ANALYSIS OF A COUNTER ROTATING VERTICAL AXIS WIND TURBINE

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ABSTRACT

This study analyses the performance of a counter rotating vertical axis wind turbine (CRVAWT). The CRVAWT consists of two separate three-blade rotors where conducting coils were fixed onto one turbine and permanent magnets were attached to the other turbine. Both rotors rotate in the opposite direction which, according to Faraday's law of electromagnetic induction, significantly increases the performance of the device. A H-Darrieus type turbine was chosen for the analysis due to its higher efficiency. Both turbines were made to rotate in a counter-rotating motion by orientating their airfoil blades in the opposite direction. The device was fabricated, assembled and tested in a low-speed wind tunnel. Experimental results show that the CRVAWT obtained a much larger power output of up to five times that of the conventional VAWT (CVAWT). However, the coil-attached turbine displayed a lower rotational speed than the magnet-attached turbine due to resistance from the slip ring. This also caused the cut-in wind speed for the former turbine to be higher than the latter one. Additionally, while the coefficient of power for the CRVAWT is identical to the CVAWT, the efficiencies for both rotors vary differently with wind speed due to the slip ring. Nevertheless, the CRVAWT demonstrated a higher overall efficiency at wind speeds larger than 8.0 m/s and similarly, the power density of the CRVAWT becomes significantly larger than the CVAWT at wind speeds above 8.0 m/s.

KEYWORDS

Counter-rotating; Vertical axis wind turbine; H-Darrieus; Powerl; Efficiency

INTRODUCTION

The increasing awareness on the risk and limitations of energy produced from burning fossil fuels has encouraged research in renewable energy technologies such as wind turbines. Vertical Axis Wind Turbines (VAWT) have gained significant attention in recent years as a promising stand-alone alternative to traditional Horizontal Axis Wind Turbines (HAWT). VAWTs offer various advantages, including lower cost of installation and maintenance, scalability, lower noise and improved performance in turbulent wind conditions [1, 2]. Additionally, most VAWTs do not require yaw-control to rotate the turbine towards the desired wind direction since they are omnidirectional due to their vertical axis rotation [3]. VAWTs come in various designs and configurations, which can be broadly categorized into Darrieus and Savonius types. Darrieus turbines are among the most common VAWT designs [4].
Savonius type VAWTs utilizes the drag force on the rotor surface to induce a positive drag force which rotates the shaft [5]. This type of turbine has a high starting torque at low wind speed, giving it the advantage at the low wind speed range. However, the average coefficient of power (CP) for Savonius turbines tends to lean towards the lower range (CP □ 0.15) compared to HAWTs (CP □ 0.45) and Darrieus type VAWTs (CP □ 0.35) [6]. On the other hand, Darrieus type turbines rotate using the lift force generated on the rotor blades. Due to this, Darrieus turbines are unable to self-start, but produce a better efficiency compared to the Savonius type [7].

Conventional vertical axis wind turbines (CVAWT) have only one rotor component which limits the performance of the device. By having two counter-rotating rotors instead, they form a positive coupling effect which significantly boosts the power output of the device based on Faraday's law of electromagnetic induction [8]. Hence, comes the idea of counter-rotating vertical axis wind turbine (CRVAWT). Lee et al. [9] showed that the structural integrity of a CRVAWT is superior to the CVAWT due to smaller aerodynamic loads. Shchur et al. [10] demonstrated that the optimal distance between the two rotors for a CRVAWT is 30.0% the height of a single rotor blade. On the other hand, Poguluri et al. [11] studied the effects of the blade pitch angle for a H-Darrieus type CRVAWT and showed that the performance of the device significantly decreases with blade angle.

This study analyses the performance and efficiency of a H-Darrieus type CRVAWT compared to a CVAWT. The CRVAWT was fabricated using 3D-printed material (polylactic acid) and fixed onto a self-made three-phase electromagnetic generator. The device consists of two rotors which rotate in the opposite direction when subjected to the same wind flow. One rotor is fixed onto the conductor component of the generator while the other rotor houses the magnetic component. An experiment was conducted in a low-speed wind tunnel to evaluate the performance of the wind turbine at different wind speeds. Finally, the performance of the CRVAWT and the CVAWT were compared and analyzed.

