THE INFLUENCE OF THE GEOMETRICAL PARAMETERS OF PROPELLER-TYPE CURRENT-METER ON ITS PERFORMANCE

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Abstract- For many decades, current-meters are used to measure flow velocity in open channels and also closed conduits. Nevertheless, there is not much information on basic equations of propeller-type current-meter. In this paper, by using momentum and airfoil theory approaches, we tried to find theoretical equations for driving torque exerted on blades. Then by equating two obtained equations, the influence of solidity, pitch value and hub to tip radius ratio on full fluid guidanceis investigated.

Keywords- driving torque, theoretical equation, Propeller-type, Current-meter, Velocity measurement

I. INTRODUCTION

Current-meters are one of the most reliable instruments for flow measurement. The instrument is being used to measure the discharge rate in natural and artificial channels. Up to now, it is seen that using propeller-type current-meters is the most accurate method (amongst the practical methods) to measure the flow rateat hydro-power plant works.

Although, many works are published on all kinds of flowmeters(which work in a limited-radius pipe)[1]-[3] there is notmuch information on design equations of propeller-type current-meter(which works in open channels as point-velocity measurement utilities.) For so many years, Ott's theory of 1925 [4] had been used as a fundamental equation for design of propeller-type current-meters. Takeda [5], [6] used lifting surface and lifting line theories to obtain theoretical results of the motion of current-meters with low aspect ratio blades. Thibodeaux [7] wrote a comprehensive literature review on testing of point-velocity current-meters (including vertical- and horizontal-axis mechanical current-meters, electromagnetic and acoustic electronic current meters).

The purpose of this paper is to obtain theoretical equations for exerted driving torque from fluid to the blades. Here we used two different approaches, 1. Momentum 2. Airfoil theory.Thenby equating the equations, the influence of three geometrical parameters (solidity, pitch and hub to tip radii ratio) on the performance of current-meter is investigated.

II. OVERVIEW

In this paper, we calculated the driving torque by using momentum approach and airfoil theory approach. The assumptions of our model are as below:

a. The current-meter works steadily at its runaway speed. So full fluid guidance is considered as a tool to measure whether a current-meter works properly or not. Full fluid guidance means that any particle of the fluid adjacent to the blade has the same velocity as blades.

b. Flow enters the blades completely parallel to the axis of current-meter.

c. Blades are three dimensional. Along radius, any differential-area element of the blade is an airfoil. And along the axis of the current-meter, the blades form a helicoid with the pitch (lead) value of $L = 2\pi r / \tan\theta$.

At steady state condition the total torque exerted on the rotor is equated to zero.

$$\sum \vec{T} = 0 \qquad (1)$$

So

$$T_d = T_B + T_W + T_t + T_h \qquad (2)$$

Where T_d, T_B, T_W, T_t and T_h respectively are driving torque, bearing torque, hub disk friction torque, tip clearance torque and hub fluid torque.

This paper is dedicated to show our works on investigating the governing equations only to study driving torque.

Fig. 1 shows a general schematic of the current-meter. As can be seen in the fig., flow enters the blades parallel to the axis of the current-meter.

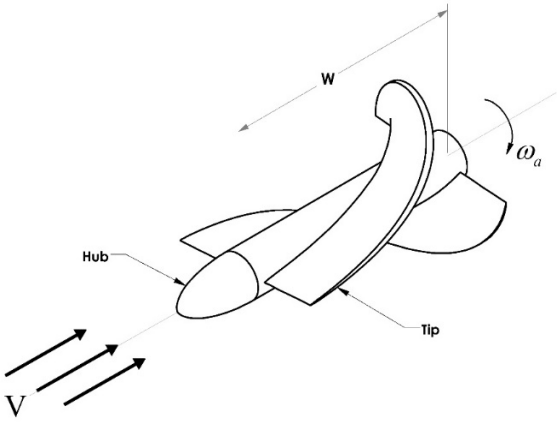


Figure 1. General schematic of the current-meter

Velocity triangles at inlet and outlet of the blades are shown in Fig. 2.

