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DEVELOPMENT OF AN EDDY CURRENT BRAKE APPLIED IN SMALL SCALE WIND TURBINE TESTS

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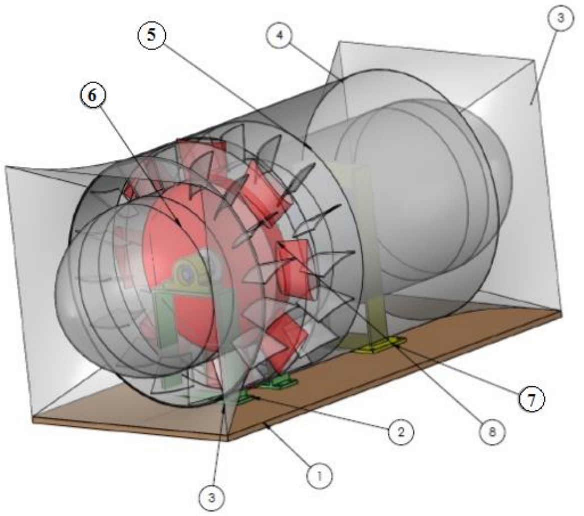
Abstract. *Studies about wind turbines performance are generally preceded by model scale test. This analysis depends on torque measurement and breaking force exerted to the turbine rotor. For small turbines, the values of torque are also smaller and the development of the systems with low inertia and data repeatability have been a challenge. In this study, it is performed a theoretical and experimental study about the development of a Foucault break. An eddy current break was designed based on the theoretical aerodynamics results of a Wells turbine. The model of Wouterse was used in the theoretical electromagnetic design. The building of a magnetic circuit, coils and a stator were conducted along the bench tests construction. A DC motor was used to simulate the turbine movement. The differences between analytic and experimental for magnetic field results remained below 5%. In the dynamic tests, the eddy current brake was able to reduce the rotational speed by 83% in the rated range of the turbine. Results obtained in this present work encourage the development of a device to measure low torques in small wind turbines*.

Keywords: *Small wind turbine, Eddy current brake, Model of Wouterse, experimental test bench*

1. INTRODUCTION

The search for renewable energy alternatives is always present in the scientific/technological communities. Among these forms is wave energy, where oscillating water column (OWC) devices have been one of the most used to convert the energy of the oncoming waves into mechanical and electrical one (Falcão, 2010; Liu et al., 2021). The main operational principle of this device consists on the hydro-pneumatic chamber partially submerged in the sea that leads to the movement of the water inside the chamber, expanding the air into the turbine placed in the air duct connected to the chamber, regardless of the movement of the water into the chamber. One of the most important components of the device is the Wells turbines for energy generation. As these turbines need to maintain the same direction of rotation regardless of the direction of the air flow that crosses them, they use symmetrical aerodynamic profiles, as can be seen in the Fig. 1. The consequence of this characteristic is that the angles of attack are at most 15°, imposing high rotation frequencies on the turbine and low torque values. Thus, to enable the construction of a prototype, a scale model is being developed by the FURG research group. In order to obtain turbine characteristic curves, it is essential to apply resistant conjugates that allow the control and repetition of the tests. Figure 1 also illustrates the main components of the experimental setup studied in the present work.

There are several types of dynamometers, which use different ways to induce braking forces in tests of rotating machines, such as: friction, hydraulics, water brake, electric generators and eddy current. However, for low torque measurements, it is important to analyze which alternative offers less influence on the system being tested. Thus, the electromagnetic brake would be a better applicable choice. Eddy current appears when an electric conductor undergoes conditions of variable magnetic flux and it is possible to occur in two ways: exerting a varying magnetic flux on conductor or moving this metal or alloy in a steady magnetic field. Unlike most electrical machines, the eddy current brake introduces a braking force into a conductive material, which usually uses thin aluminum or copper discs (Gulec et al., 2021).



Number	Description
1	Wind tunnel base
2	Support bearing
3	Diffuser
4	Stator tube
5	Guide vanes
6	Hub and nozzle
7	Support bearing
8	Rotor

Figure 1. Main parts of a Wells turbine investigated in the present work.