METHODOLOGY

Assuming that no loss of wind speed of the rotor blade, the relative velocity of a single rotor blade, W, and its corresponding angle of attack, α, is [12]

$$W = V_\infty \sqrt{(\lambda + cos\theta)^2 + sin^2\theta} \quad (1)$$

$$\alpha = tan^{-1}\left(\frac{sin\theta}{\lambda + cos\theta}\right) \quad (2)$$

$$\lambda = \frac{R\omega}{V_\infty} \quad (3)$$

where V_∞ is the freestream wind velocity, θ is the azimuth angle and λ, R and ω is the tip speed ratio, radius and angular speed of the rotor respectively. The total turbine torque, T, can be calculated as:

$$T = \frac{N_b R \rho_a C H}{4\pi} \int_0^{2\pi} c_t W d\theta \quad (4)$$

$$c_t = c_l sin\alpha - c_d cos\alpha \quad (5)$$

where N_b is number of rotor blades, ρ_a is the density of air, C and H are chord length and height of the rotor blades and c_t, c_l and c_d are the torque, lift and drag coefficients respectively. The lift and drag profile of the airfoil rotor blades can be obtained from past literature. The maximum mechanical (P_m), electrical (P_e), and available (P_a) power of the VAWT can be determined by [13]:

$$P_m = T\omega \quad (6)$$

$$P_e = \frac{0.3745}{Z}(N_m N_c \omega B A_c)^2 \quad (7)$$

$$P_a = \rho_a R H V_\infty{}^3 \quad (8)$$

where N_m, N_c, B, A_c and Z are variables that defines the properties of the electromagnetic generator which are the number of magnet poles, the number of conductors, the magnetic flux density, the effective area of the conductor and the generator's impedance respectively. Finally, the coefficient of power, c_p, and the overall efficiency, of the wind turbine can be defined as

$$c_p = \frac{P_m}{P_a} \quad (9)$$

$$\eta = \frac{P_e}{P_a} \quad (10)$$

Design, fabrication and experimental setup

In this study, a H-Darreius type CRVAWT including its generator was fabricated and experimentally tested inside a low-speed wind tunnel to evaluate its performance.

Design and fabrication of CRVAWT

According to Hamdan et al. [14], the best performing airfoil for a H-Darrieus type wind turbine is the Selig S1046 airfoil, which was later supported by Tjiu et al. [15]. Hence, two rotors were fabricated using polylactic acid (PLA) material that consist of three Selig S1046 airfoil blades each with a chord length of C = 55.0 mm and a blade height of H = 140.0 mm. The distance between the blades and the center of the rotor is R = 100.0 mm as seen in Figure 1. The gap between the two rotors was measured to be 10.0 mm.

The only difference between the first and the second rotor is that the airfoil blades are oriented in the opposite direction to induce counter rotating motion. The conductor, which consists of 12 wounded enameled copper coil wires arranged in a three-phase wye circuit (Figure 2a) was fixed onto one rotor whereas eight permanent neodymium magnets of grade N35 (Figure 2b) were attached onto the other rotor. Each magnet measures 5.0 x 10.0 x 25.0 mm and the diameter of the coil wire used is 0.25 mm. The blow-up schematic diagram representing the assembly of the whole CRVAWT is shown in Figure 2c. The assembled device consists of two rotors, four ball bearings, magnets, conductor, a steel shaft and a six-wire slip ring to connect the rotating conductor coils to a static measurement output. Rotor 1 corresponds to the conductor-attached rotor whereas rotor two corresponds to the magnet attached rotor.

Experimental setup

An experiment was conducted to evaluate the performance of the fabricated CRVAWT. The assembled device was placed into the test section of a low-speed wind tunnel measuring 1270.0 × 450.7 × 450.7 mm as displayed in Figure 3a. The output from the slip ring was connected to a data acquisition device to transfer the induced voltage reading to a computer. A digital manometer was used to measure the dynamic pressure inside the wind tunnel which can then be converted into its respective wind speed. The CRVAWT tested at different wind speeds ranging from 2.0 ms-1 to 15 ms-1 and the three-phase voltage output of the device was recorded for ten seconds at each interval.

Afterwards, the rotation of the lower rotor (Rotor 1) was halted using a metal obstacle. The purpose of doing so was to emulate the conditions of a CVAWT. The experiment was then repeated under this condition and compared to the results of the previous experiment. Since the properties of the turbine were measured based on its voltage output, the wind tunnel blockage correction factor was not considered.