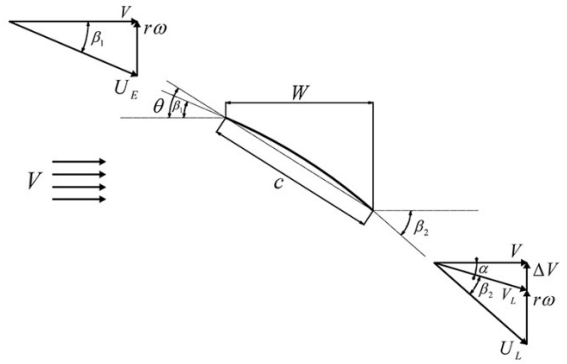


Figure 2. Velocity triangles at inlet and outlet of the blades

In this fig., β_1 and β_2 are blade angles at inlet and outlet respectively. θ and α are, respectively, camber and attack angles, which are defined as

$$\theta = \frac{\beta_2 + \beta_1}{2} \quad (3)$$

$$\alpha = \frac{\beta_2 - \beta_1}{2} \quad (4)$$

From fig. 2, the relation between c and W is

$$c = \frac{W}{\cos\theta} \quad (5)$$

To find atheoretical equation for T_d, we used almost the same way as Rubin used to study two dimensional blades of flowmeter. In this paper, two approaches are used to obtain a formula for T_d, 1.Momentum approach 2. Airfoil theory approach. To make sure that fluid is fully guided around the blades, the value of T_d which results from two approaches should be equal.Here, we considered that a well-designed current-meter is the one which have full fluid guidance.

III. METHODS

3.1. Momentum approach

The torque exerted on blades at a differential area of fluid can be expressed as

$$dT_M = rdF \quad (6)$$

where

$$dF = \rho V(2\pi r dr)\Delta V \quad (7)$$

From fig. 2 and by keeping in mind that $\theta = \beta_2 - \alpha$, the ΔV is

$$\Delta V = V\tan\theta - r\omega_d \quad (8)$$

Substituting 7 and 8into 6 and integrating along r yields to driving torque as

$$T_M = \frac{\pi\rho V^2 R_t^4}{2}\left(\frac{2\pi}{L} - \frac{\omega_d}{V}\right)\left(1-\sigma^4\right) \quad (9)$$

σ represents hub to tip radii ratio in this equation.

To normalize T_M, the parameter T_N is defined as

$$T_N = \frac{\rho Q^2}{L\left(1-\sigma^2\right)^2} \quad (10)$$

where Q is the rate of fluid which passes through blades

$$Q = \left[\pi\left(1-\sigma^2\right)R_t^2\right] * V \quad (11)$$

So the dimensionless driving torque can be written as

$$T_M^* = \frac{T_M}{T_N} = (1-\sigma^4)\varepsilon \quad (12)$$

where slip is defined as

$$\varepsilon = \frac{\frac{2\pi}{L} - \frac{\omega}{V}}{\frac{2\pi}{L}} \quad (13)$$

3.2. Airfoil theory approach

Airfoil theory indicates thatthe exact amount of torque can be obtained by integrating of lift and drag forces, which is exerted on each differential element of the blade, along r.

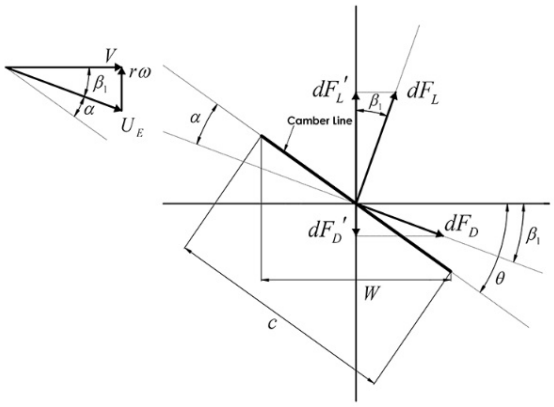


Figure 3. Forces that are exerted on a differential-area element of the blade

Fig. 3 shows the forces that are exerted on a differential-area element of the blade. dF_L' and dF_D' are respectively the components of the lift and drag forces that produce torque.

