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Equipment for fully homologous bulb turbine model testing in Laval University

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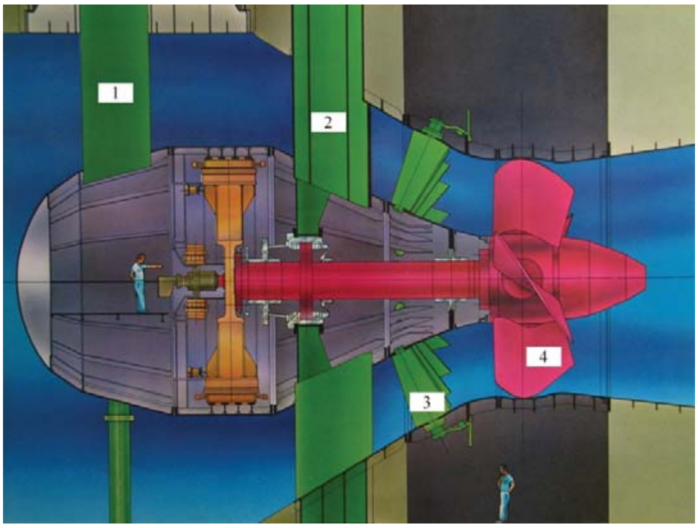
Abstract. Within the context of liberalisation of the energy market, hydroelectricity remains a first class source of clean and renewable energy. Combining the growing demand of energy, its increasing value and the appreciation associated to the sustainable development, low head sites formerly considered as non-profitable are now exploitable. Bulb turbines likely to equip such sites are traditionally developed on model using right angle transmission leading to piers enlargement for power take off shaft passage, thus restricting possibilities to have fully homologous hydraulic passages. Aiming to sustain good quality development on fully homologous scale model of bulb turbines, the Hydraulic Machines Laboratory (LAMH) of Laval University has developed a brake with an enhanced power to weight ratio. This powerful brake is small enough to be located in the bulb shell while dissipating power without mandatory test head reduction. This paper first presents the basic technology of this brake and its application. Then both its main performance capabilities and dimensional characteristics will be detailed. The instrumentation used to perform accurate measurements will be finally presented.

1. Introduction

BulbT, the second project of the Consortium on Hydraulic Machines based at Laval University which aims at achieving a better understanding of the hydraulic behaviours of low-head turbines, consists in measuring and numerically simulating the flow in a scaled bulb turbine. Among numerous challenging measurements to perform at different location in the whole turbine for such extensive project, it has been judged necessary by the scientific committee to explore the dynamic behaviours of the flow in the runner. To achieve this objective, thirty pressure sensors will be located on both sides of a runner blade, fifteen on pressure side and fifteen on suction side. The main difficulty by comparison with a similar experimental program on an S shape turbine [1] was extracting pressure measurements from the rotating referential. The traditional right angle transmission filled of oil and presenting a rotating shaft in the sole passage makes this project almost impossible. From this requirement has raised the idea to design and manufacture a tool that gets rid of this transmission for proper bulb turbine model testing. By allowing real hydraulic profiles, it will also improve the accuracy and reliability of the results when transposed from model to prototype, then providing the possibility to tackle all interactions between components since complex unsteady interactions have been noticed numerically between the two upper piers.

The scientific literature shows numerous projects of bulb turbines with an asymmetric pier arrangement. For example, the 66MW units of Tadami, Japan and the 39MW units of Crestuma, Portugal shown in figure 1. One can also find some configurations with one large pier below the bulb and two different accesses above the bulb, one upstream and one downstream of the generator as for the 46MW units of Greifenstein, Austria. The idea of using a traditional right angle transmission in the BulbT model has been discarded since it would have led to an important pier enlargement for the passage of power take-off shaft. This is obvious in figure 1, where one can see two single structures, item one used as access to the upstream side of the generator and item 2 used both as man hole to reach the downstream part of the generator and as stay vane. It is then impossible to model both properly with a large transmission. It is easy to understand that it is also impossible to model a bulb without including the supporting piers while respecting a perfect homology.



1- Access to the generator
2- Access to the generator
3- Wicket gates
4- Runner

Figure 1: **Piers arrangement of 39 MW units of Crestuma (Neyrpic)**

Therefore, the solution for BulbT was to design an eddy current brake that would fit in the bulb of the turbine, adjoining to it a telemetric data transmission system to transport the pressure signals coming from rotating parts, therefore freeing the possibility for the piers to be homologous. The following sections detail the design of the brake, its instrumentation and performances results.