Results and Discussion

Results in Figure 4a describes the variation in wind speed (V_∞) with rotational speed (ω) of both rotors and Figure 4b describes the variation in wind speed (V_∞) with electrical power output (P_e) for the CRVAWT and the CVAWT. The angular speed was measured based on the output voltage of the turbines.

The theoretical approximation in Figure 4b was calculated using equation (7) using the generator properties in Table 1 which were obtained from the experiment. Results in Figure 4 demonstrate that Rotor 1 has larger cut-in wind speed than Rotor 2. In other words, Rotor 1 starts rotating at a higher wind speed compared to the other rotor. Rotor 2 starts rotating at wind speeds as low as 2.5 ms-1 whereas Rotor 1 only starts spinning at 6.0 ms-1. The reason for this is due to resistance from the slip ring that is connected to Rotor 1, which introduces more friction into the system. In the experiment, a brushed slip ring was used which operates based on a similar concept to a brushed motor, where electrical flow is maintained through contact between gold brushes and a conducting surface. Although the use of brushes does minimize the contact surfaces, the friction generated by them is not negligible.

In terms of electrical power output, the CRVAWT exhibits a greater larger output compared to the CVAWT especially at larger wind speeds, reaching up to five times larger output at a wind speed of 13.2 ms-1. This observation agrees with the fundamental law of electromagnetic induction where the power output of an electromagnetic generator is proportional to the square of its relative rotation speed. It is worth mentioning that prior to reaching a wind speed of 6.0 ms-1, the power outputs of both turbines are very similar since only Rotor 2 is rotating within the said range.

Table 1: Electromagnetic properties of the CRVAWT generator.

Properties	Value
Number of magnet poles, N_m	8
Number of conductors, N_c	12
Magnetic flux density, B (T)	0.135
Conductor effective area, A_c (cm^2)	45.0
Generator impedance, Z, (Ω)	11.8

One of the main parameters used to evaluate the performance of a wind turbine is the coefficient of power or the efficiency of the turbine. Figure 5a illustrates the coefficient of power (c_p) for the Rotor 1 and Rotor 2 against the tip speed ratio ((), which was calculated using equations (1) to (9). Both rotors demonstrate the same curves, which is expected since they are identical.

