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Experimental validation of icing rate using rotational load

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ABSTRACT

Icing load and icing rate are necessary feedback variables for an intelligent anti/de-icing system to work effectively in harsh cold environment of high north. These parameters may be measured by axial loadings or by rotational loadings, as a function of current demand. However the former may not necessarily be dynamic, whereas the later necessarily be rotational. Sufficiently at a fixed rpm, a mathematical model between additional polar moment of inertia vs electrical demand of the sensor can be established to analytically shape the icing load and icing rate adequately as hypothesized in Cost 727. This paper aims to develop such model and is validated using experimental data from a case study conducted by Atmospheric Icing Research Team of Narvik University College at Cryospheric Environmental Simulator, Snow and Ice Research Center, (NIED) Japan.

1. Introduction

Generally atmospheric icing is considered as a potential hazard for structures particularly in polar domains. Icing is often accepted as an inconvenience, but that tolerance can rapidly become a safety hazard that may require solutions (Ryerson, 2009). To reduce the effects of atmospheric ice accretion, necessary design modifications coupled with selective anti/de-icing system are required for these structures/platforms. An efficient anti/de icing system is somehow dependent upon the information from the atmospheric icing sensors and works on the principle to optimize the energy demand based upon the feedback related with accreted icing load, icing rate and preferably ice type information from the icing sensor. Therefore the most important variables for an icing sensor are icing load and icing rate. Today there are few available solutions/sensors that can measure icing load and icing rate, such as IceMonitor™ by Combitech (Ice Load Monitor Webpage, 2014), Sweden and IceMeter™ by IAP, Czech Republic (Ice Meter, 2014) which work using load cells. Both of these sensors use axial load physics to measure the required parameters. Also Holo-Optics icing rate sensor (Holo Optic Icing Rate Sensor) uses near infrared electromagnetic band absorption scheme to distinguish between different types of ice whereas Rosemount icing sensor uses ultrasonic probe based upon magnetostrictive technology to measure icing rate. One possible drawback with most of these sensors is the non-symmetric distribution of the ice load around the sensor as due to free rotation, ice deposit on the windward side and hence the wind loads on icing sensor generally effect the resultant icing load measurements. Also there are some recommended changes in icemeter as mentioned in Fikke (2006),

i. Possibility to build an instrument with a rotating collector.
ii. More focus on the sensors that measure accumulated icing.

These recommendations are based upon a hypothesis without any analytical or experimental validation. Keeping in view the limitations of available sensors in the market, a prototype atmospheric icing sensor as been developed by Atmospheric Icing Research Team. This sensor utilizes rotational load measurement physics for measuring icing load and icing rate together with capacitive loading to detect an atmospheric icing event, icing type and melting rate. In this paper, an analytical relationship between a motor's load (at fixed rpm) and current is aimed to be developed in order to analytically and experimentally support the hypothesis during the research expedition at Cryospheric Environmental Simulator, Shinjo, Japan. This sensor utilizes constantly slowly rotation for two purposes,

i. To measure icing load and icing rate using rotational physics
ii. To provide uniform deposition of atmospheric ice on the capacitive plates

2. Curvilinear motion

In Fig. 1 the curvilinear motion is shown in the general form where ϕ denotes the angle between the force F and radius vector r position.

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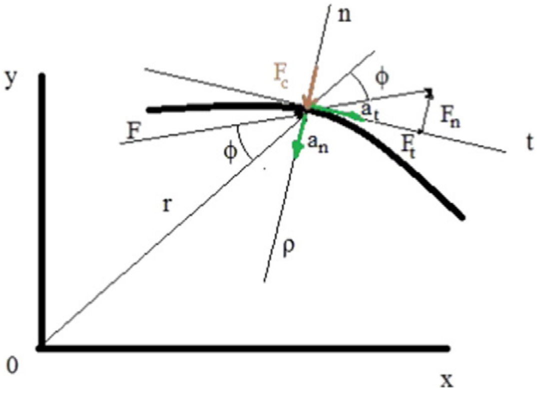


Fig. 1. Curvilinear motion.