2. Eddy current brake design

Eddy current clutches or brakes exist for decades, carrying a resistive torque proportional to magnetic field fluctuations in a non-magnetic conductor. The particularity of the one that has been designed for BulbT is its optimization to enhance its power to weight ratio, then becoming small enough to be located in the bulb shell. Figure 2 presents a cross section of the brake.

2.1. Electrical design

Having magnetic properties close to electrical steel with its low hysteresis and its high permeability, low carbon steel has been selected to manufacture the magnetic circuit of this brake. The rotor, poles and outer shell have then been manufactured of AISI C-1018, lower carbon content being unavailable for such size of raw material. Looking for magnetic insulation to avoid leakage losses, both upstream and downstream flasks used as bearing housings were made of aluminium. For the same reason, the main shaft should be manufactured of AISI 316 stainless steel; not for losses since it is part of the whole magnetic circuit but for avoiding any problem with the embedded telemetric data transmission system which contains regulated power supply and signal conditioning of all connected sensors. There is no inconvenient to place a nonmagnetic material at this section of the magnetic circuit since it is far away from the bottle neck of the magnetic field.

One of the particularities of the arrangement of this brake is the inducer, which has contact with its heat sink on its outside diameter. This however complicates the thermal dissipation. The inducer is a coil with a 4 165 mm² section on which there are ~2800 turns of #17 AWG wire coated with heat class H enamel, representing a fill factor of ~80 %. The coil has been soaked in a thermal conductive epoxy under vacuum to help dissipating heat produced by Joule effect. In addition to this, a black epoxy potting and casting resin with very high thermal conductivity of 1.153W/m-K (8 BTU-in/hr/ft²-°F) has been used between the coil and the outer shell to evacuate the Joule effect heat produced by the inducer coil. The nominal resistance of the inducer coil is 35 Ω. The maximum power produced by the inducer, according to the current source available at LAMH, is 560 W (4 A @ 140 V). However, since the unit is thermally monitored by a thermocouple placed in the center of the coil on the inner diameter, which is theoretically the hot point of the coil, it has been noted that the inducer, then the resin, evacuates a small part of the power produced by the eddy currents.

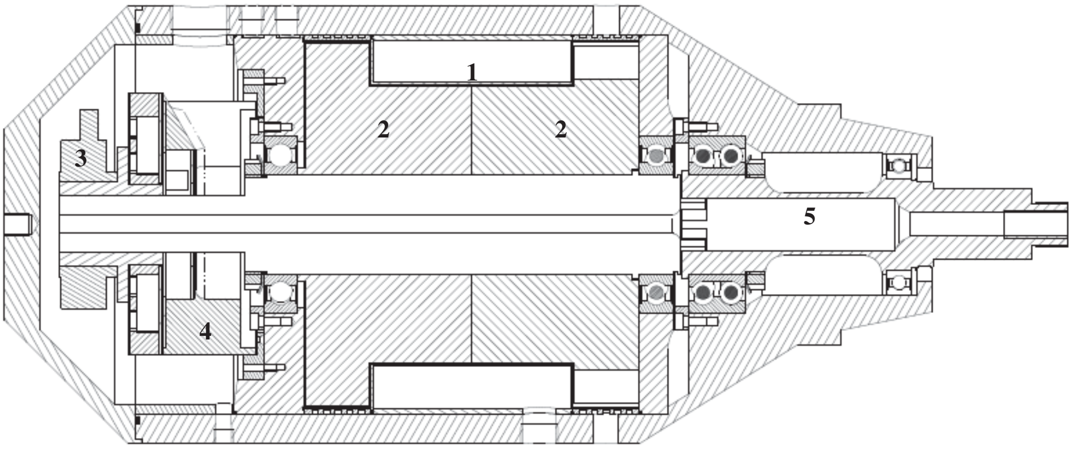
2.2. Cooling

The whole system is liquid cooled. This is the most important point to achieve the very high power to weight ratio, allowing using an internal electrical dissipation to regulate the rotation speed instead of the traditional right angle transmission driving a standard DC motor. This method limits as much as possible the heat transferred to the test stand water, therefore helping the temperature regulation of the whole volume of water in the test stand. The cooling of the poles is done with a glycol/water mix avoiding corrosion in the water passage inside the brake. The heat exchange coefficient is then kept at the optimum over time. This external closed loop of glycol is cooled by the chilled water network of the building through a plate heat exchanger with a nominal capacity of 40 kW. The glycol temperature is measured with a RTD probe and controlled with a temperature controller acting on a proportional valve installed on the chilled water network.