Gulbahce et al. (2013) investigated the effect of pole shape on braking torque for a low power eddy current brake. In a numerical simulation, 25 different speed levels between 50 and 7500 rpm were used to determine the characteristics. All parameters were kept unchanged while the rectangular pole shape was changed for a round pole. It has been concluded that the rectangular pole presented maximum braking torque besides dissipating greater power than the round pole.

Balte et al. (2015) explored the magnetic force applied to a flywheel. An universal electric motor was utilized as a prime mover which rotates a pulley arrangement to reduce the flywheel velocity. Results showed an increase on braking force when the gap between coils was reduced, the magnetic force did not experience large variations for different applied voltages in the coils and the electric motor velocity was reduced for a specific range from 25 to 80 rpm.

A model to analyze the sensibility of internals parameters was shown by Zhou et al. (2015). In this study, it was possible identify that the stabilization of torque could be enhanced by obtaining the optimal combination of demagnetization speed point and the nominal maximum braking torque. The air gap thickness is the most remarkable influencing factor on the shifting the demagnetization speed point of eddy current brake. Other parameters that most influences in the nominal maximum brake force are the radius of pole shoe’s cross section area and the distance from the pole shoe center to the rotation center.

An eddy current brake design was presented by Rodrigues et al. (2016). A theoretical and numerical study was performed in which a small difference between simulation and the model of Schiebers was encountered. A bench test and experimental setup for an electric motor with five angular velocities and four air gaps was analyzed. The evaluation of the application of a Foucault brake was presented by Micco et al. (2017). In that work it was developed a roadmap and tests obtaining a brake system coupled to a Tesla turbine rotor. Putra et al. (2020) evaluated the design of a compact eddy current brake. The authors distributed multiple electromagnetic poles along the brake disc, which resulted in a generation of 93.66% of the torque required for braking.

The devices used nowadays to small scale turbine test depend on the coupling with generators to apply the resistance torque. The consequence is the insertion of uncertainties in the experiment, e.g., the influence of inertial moment on the resistance dynamic friction. There is also the need to add other instruments to define the performance characteristic curves. In this sense, the existent devices in the market does not comply with the application of the resistance torque and perform the required measurements in a simultaneous form. This work presents the analytical and experimental development of a Foucault brake to be coupled to a scale model of a Wells turbine allowing the achievement of an universal device to apply the resistance torque and measure the desirable variables concurrently. The main purpose is to define a setup that worked adequately for prediction of torque in small-scale turbines without large uncertainties, which has been few explored in the literature.

2. MATERIALS AND METHODS

The methodology was based in Wouterse (1991) work, which assumes equality between magnetic induction, acting on rotor plane and air gap induction when velocity is null. Figure 2(a) shows a Wells turbine rotor connected to an eddy current brake through a shaft and a breakdown and Fig. 2(b) shows the schematic of the studied setup with the main variables involved in its design. The disk of a conductive and non-magnetic material is coupled to the shaft of a turbine rotor. This disk is immersed in a magnetic field created by the coil and induced in the air gap through the core. Eddy currents are generated in this disk that opposes the movement of the field that originated it, thus creating a resistance torque on the turbine shaft.

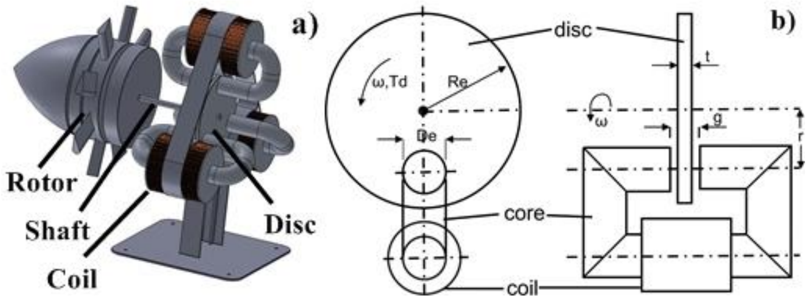


Figure 2. (a) Rotor of Wells turbine and Foucault Brake. (b) Main project variables.

The turbine power, tip rotor speed and torque are known due to aerodynamic design of the rotor. These information are shown in the Table 1.

Table 1– Information about the used Wells turbine model scale.

