, 25^o and 30^o). It was found that there is no homogeneous trend of voltage and power increase with the increase in turbine blade pitch angle. In addition, the best turbine performance showed at 15^o turbine pitch angle.

(Aldair, 2014) Performed a study of the pitch-angle control design of wind-turbines using Fuzzy-ART network. The power extracted from the wind-turbine can be enhanced by adjusting the blades pitch-angle of the wind-turbine. In the work, the fuzzy- ART (Adaptive Resonance Theory) system has been utilized to control the angle between the approaching wind direction and-the chord-line of the blade. The results show that the system controller is very effective to adjust the blade angles.

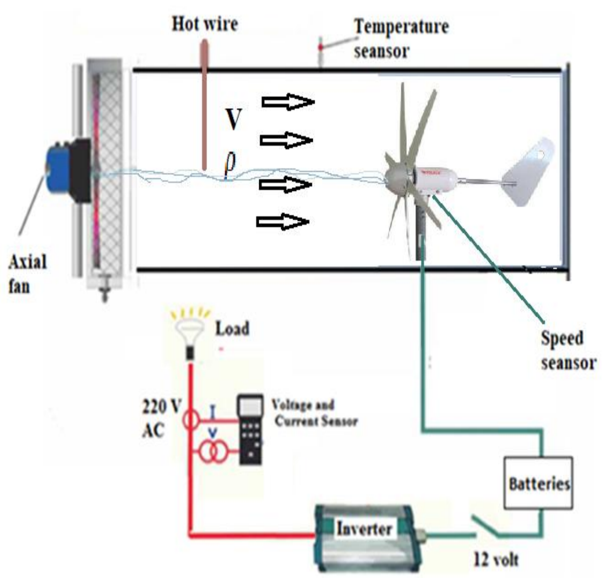
(Dakeev, 2013) Performed a study of analyses of wind-power-generation with application of wind tunnel attachment on wind-turbine unit. The wind tunnel apparatus is used for enhancement the power-generation efficiency of a wind-turbine. The power generated by the wind-turbine at various wind-speeds was utilized to develop a characteristic performance curve. The experimental work included operating the wind-turbines at variable wind velocity values with and without the wind tunnel attachment. Experimental results indicate that the power generated when using the wind tunnel attachment was 60% higher when compared to that without the wind tunnel attachment.

In this paper, the performance of a six blades axial type wind-turbine will be studied experimentally to estimate the wind-power, the electrical generated power and-the modified power-coefficient of the wind-turbine. In addition, it will investigate the effect of altering the wind-speed, the electrical load that is applied on the terminals of the electrical generator and altering the blades angle of the wind-turbine to estimate the optimum operating condition of the wind-turbine. To validate the results of the present work, it will be compared with results of a previously published article.