So to find the total amount of torque we can use

$$dT_A = Nr(dF_L' - dF_D') \quad (14)$$

Based on airfoil theory, the components of lift and drag forces are

$$dF_L' = \frac{1}{2}\rho U_E^2 C_L(c\cos\beta_1)dr \quad (15)$$

$$dF_D' = \frac{1}{2}\rho U_E^2 C_D(c\sin\beta_1)dr \quad (16)$$

where C_L and C_D are lift and drag coefficients, respectively.

From velocity triangle at inlet (fig. 2) we have

$$\cos\beta_1 = \frac{V}{U_E} \quad (17)$$

and based on Rubin, for attack angles up to 25

$$C_L = C_1\sin\alpha \quad (18)$$

Then substituting 15, 16, 17And 18 into 14 and integrating along r yields to

$$T_A = \frac{\pi}{L}\rho V^2 NWR_t^3\{[C_1\varepsilon_d - C_D(1-\varepsilon_d)]\left(\frac{1-\sigma^3}{3}\right) - \left[\left(\frac{2\pi}{L}\right)^2 C_D(1-\varepsilon_d)^3 R_t^2\right]\left(\frac{1-\sigma^5}{5}\right)\} \quad (19)$$

It can be normalized as below

$$T_A^* = \frac{T_A}{T_N} = \frac{L}{\rho}\left(\frac{1-\sigma^2}{Q}\right)^2 T_A \quad (20)$$

$$T_A^* = (s)\left(\frac{2}{\pi}\right)\{[C_1\varepsilon_d - C_D(1-\varepsilon_d)]\left(\frac{1-\sigma^3}{3}\right) - \left(\frac{\pi D_t}{L}\right)^2 C_D(1-\varepsilon_a)^3\left(\frac{1-\sigma^5}{5}\right)\} \quad (21)$$

where solidity is

$$s = \frac{NW}{D_t} \quad (22)$$

IV. RESULTS AND DISCUSSION

To ensure full fluid guidance,as mentioned before,the obtainedequations from two approaches must resultin same answers for driving torque. So we have to equate12 and 21. The equation 12 from momentum approach is linear whereas the other equation, from airfoil theory, is much more complicated. So the best way to make a comprehensive comparison is through graphs.

T_M^* and T_A^* are shown for different values of solidity in fig. 4. As can be seen in the fig., for any certain values of solidity, T_M^* and T_A^* intersects at a unique point with a certain value of ε. Table 1 shows the exact value of solidity and slip for each intersection in fig. 4. It can be inferred from fig. 4 that for solidities less than a certain value (here 2.343) two equations never touch each other. So it is necessary to choose solidity from a reasonable range to have full fluid guidance.

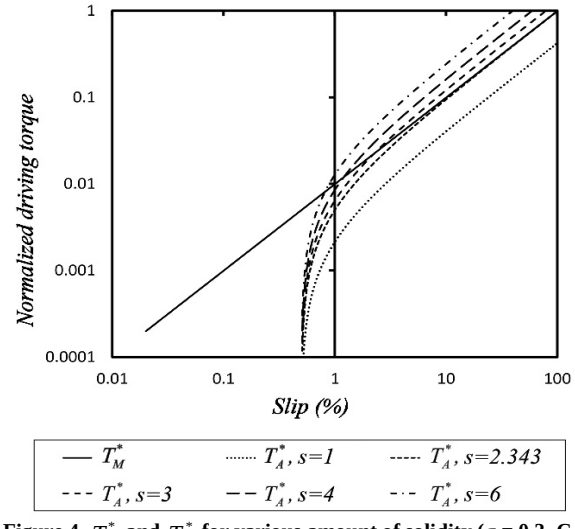


Figure 4. T_M^* and T_A^* for various amount of solidity (σ = 0.3, C_1 = 2, C_D = 0.005, $L/D_t = \pi$)

Table 1. Intersection points of fig. 4

solidity	Slip of intersection (%)
1	---
2.343	100
3	2.24
4	1.2
6	0.8

In continue we try to show the influence of pitch value on current-meter. By equating 12 and 21 we can obtain a formula for solidity at which we have full fluid guidance.

$$s = f(\varepsilon) \quad (23)$$

This equation is plotted in figure 5 for different values of L. As can be seen in the figure, the graph can be divided into two parts, 1. semi-linear and 2. non-linear parts. It can be inferred from the figure that by increasing L, the semi-linear part covers a wider range of slips.