Power	95 W
Rotation	3395 min^{-1}
Torque	0.26 Nm
Force	2.17N
Hub radius	0.125

According to Brin (2013) the magnetic field density is determined by,

$$B = \sqrt{\frac{T}{-0.5\cdot\omega\cdot\sigma_{al}\cdot t\cdot c\cdot R^2.an^2}} \quad (1)$$

where, T is the turbine torque, ω is the angular velocity of turbine, σ_{al} is the electrical conductivity of aluminum, t is the disc thickness, c is geometric efficiency coefficient, r is the disc radius, an is the electromagnetic core edge. According to Fig. 2, the geometric efficiency coefficient is an adjustment which takes into account the relationship between the total resistance of the disk and the resistance of the area under the poles of the electromagnet, given by:

$$c = \frac{1}{2}[1 - \frac{1}{4}\frac{1}{\left(1+\frac{r}{R}\right)^2\left(\frac{R-r}{D_e}\right)^2}] \quad (2)$$

where D_e is the coil core diameter and r is the distance between the centers of the disk and the coil.

With the magnetic flux density determined, it is possible to calculate the magnetic force F, in order to determine the number of turns N, which will compose the coil, and is given by:

$$N = \frac{B.A.\Re}{I} \quad (3)$$

where $\Re$ is the total reluctance of electromagnetic circuit, A is the area of the electromagnetic core section and I the electric current of coil and B is the magnetic field at the center of the air gap. According to Umans (2014) the total reluctance can be obtained by:

$$\Re = \Re_g + \Re_c + \Re_d \quad (4)$$

where $\Re_g$, $\Re_c$ and $\Re_d$ are gap, core and disc reluctance, respectively, which can be calculated by:

$$\Re_g = \frac{g-t}{\mu_0(1{,}05.A)} \quad (5)$$

$$\Re_c = \frac{l_c}{\mu_0\mu_c A} \quad (6)$$

$$\Re_d = \frac{t}{\mu_r\mu_0(1{,}05.A)} \quad (7)$$

where g is the air gap distance, μ_0 is the vacuum magnetic permeability, l_c is the core length and μ_c is the relative magnetic permeability of the core material. However, the torque imposed by the brake on the disc T_d can be determined by:

$$T_d = -\omega.\sigma_{al}.t.{r_e}^2.A^2.B \quad (8)$$

To evaluate the analytical model, a single coil was built with a core composed of SAE 1020 steel bars. A test bench was created to simulate the behavior of Wells turbine. A direct current motor was connected to the eddy current brake disc to simulate turbine operating conditions. Its speed was controlled by a two-channel direct current source, the other channel limiting the power applied to the brake coil. A torque transducer was installed between the turbine and brake disc shafts. The bench instrumentation was complemented by a photo encoder to measure the rotation. The data were acquired by a National Instruments Model 6363 board (DAQ) that was connected to a PXIe 8135 instrumentation computer. The Figure 3 shows a blocks diagram of the instrumentation system.

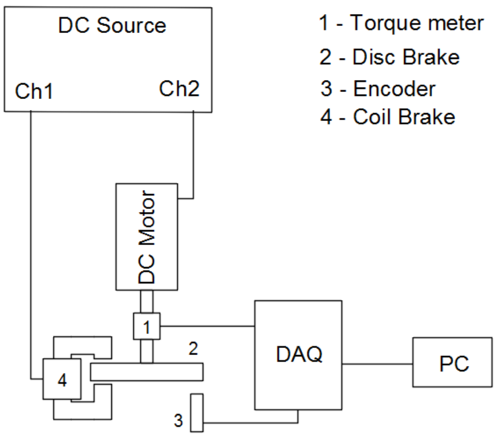


Figure 3. Schematic blocks diagram of test bench

First, the voltage of channel 1 was set to zero. The DC source channel 2 applied a fixed power to the motor maintaining a constant rotation that was measured by the encoder. After stabilizing the motor speed, channel 1 controlled the power applied to the coil brake. For each electrical current resolution established, the torque and rotation values were acquired by the acquisition board (DAQ) with a computer interface.