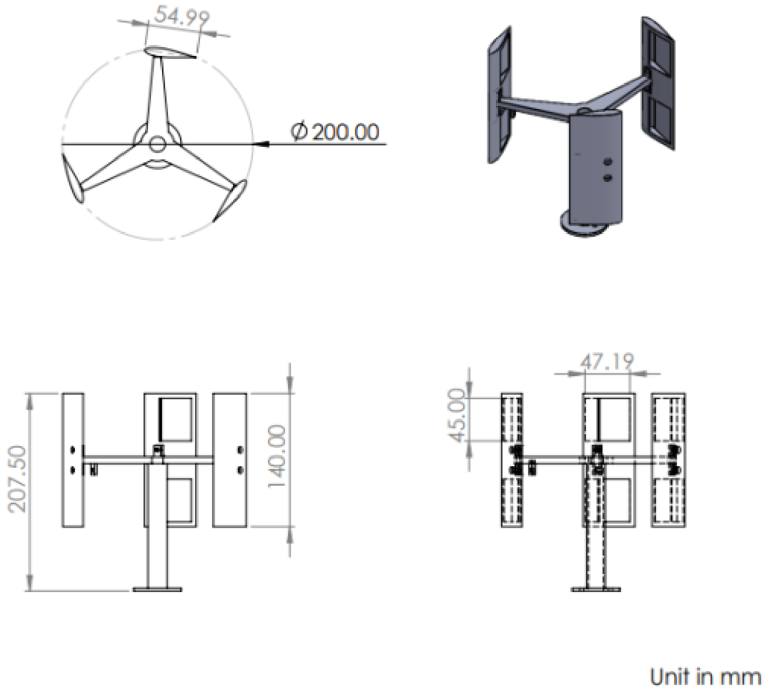

Figure 1: Design of H-Dariues type VAWT rotor

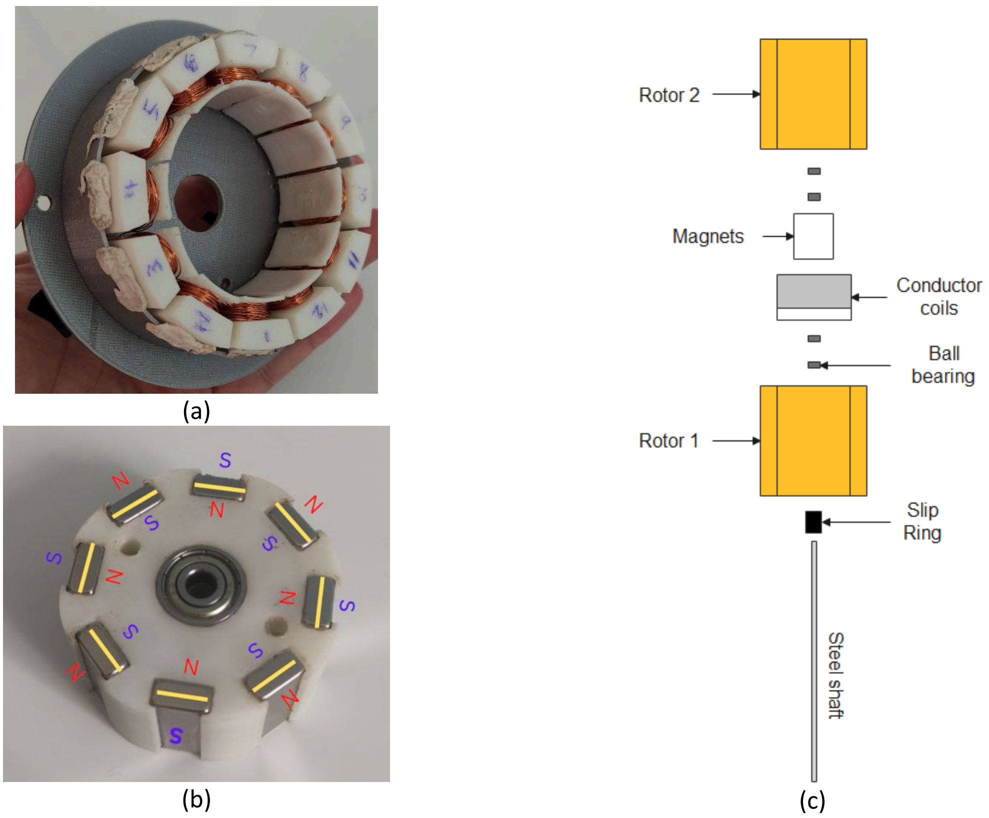

Figure 2: (a) Conductor design, (b) Magnet design, and (c) schematic assembly of CRVAWT.