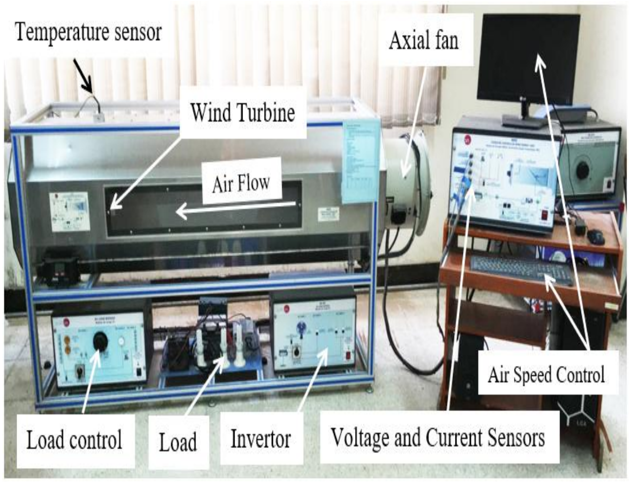
2. Experimental Work

Figure 1-a illustrates the schematic diagram of experimental apparatus. It consists basically of an axial fan, tunnel, rotor of six blades, speed sensor, wattmeter and loads module. The axial flux fan introduces to supply air in the tunnel of (2 to 5.6 m/s), to simulate the same wind-speed range in many regions in Iraq that have a wind-speed range of (3.5 to 5 m/s) which is useful for the wind-energy applications (Darwish and Sayigh, 1988 a) and (Darwish and Sayigh, 1988 b). The tunnel is manufactured from a stainless steel of (2 x 0.55 x 0.55 m) approximately as shown in Figure 1-b. The turbine is a simple injection model that joins the tips of the six blades were shown in Figure 2-b. There is no twist in blades due to very small blade size. The aspect ratio of the rotor diameter of the turbine to the diameter of the wind tunnel test section is (d/D=16 cm / 52 cm = 0.3) which is less than (0.5) to avoid the boundary layer effect. The blade is placed along a perpendicular direction to that of the wind, and can be changing the angular position of blades (0° to 90°), as shown in Figure 2-a.

The speed of air is measured by using a sensor placed in the tunnel and also measure the rotational-speed of the wind-turbine rotor. There is one temperature probe before the rotor, in order to measure the temperature of the air. The wattmeter is to measure the value of voltage and current given produced by the electrical generator.

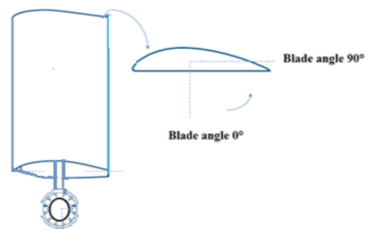


(a)

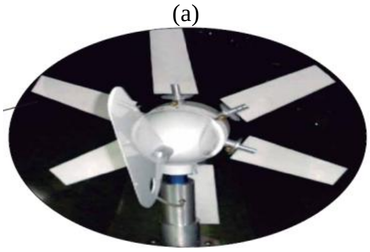


(b)

Fig. 1: Test rig of wind-turbine: (a) Schematic diagram (b) Photo



(a)



(b)

Fig. 2: Scheme of axial type wind-turbine: (a) Turbine blade (b) Scheme of turbine

3. Theoretical Analysis

The higher the amount of kinetic-energy extracted from wind is, the slower the outlet air speed will be. If kinetic-energy is completely extracted, the air speed in the outlet will be zero, the air will not be able to get out of the turbine and no energy will be obtained. If the air passes through the turbine with no speed change, then no energy would be obtained. In an ideal aero generator, the outlet air speed is about 2/3 of the inlet air speed. In order to demonstrate this, fundamental aero dynamics law is used (Betz-Law). Betz-Law says that less than 59% of the kinetic-energy of the wind can be converted into mechanical-energy when using an aero generator (Darwish and Sayigh, 1988 a) and (Darwish and Sayigh, 1988 b). To analyse the wind-turbine performance. The following assumptions apply:

- Steady-state flow.
- Isothermal flow.
- Incompressible flow.

In control volume section AA' as shown in figure 3, a tube, with this section fixed into space. The fluid in A section moves with speed V of constant module and direction perpendicular.

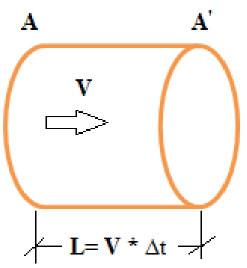


Fig. 3: The control volume

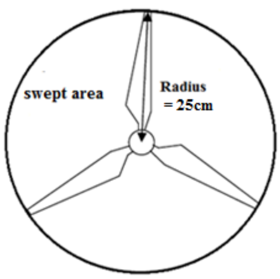


Fig. 4: The swept-area

The length (L) travelled by A' section will be obtained in equation (1):

$$L = V\,.\Delta t\; L = V\,.\Delta t \tag{1}$$

The fluid contained in the volume over the tube defined by this length (L) has a mass (M):

$$M = \rho\,.A\,.V\,.\Delta t\; M = \rho\,.A\,.V\,.\Delta t \tag{2}$$

ρ ρ = air density, (kg/m^3)
A= rotor or swept-area, (m^2), see figure 4.
Δt = Period of time, (sec), and
V =wind-speed, (m/s).