According to Newton's second law, force vector that produces *ma* is represented by normal and tangential components, namely,

$$m\overrightarrow{a} = a_t t + a_n n = m\rho\alpha t + m\rho\omega^2 n \tag{1}$$

where *n* is the unit normal vector, *t* is the unit tangential vector, a_n is the normal component of acceleration directed to the center of the circle and a_t is the tangential component of the acceleration for an object. Note that the position vector $\overrightarrow{r}$ in Fig. 1 is other than ρ which is the radius of curvature of the field. However if the motion is on a cylinder of radius $\overrightarrow{r}$ then it is reasonable to assume that the magnitude of $|\overrightarrow{r}| = \rho$. Similarly if a body of mass *M* with an effective radius *k* passing through its center of mass will have a mass moment of inertia *J*, given as,

$$J_{Center\ \ of\ \ Mass} = Mk^2. \tag{2}$$

The mass moment of inertia of other circular geometries can also be found, the results can be seen in Fig. 2b. Sufficiently the mass moment of inertia of same body of mass *M* around any other axes can be determined using the Parallel Axis Theorem which states, *the rotational inertia of an object about any axis is given by the sum of the rotational inertia about an axis that goes through the center of mass and is parallel to the given axis*, *and of the product of the total mass M of the object and the square of the perpendicular distance d between the two axes*. Mathematically it can be written as,

$$J_{Axis\ \ at\ \ distance\ \ d} = J_{Center\ \ of\ \ Mass} + Md^2. \tag{3}$$

If it is considered that the system is only rotating at constant rpm Ω, then the Kinetic Energy *K*.*E*. of the system can be written as Eq. (4),

$$K.E. = \frac{1}{2}J\Omega^2. \tag{4}$$

3. Analytical study of rotational load measurement

The physics for measuring forces in curvilinear motion in any system should start by an energy method or principle of conversation of energy. For rotational loading measurements it is typically considered that the electromechanical systems follow the law of conversation of energy, which is given as,

$$\begin{aligned} InputfromElectricSource = {} & MechanicalOutput \\ & + IncreaseinStoredMagneticField \\ & + Loss\ (Heat, Sound, etc.). \end{aligned}$$

3.1. Power–loading relationship

Typically, the power input to the motor could be described as,

$$P_{in} = P_{in}(V_{in}, I_{in}) = \alpha V_{in} I_{in} \tag{5}$$

where P_{in} is power input, V_{in} is voltage input, I_{in} is the current input and α can be any constant (e.g. calibration constant). Similarly the power output can be defined as,

$$P_{out} = P_{out}(K.E._{out}, \omega_m) = \beta K.E._{out}\Omega_m = P_{in} - \eta \tag{6}$$

where P_{out} is power output, $K.E._{out}$ is the kinetic energy output, β is calibration constant, η defines the losses (field loss, armature loss, rotational losses etc.) associated with the motor performance and Ω_m is the angular speed of the load.

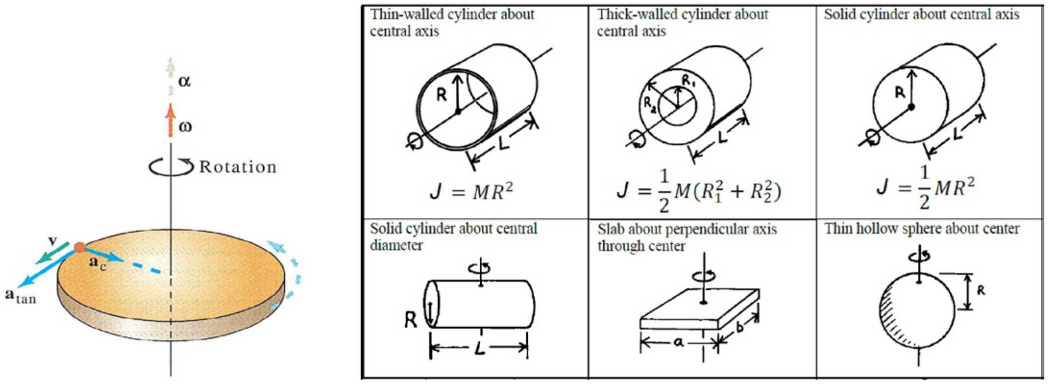
3.2. Current–inertia relationship

Eq. (4) can also be rewritten as,

$$K.E._{out} = \gamma J\Omega_m^2 \tag{7}$$

where γ is any constant (e.g. calibration constant). Using Eqs. (5) and (7) in Eq. (6), we Eq. (8) can be formed.

$$\alpha V_{in} I_{in} - \eta = \beta\gamma J\Omega_m^3. \tag{8}$$



(a) Rotational Motion [4] (b) Mass moment of inertia of other circular geometries [4]

Fig. 2. Mass moment of inertia (Fishbane et al., 1996).