3. RESULTS AND DISCUSSIONS

A routine was established for the dimensioning based on the assumptions and restrictions of the project. The disk should be made of diamagnetic material and have a low specific mass in order to reduce the moment of inertia, so an aluminum disk was chosen. As the initial objective was to validate the analytical model, two ½ x 1inch SAE 1020 bars were used as a magnetic circuit core, forming a cross section of 1in². The coil was built with 1168 turns of 22AWG wire, which would allow the generation of 1227A.esp of magnetic force within its carrying capacity of electric current. The Table 2 presents the other parameters used for the sizing of the brake.

Table 2 – Parameters used for prediction of the analytic results.

Length circuit magnetic core (l_c)	0.0648 m
Length of the gap (g)	0.007 m
Disc thickness	0.005 m
Disc diameter (t)	0.125 m
Core cross sections (A)	6.45×10^{-4} m²
Spiral number (N)	1114 esp
Electric Current (I)	1.05 A
Magnetic flux density (B)	0.135 T
Coil Electrical resistance (R_b)	11.58 Ω
Torque (T)	0.53 N·m

After construction and assembly of the magnetic circuit and the coil, the air gap was positioned around the disk. Thus, it was possible to finalize the bench with the appropriate instrumentation for the braking tests of the system.

Figure 4 illustrates the configuration of the Foucault break setup. In Figure 4(a) it is presented the detail of the Foucault brake and Fig. 4(b) an overview of the test bench.

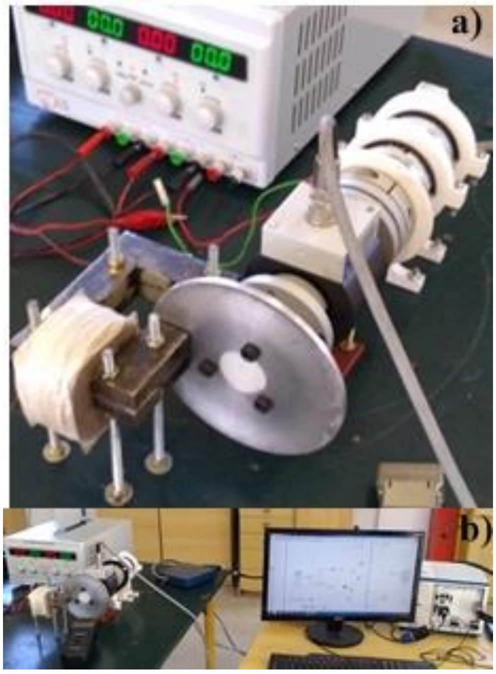


Figure 4. Illustration of the constructed brake a) Foucault brake detail b) Test bench.

Static measurements of electrical resistance of the coil and magnetic field at the center of the air gap were performed by an ohmmeter and a gausimeter, respectively. The comparison of theoretical and experimental of magnetic flux density (*B*) for each power applied to the coil (*Pb*) is shown in the Fig. 5, where it is possible to verify that in the nominal operating range of the brake the relative error is 4.43%. Results demonstrated that the main purpose of developing a Foucault brake for adequate prediction of the torque in a disk was achieved. This system can be used to predict the torque in the Wells turbine.