The kinetic-energy (E_K) (E_K) of the wind that corresponds to this mass definition is:

$$E_K = \frac{1}{2}\,.\;(\rho\,.A\,.V\,.\Delta t)\,.V^2$$
$$E_K = \frac{1}{2}\,.\;(\rho\,.A\,.V\,.\Delta t)\,.V^2 \tag{3}$$

Dividing the kinetic-energy (E_K) (E_K) of the wind by the time spent (Δt) (Δt) in travelling along the tube will give us the total wind-power (P_w) (P_w), as follows:

$$P_w = \frac{1}{2}\,\rho\,.\,A\,.\,V^3\; P_w = \frac{1}{2}\,\rho\,.\,A\,.\,V^3 \tag{4}$$

The power-coefficient (C_P) (C_P) is the ratio of the total hydraulic power (P_T) (P_T) extracted by the wind-turbine to the total wind-power (P_w) (P_w) that is stored in the wind flow:

$$C_P = \frac{P_T}{P_w}\,C_P = \frac{P_T}{P_w} \tag{5}$$

Therefore, the total hydraulic power (P_T) (P_T) extracted by the wind-turbine is:

$$P_T = C_p\,.\,\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3$$
$$P_T = C_p\,.\,\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3 \tag{6}$$

However, mechanical and electrical energy losses are present. Therefore, mechanical efficiency of the rotor axis transmission and electrical efficiency of the electrical generator is introduced to define the total actual generator power (P_G) (P_G) extracted from the wind. Hence, the total actual generator power (P_G) (P_G) extracted from the wind is given as:

$$P_G = \eta_{mec}\,.\,\eta_{elec}\,.\,C_p\,.\,\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3$$
$$P_G = \eta_{mec}\,.\,\eta_{elec}\,.\,C_p\,.\,\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3 \tag{7}$$

Also, the total actual generator power (P_G) (P_G) can be obtained from the produced electrical-power. The output power of the wind-turbine can simply be measured from the current and voltage across the generator:

$$P_G = I\,.\,v\,P_G = I\,.\,v \tag{8}$$

I = The current, (Ampere)
v = The voltage, (volt)

Merging the mechanical efficiency (η_{mec}) (η_{mec}), the electrical efficiency (η_{elec}) (η_{elec}) and the power-coefficient (C_P) (C_P) into one coefficient will introduce the modified power-coefficient (C_p^*) (C_p^*) as follows:

$$C_p^* = \eta_{mec}\,.\,\eta_{elec}\,.\,C_p\; C_p^* = \eta_{mec}\,.\,\eta_{elec}\,.\,C_p \tag{9}$$

Therefore,

$$C_p^* = \frac{P_G}{P_W} = \frac{I\,.\,v}{\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3}$$
$$C_p^* = \frac{P_G}{P_W} = \frac{I\,.\,v}{\frac{1}{2}\,.\,\rho\,.\,A\,.\,V^3} \tag{10}$$

4. Results and Discussion

An experimental performance study of a six blades axial type wind-turbine was conducted to estimate the wind-power, the electrical generated power and-the modified power-coefficient of the wind-turbine. This study was focused on the effect of altering the wind-speed and electrical load that is applied at the terminals of the electrical generator. In addition, the effect of altering the blades angle of the wind-turbine to estimate the optimum operating condition of the wind-turbine.

Figure 5 shows the relation between the wind velocity and its power. The predicted results of the experiments indicated that the wind-power increases when the wind-speed increase. Also, it shows that the maximum wind-power is (21 watt).