2.3. Mechanical design

With its outside diameter of 310 mm (D_b), this unit has been designed to be used with a 340 mm runner diameter (D_r). This is representing a minimum D_b/D_r ratio of 0.912, which does not constitute a limitation since most bulbs in operation are ranging from 1.12 to 1.25. As a counter example, when a situation similar to the turbine of the Sidney A. Murray Jr. powerhouse in Louisiana, USA, occurs, one could manufacture a 360 mm runner, respecting a 0.866 ratio [2], since the power delivered by the brake is high enough. If one considers both together the copper thickness and the air gap between rotor and stator, the magnetic equivalent air gap is 0.58% of the rotor diameter, while keeping an actual standard air gap for an electrical machine.

As required for any rotating machine, dynamic balancing has been performed on this eddy current brake. The assembly shaft / rotor of the brake has been balanced in such a way to meet a G 0.2 criterion. Since this brake has been developed in the framework of the BulbT project, for this first use, the runner has been balanced in order to meet a G 0.25 criterion. This is a very strict criterion since the turbine industry generally uses a less restrictive criterion of G 2.5 [3, 4]. This restricting choice originates from AxialT, the first project of the consortium research group, to make sure that unit normalized frequencies found during the data processing stage come from physical phenomena and that balancing will not be questioned [1].



1- Inducer
2- Rotor
3- Encoder
4- Telemetric data transmission system
5- Torque meter

Figure 2: Cross section of the Eddy currents brake

Natural frequencies have been measured according to directions X & Z and around axes Y and Z shown in figure 3 with a LMS SCADAS Mobile SCM05 having the following characteristics:

- 40 channels
- 204.8 kHz sampling rate per channel
- 24-bit ADC technology
- 150 dB dynamic range

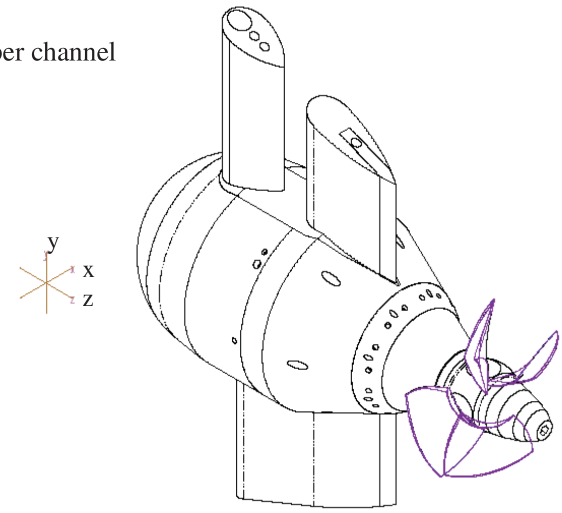


Figure 3: Axis definition

Not surprisingly, it has been found that the natural frequency (ω_n) according to direction X and around axis Z is the same. Taking the revolution frequency (ω_r) as a reference, the ratio ω_r/ω_n was 0.133. According to direction Z, the ω_r/ω_n ratio measured was of 0.067. The lower Eigen frequency of the whole assembly including wicket gates was around axis Y presenting a ω_r/ω_n ratio of 0.200. Figure 4 shows the relative displacement of the structure in relation with relative excitation frequency. One can see the almost negligible displacement when the excitation frequency is low in relation to the first Eigen frequency.