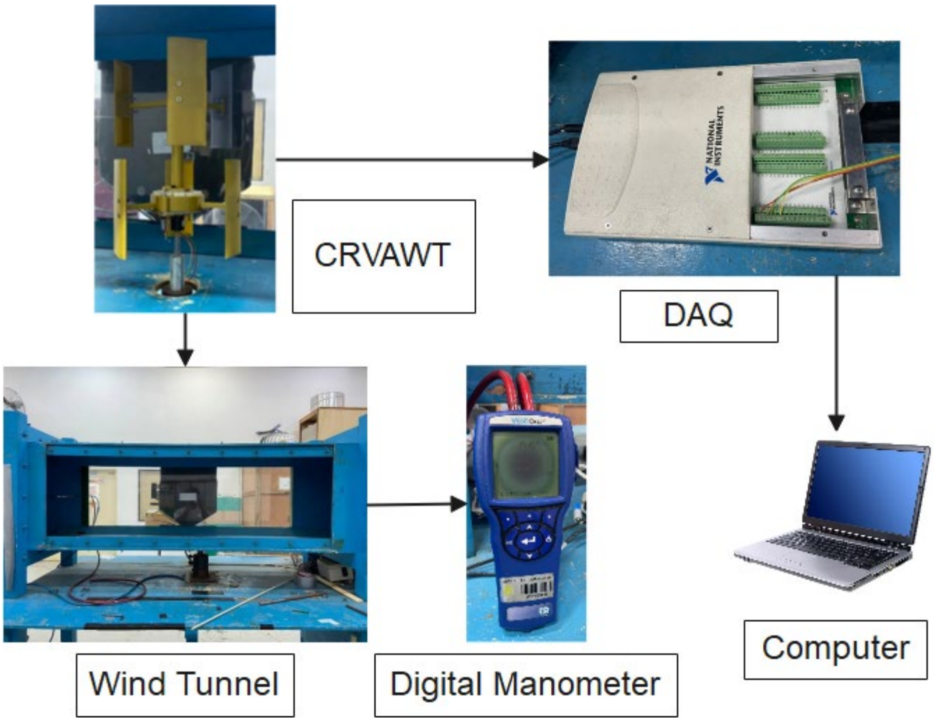

Figure 3: Experimental setup to evaluate the performance of the CRVAWT.

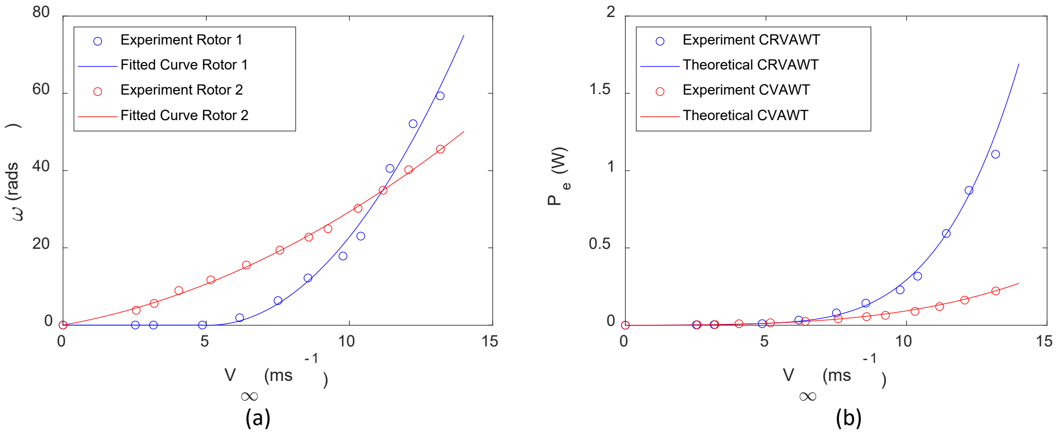

Figure 4: (a) Rotor speed against wind speed and (b) electrical power output against wind speed.

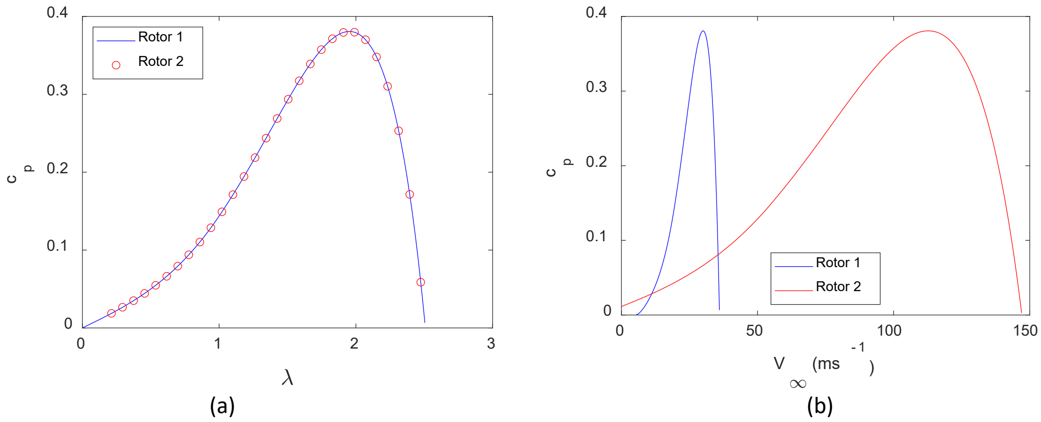

Figure 5: Coefficient of power against tip speed ratio for Rotor 1 and Rotor 2.