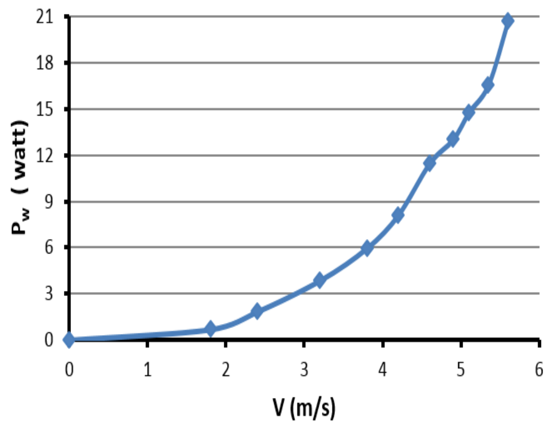


Fig. 5: Wind-power versus the wind velocity

Figure 6 shows the relation between the measured values of rotational-speed of the wind-turbine model with different wind velocity. In general, the rotational-speed of the wind-turbine increases when the increase of wind velocity. A high level of wind-turbine vibration will start to grow as the blade angles is increased above (10°- 20°) associated with a high value of wind velocity. It was found that when operating the wind-turbine at (80°) blades angle associated with a wind-speed range that is above (3.8 m/s), a high level of wind-turbine vibration was observed to reach a critical point. It's clear that this high level of wind-turbine vibration was caused by the increase of boundary layer separation due to the increase of angle of attack of turbine blades. As a result, a vortex shedding will be generated downstream the rotating blades of the wind-turbine causing a pulsating pressure difference between either side of the wind-turbine rotating blades. Hence, a pulsating drag force is generated and causing a high level of wind-turbine vibration.

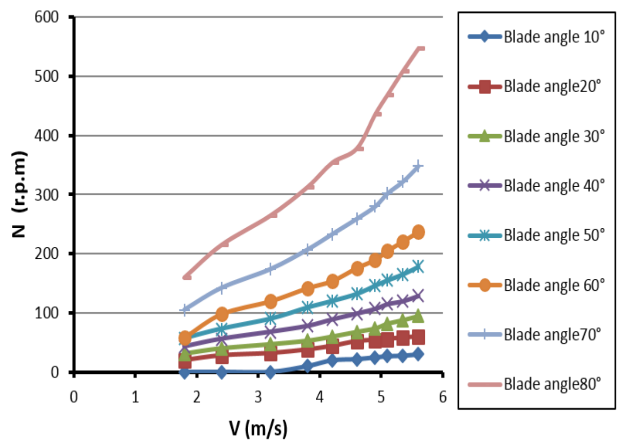
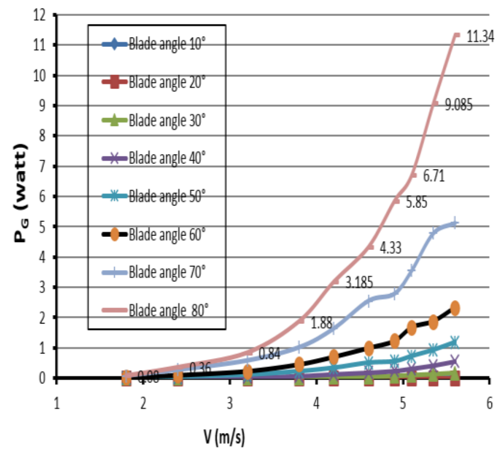
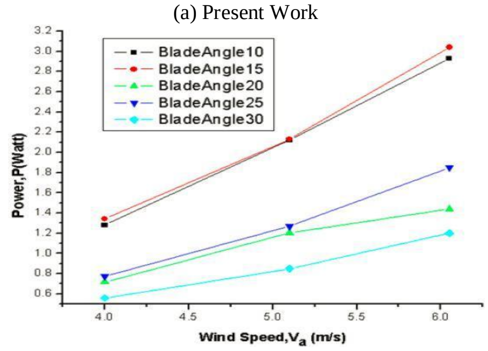


Fig. 6: Turbine speed versus the wind velocity, at different blade angles

Figure 7-a shows the relation between the total generated power from the wind-turbine model for different wind velocity. It's clear that, at any value of blade angle, no power is generated when the wind velocity is less than (2 m/s). The power generated is increased with both; increasing the value of blade angles between (60° to 80°) and increasing the wind velocity. The maximum-value of the generated power is (11.34 watt). The same behavior of the generated power from the wind-turbine for different wind velocity is illustrated in figure (7-b), (Abdin *et al.*, 2012).