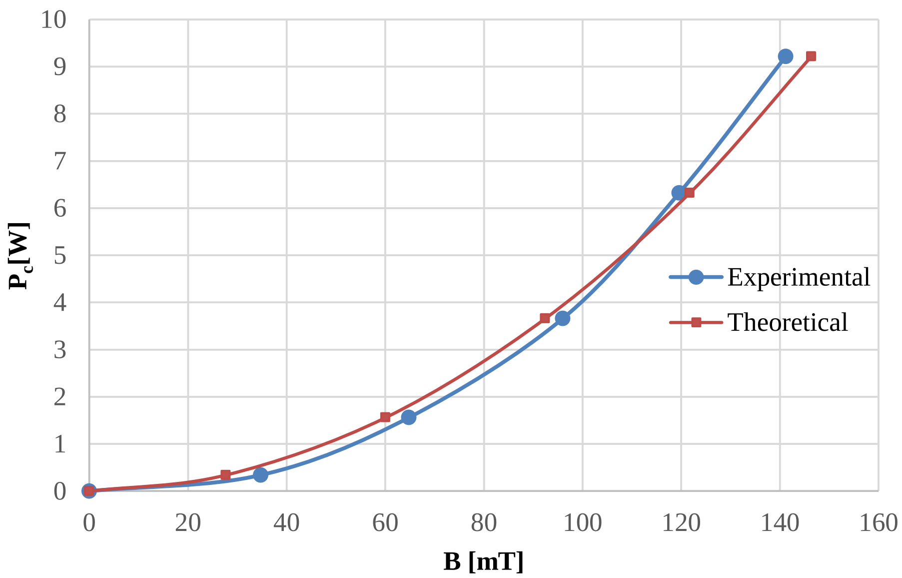


Figure 5. Comparison of theoretical and experimental values of the magnetic flux density (*B*) as a function of the power applied to the coil (*Pc*).

Dynamic tests were performed on the developed bench. The data of the disc rotating speed and torque were acquired for each power applied to the coil. The acquisition frequency was 1Hz during an interval of 60s for each resistance torque applied to the coil. The input resolution established was 180 mA of current in the brake coil until reaching 0.97A, which is the conduction capacity of the 22AWG wire. The braking capacities in the range of 3000 to 500rpm were evaluated as shown in Fig. 6.

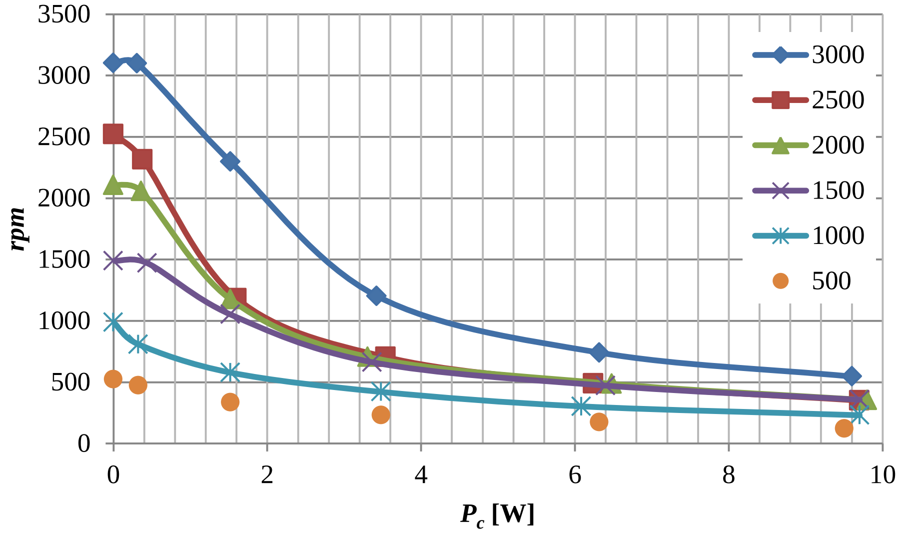


Figure 6. Investigation of the influence of power applied to the Foucault brake over the rotation of the disk for different initial rotations.

As can be seen in Fig. 6, there was the generation of resistance torque by the brake for all speed ranges tested. The brake generated a reduction of 2493 rpm at the rated engine speed of 3000 rpm. Results indicated that the setup is not only able to indicate the capability of the Foucault brake to estimate the torque on the system, but also to show that the principle works regardless of the inertial condition of the disk (or turbine) rotation in the system.

4. CONCLUSIONS

The study provided the comparison of analytical and experimental results of the methodology used for the dimensioning of the Foucault brake. The experimental setup was developed in the present work with the aim to estimate the torque in small-size turbines, which are hard to be estimated with conventional brake systems, e.g., dissipative ones. Moreover, the principle used here allowed the developed of an universal system of torque measurement for small size turbines, which at the best of authors knowledge has not be seen in other works or available in the market. Although the electric motor used to simulate the behavior of the Wells turbine has 10% less rotation, it was possible to evaluate the braking capacity of the proposed system. The results encourage the development of a device for the application of resistant conjugates and measurement of these efforts, providing less interference in the mechanical powers generated by micro-turbines, which will allow tests of small-scale models in a wind tunnel.

5. ACKNOWLEDGEMENTS

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