However, Figure 5b shows that the variations in c_p against the wind speed for the two rotors are quite different. This essentially means that Rotor 1 and Rotor 2 have different efficiencies at different wind speeds due to the effect of the resistance from the slip ring as stated earlier. Nevertheless, considering the non-dimensional tip speed ratio parameter, it suggests that the coefficient of power for the CRVAWT is equal to the CVAWT. Similar observations have been mentioned in [10]. Figure 6a describes the variation in the overall efficiency (η) against wind speed for both turbines, based on the results from Figure 4b. It is that initially, due to the small rotation of Rotor 1, the overall efficiency of the CRVAWT is lower than the CVAWT. However, after a wind speed of 8.0 ms^{-1}, the efficiency of the CRVAWT greatly surpasses the CVAWT, achieving nearly four times larger efficiency at 15.0 ms^{-1}.

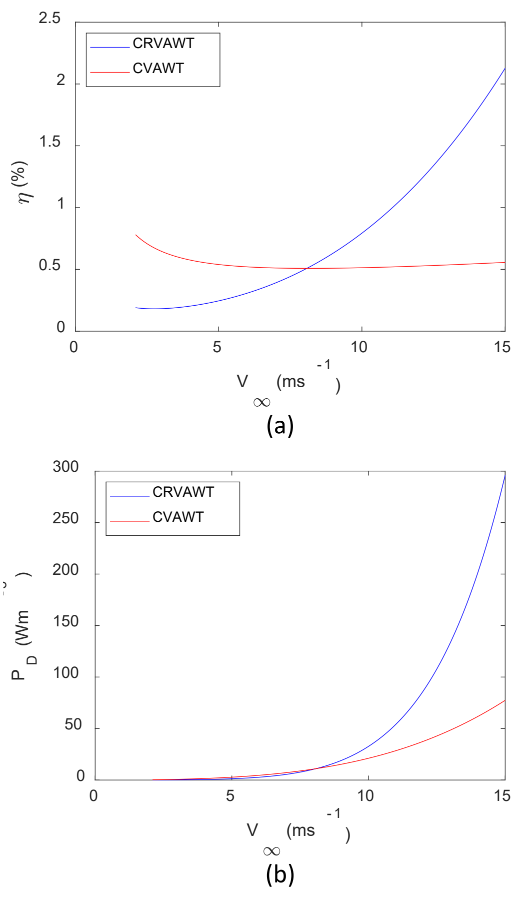

Figure 6: (a) verall efficiency and (b) power density against wind speed (b).

Another common method to compare the performance of an energy harvesting device is to compare its power density, P_D. In general, the power density defines the ratio of the electrical power output to the volume of the device. While the CRVAWT clearly demonstrated a significantly larger power output than the CVAWT, it occupies twice as much volume since it requires two rotors. Figure 6b shows the variation of the power density against the wind speed for both turbines. The volume of the CVAWT was measured to be 4.4 × 10^{-3} m^3 whereas the volume of the CRVAWT is twice that. Similar to the efficiency trend in Figure 6a, the power density of the CRVAWT becomes much larger than the CVAWT after a wind speed of 8.0 ms^{-1}. Prior to that, it exhibits a lower power density than the latter turbine.

Conclusion

This study analyses the performance of a H-Darrieus type counter rotating vertical wind axis turbine (CRVAWT). The turbine consists of two counter-rotating rotors which separately rotate the conductor and the magnetic components of the electromagnetic generator to drastically enhance its power output. The turbine including its generator was fabricated and tested inside a low-speed wind tunnel. Experimental results showed that the power output of the CRVAWT was significantly larger than the conventional VAWT (CVAWT). However, due to friction from the slip ring, the conductor-attached rotor started rotating at a larger wind speed than the magnet-attached rotor. This also caused the coefficient of power for the two rotors to vary differently with wind speed, although their variation with the tip speed ratio is still identical. Nevertheless, it can be argued that the coefficient of power for the CRVAWT is equal to the CVAWT. In terms of overall efficiency, the CRVAWT achieved an efficiency that is nearly four times larger than the CVAWT. However, the efficiency of the former device fails to exceed the latter device below wind speeds of 8.0 ms^{-1}. Likewise, the power density of the CRVAWT greatly surpasses the CVAWT after 8.0ms^{-1}. Overall, the performance of the CRVAWT is superior to the CVAWT, but further analysis should be made to explore a CVAWT with rotor blades that has the same height as the total height of both rotor blades from the CRVAWT before a solid conclusion can be formed.

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