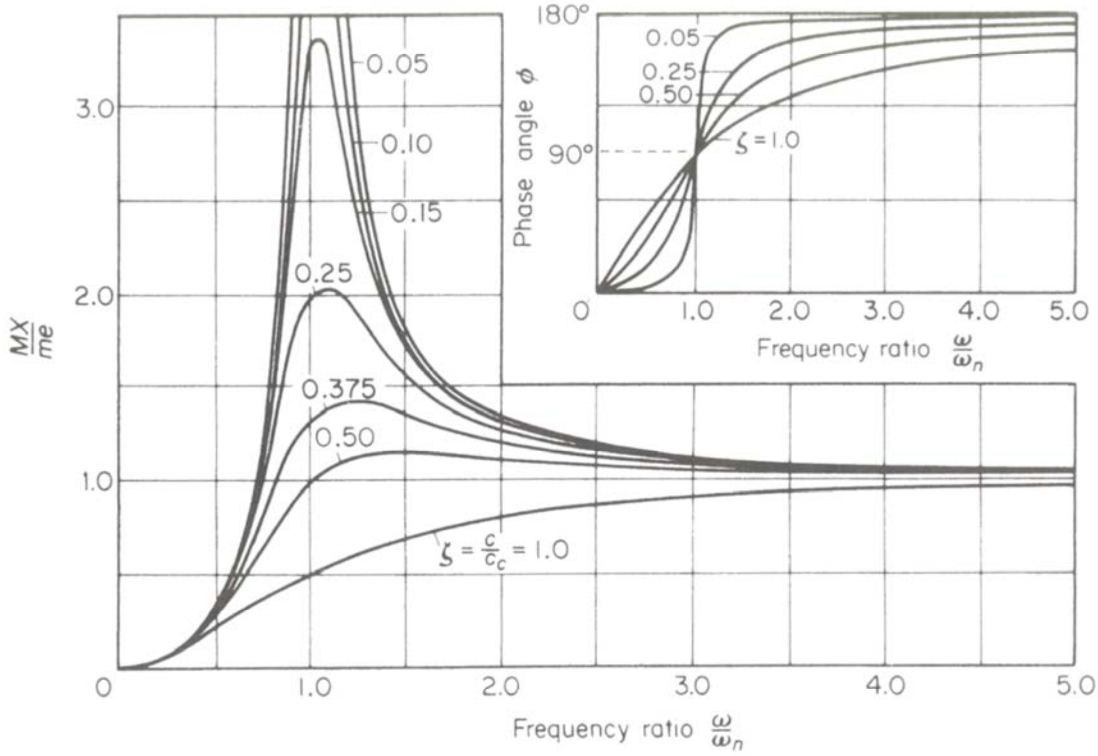


Figure 4: **Forced vibration with rotating unbalance** [5]

3. Instrumentation

3.1. Telemetric data transmission system

One can see in figure 5 the hollow shaft optical encoder with a glass disk including two tracks A and B mounted on the brake's shaft. Each track has 2 048 pulses per revolution (11 bits), then a 1 / 8 192 resolution (13 bits) when used in quadrature mode. This fine resolution is used to define the runner position over time; however, for both velocity measurement and velocity control, phase A and B are both used in single mode.

Under the encoder is mounted the rotor of the telemetric data transmission system. This system includes 32 synchronized channels with a possibility of extension up to 40 without hardware modification. Its sampling rate is 5 000 Hz and the digital to analog conversion has a resolution of 12 bits. The rotor also includes an induced regulated power supply to power up both signal conditioners and all sensors.