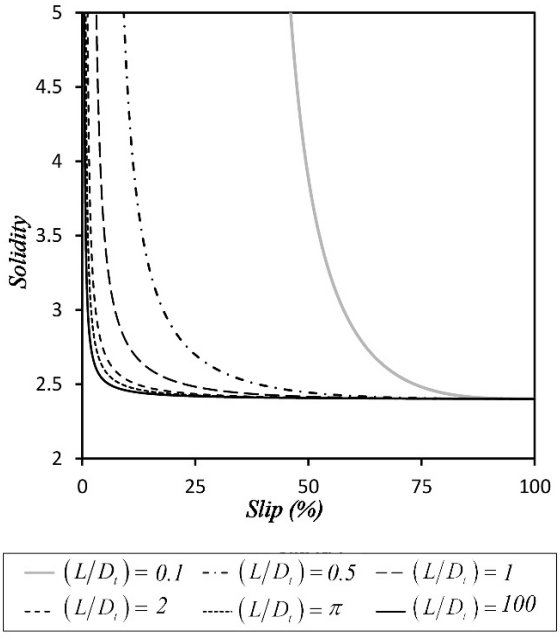


Figure 5. Influence of L on equation 23, σ = 0.3

By using the before-mentioned equations we can design a current-meter by a certain values of solidity and slip, but the point is that we can't guarantee the current-meter always works under its design condition. In real condition, we may see deviation from design condition due to lots of reasons, such as oblique flow, pulsating flow and etc. So in designing procedure, it is wiser to choose a solidity which covers a wider range of slips, the solidity that belongs to the semi-linear part of the diagram.

It can be inferred that by increasing the pitch value we can extend the range of actual slip under which the current-meter works properly.

Current-meters can be divided by pitch value into three groups, 1. Low pitch 2. Transient pitch from

low to high and 3. High pitch. Low pitch current-meters are more sensitive to velocity, so they are usually used to measure low velocities. Otherwise, high pitch current-meters are usually used to measure high velocity currents.

Choosing a proper solidity depends on the designer's aim. We see from fig. 5 that low pith current-meters (which are more sensitive to velocity changes) are less reliable in oblique or pulsating flows. So the designer must choose between high sensitivity and high reliability.

Figure 6 shows the influence of σ on 23.

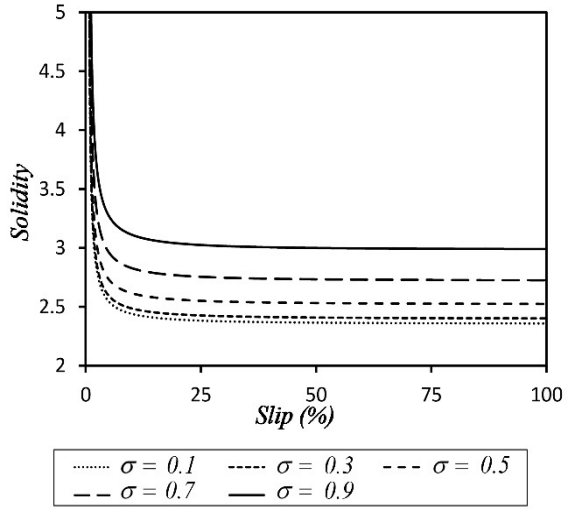


Figure 6. Influence of σ on equation 23, L/Dt = π

It is observed that changing the σ doesn't make any change in length of the semi-linear part, But it shifts the graph along solidity (vertical) axis. Increasing σ will increase the solidity of semi-linear part. It means by increasing sigma, we must choose a higher amount of solidity to have full fluid guidance.

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