(a) Present Work



(b) (Abdin *et al*., 2012)

Fig. 7: Total generated power versus the air velocity, at different angles of blade.

Figure 8 shows the variations in modified power-coefficient C_p^* C_p^* with the air velocity. It shows that the values of $C_p^* C_p^*$ will increase with the increase of both; the wind velocity and-the value of blade angle. In addition, when the value of blade angles is less than (50°), the generated power is neglected. The results show that the maximum-value of $(C_p^* = 0.57)(C_p^* = 0.57)$ at a wind velocity value of about (5.6 m/s) and a blade angle value of (80°). This increase in $C_p^* C_p^*$ is cause by both; increasing the value of blade angles between (60° to 80°) and increasing the wind velocity.

In Figure 9, the variation in the modified power-coefficient C_p^* C_p^* and-the generated power is shown for the wind-turbine model at blade angle equal 80°. It is observed that the modified power-coefficient increases with the increment in the generated power.

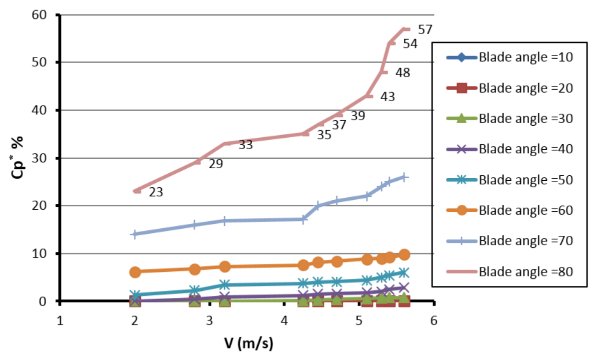


Fig. 8: Modified power-coefficient versus the air velocity, at different angles of blade

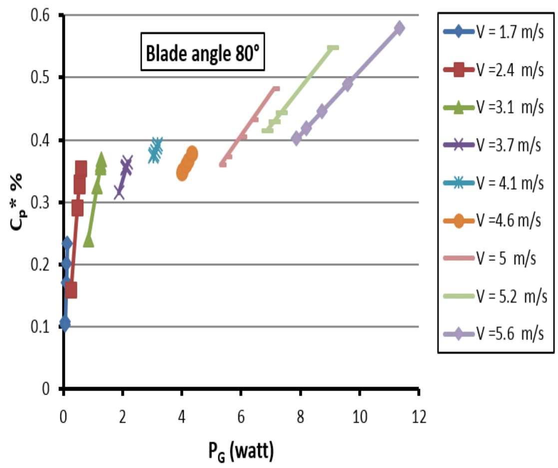


Fig. 9: Modified power-coefficients versus generated power at different wind velocities

5. Conclusions

In the present work, the performance of a six blades axial type wind-turbine was investigated experimentally to estimate the wind-power, the electrical generated power and-the modified power-coefficient of the wind-turbine. This experimental investigation focused on the effect of altering the wind-speed, the electrical load that is applied on the terminals of the electrical generator and altering the blades angle of the wind-turbine to estimate the optimum operating condition of the wind-turbine. This study has the following conclusions:

Increasing the wind-speed and-the blades angle of the wind-turbine will increase the generated power from the wind-turbine.

It's not recommended to operate the wind-turbine at (80°) blades angle associated with a wind-speed range that is above (3.8 m/s) due to a high level of wind-turbine vibration.

No power is generated from the wind-turbine at wind velocity less than (2 m/s) for different blade angle.

The maximum generated power from the wind-turbine is obtained when the blade angle value is equal to 80° and wind velocity value at 5.6 m/s.

he maximum modified power-coefficient $\left(C_p^* = 0.57\right)$ $\left(C_p^* = 0.57\right)$ was observed at a wind velocity value of about (5.6 m/s) and at a blade angle equal to (80°).

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