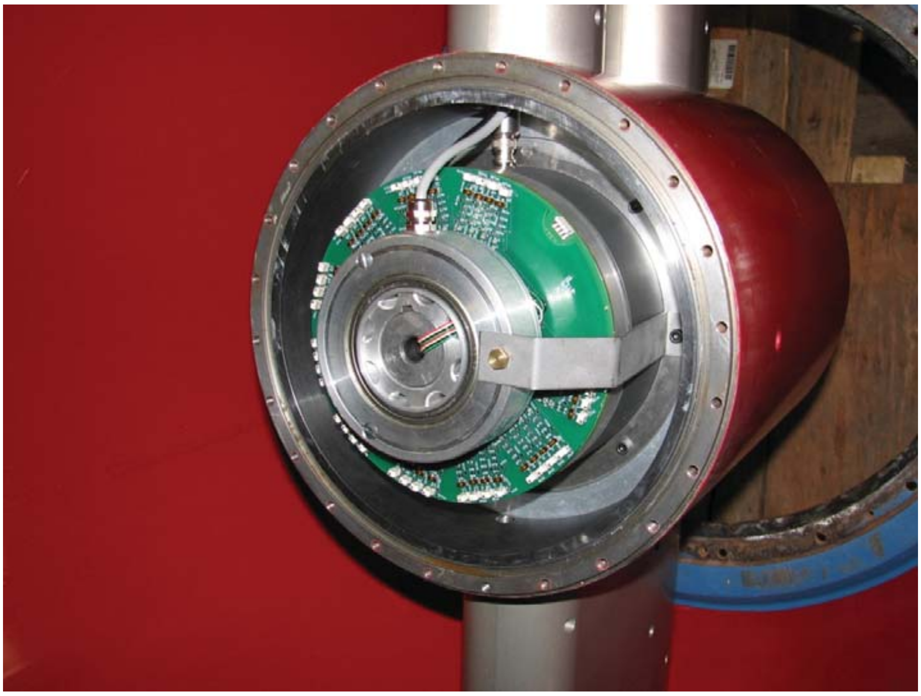


Figure 5: **Instrumentation room on the back of the bulb**

3.2. Torque meter

With all the electrical apparatus inside the bulb to produce breaking power, the room is quite limited. It has been necessary to build our own torque meter since all commercial instruments were not small enough considering the torque produced by a hydraulic turbine model. The instrument shown in figure 6 has been designed for measuring both torque and axial thrust on the same element, requiring optimized dimensions. Aluminium 7075 T651 has been preferred to stainless steel 420 for the combination of its Young modulus and its yield strength, making easier the manufacturing process while reducing buckling possibilities due to the thin walls required for proper deformation.

The torsional stiffness of the torque meter is 4.1E-5 rad/Nm. The relative natural frequency around its axis, when coupled with the inertia of the BulbT runner, is $\omega_r / \omega_n = 0.143$ in air. The relative natural frequency of the torque meter in the axial direction, representing the axial thrust fluctuation direction, is around 750 Hz, far away from any head fluctuation frequency.

Due to the bearings arrangement, there is a residual flexural torque in the shaft caused by the runner weight. The relative natural frequency of this mode is $\omega_r / \omega_n = 0.04$. All those Eigen frequencies are at least more than 7 times above runner excitation.

Figure 6: Torque meter

The sealing element selected to prevent both water infiltration in the bulb and air admission in the test stand was provided by Garlock. PS-I serie made of Gylon® minimized the friction. The friction coefficient μ is only 0.1, at least ten times less in comparison with standard compounds which are commonly over one [6]. In order to meet the surface hardness recommended by the manufacturer to use properly such sealing element, hard anodized treatment of 50μm has been done on the 7075 T651 aluminium alloy. This treatment has also another purpose: to protect from corrosion the end shaft in contact with water. The instrumented zone of the shaft hasn't been treated to make sure that the mechanical properties of this material are not modified. A sensitivity of 2.1 mV/V has been obtained for the torque (400 Nm) equivalent to 0.3Nm/μV and 1.2 mV/V for the axial thrust measurement (1 500 lbs) equivalent to 0.9 lb/μV.

An eight arms, spider type elastomer coupling ecolight®, provided by R+W Coupling technologies has been used to connect the break to the shaft. The type B elastomer (green) which has a hardness of 64 Sh D has been selected for its high torsional stiffness. Well controlled alignment allows using this type of coupling.

3.3. Speed controller

A digital signal processor (DSP) is used to control the rotational speed of the runner. The sampling rate is around 6 times above the natural frequency ($\omega/\omega_n = 6$) of the shaft/runner assembly. A PID controller is programmed in the DSP with adjustable gains. The output is a digital to analog converter (DAC) with an 11 bits resolution.

4. Performances

Eddy current brakes are considered auto stabilizing since the maximum torque increases with rotational speed up to magnetic saturation. From that point, the maximum torque decreases slightly but with a rate lower than the velocity increase so the dissipated power still increases with speed. Considering this characteristic, the limitation for using such a brake is in high torque low speed conditions, representing the high head side of an efficiency hill chart when applied to a hydraulic turbine. The characterization of the brake presented in figures 7 & 8 has then been performed only for that zone of an efficiency hill chart. Figure 8 is presenting cross sections of the surface plotted in figure 7, allowing seeing accurately where magnetic saturation occurs.

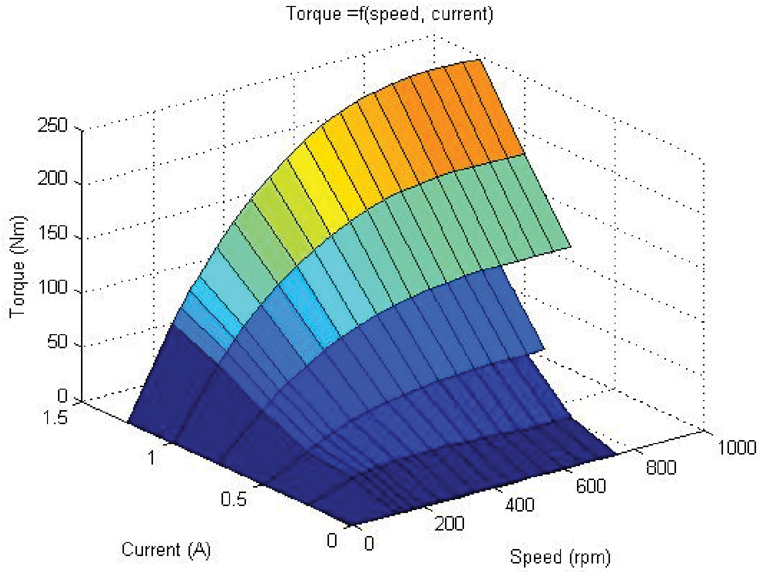


Figure 7: **Actual torque – rotation speed characteristic of the brake for different excitation currents**

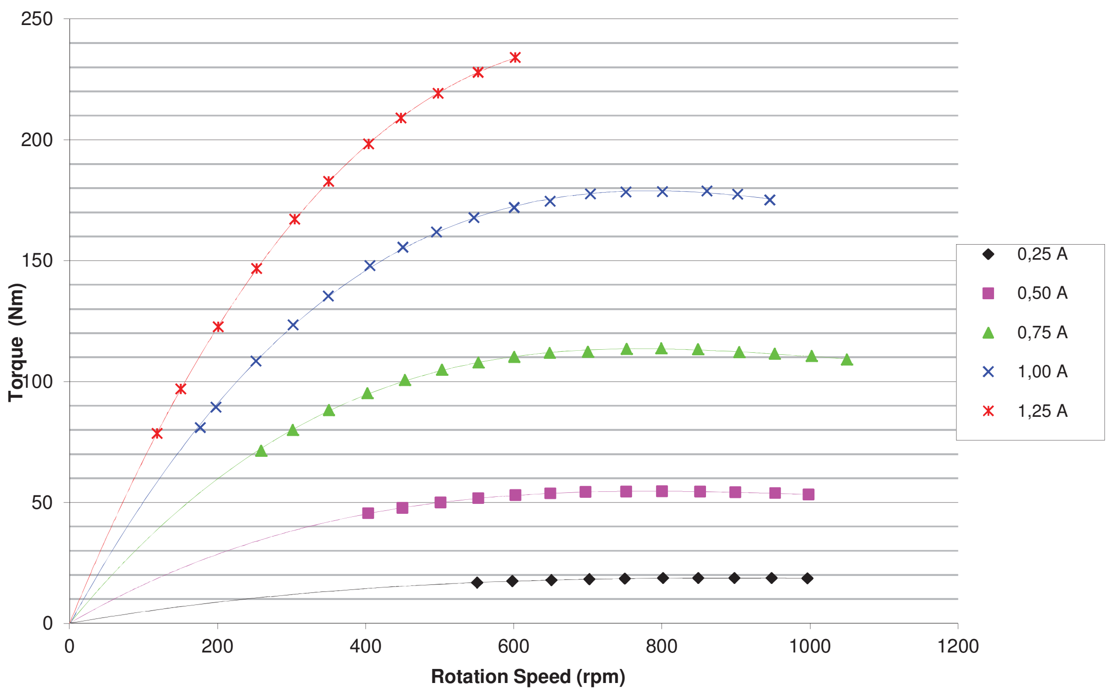


Figure 8: **Cross section of the torque – rotation speed characteristic surface for different excitation currents, showing saturation points**

5. Conclusion

An Eddy current brake dedicated to test model bulb turbines has been developed at Laval University. The existing technology has been optimized to maximize the absorbed power while reducing as much as possible both length and diameter in order to be located in a standard bulb shell. Tests of the prototype have been completed successfully. The brake presents high torque for high head operating conditions. A torque meter suitable for both the expected torque and axial thrust range has been designed, taking advantage of the 32 synchronized channel telemetric data transmission system installed in the bulb to extract signals from the rotating referential to the data acquisition system.

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