Investigations of rotating blade for energy extraction from fluid flow

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Abstract. Device for energy extraction from fluid (air or water) is investigated. The device consists of a one central rotor with energy generator and several plane blades. All blades are connected to the central rotor with gear system which allows automatically change the orientation of their working surfaces to the direction of the incoming fluid flow. It is considered task that axis of the rotor and blades are perpendicular to fluid flow. System has one degree of freedom as rotation angle of central rotor. Theoretical analysis of the one blade interaction with the fluid flow is given. Calculation of system with one blade is done with MathCAD.

Keywords: fluid flow, rotor, blade, double pendulum, energy extraction.

1. Introduction

In this work the authors continue studies initiated in previous works on energy extraction from fluid (water or air) [1, 2]. The motion of one-degree freedom system in which the central rotor is kinematic connected with several blades is analyzed (Fig. 2). The blades interact with fluid flow, automatically taking a certain orientation. According to previous studies blades angles φ and rotor turning angle α_i is related to the following Eq. (1) [2]:

$$\alpha_i = \alpha0_i + 0{,}25\pi + 0{,}5\varphi, \tag{1}$$

where $\alpha0_i$ – initial phase of each blade.

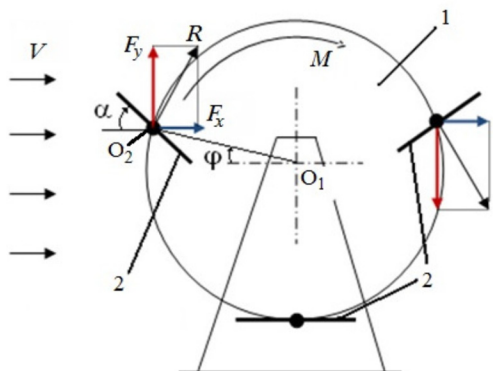**Fig. 1.** Model of a device investigated before [1, 2]

Fig. 2. A schematic diagram of a device. 1 – rotor; 2 – blades; φ – angle of rotor positions; α – angle of blade positions; O_1 – rotor axis; O_2 – blade rotation axis; F – fluid interaction forces [1]

This research analyzes the system interaction with the fluid, without taking into account the central rotor interaction, which partially is described as double pendulum in the works [3, 4].

Before the exploration of the all rotation system dynamics it is need to find one blade and fluid interaction forces. At first it is to find out reduction forces to blade rotation axis O_2. In this report is studied the case when the initial phase is zero, $\alpha0_0 = 0$, or (Fig. 2):

$$\alpha = 0{,}25\pi + 0{,}5\varphi. \tag{2}$$

1.1. Simplification of fluid flow interaction forces with one blade

For interaction forces simplification the one small ribbon of blade with length $d\xi$ is observed (Fig. 3). Then normal component of interaction force Rn at the distance ξ from center O_2 depends of normal velocity component in square Eq. (3) [4]:

$$Rn = Dn \left[V\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - \xi\frac{\omega}{2} - r\omega\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 d\xi, \tag{3}$$

where: Dn – constant including density of fluid, width of plate, drag coefficient in normal direction; ω – angular velocity of central rotor; R – radius of center O_2; V – flow velocity.

Similarly, the tangential component Rt will be Eq. (4):

$$Rt = -Dt \left[V\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - r\omega\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 d\xi, \tag{4}$$

where: Dt – constant including density of fluid, width of plate, drag coefficient along plate.
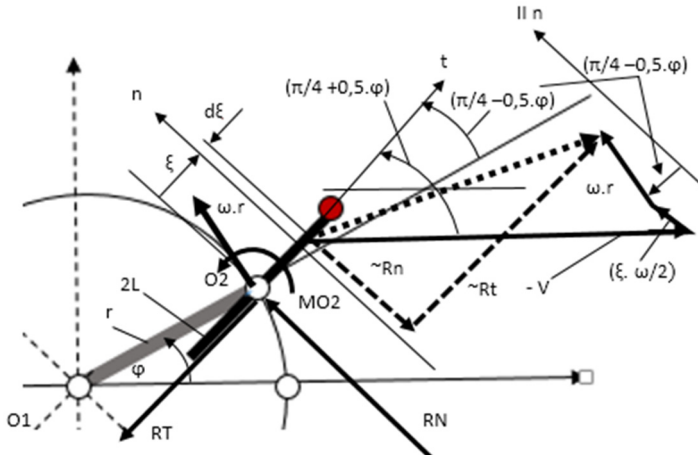

Fig. 3. A schematic diagram of interaction force calculation. V – flow velocity; ω – angular velocity of rotor; φ – angle of rotor positions; $\alpha = (\pi/4 + 0{,}5 \cdot \varphi)$ – angle of blade position; Rn – fluid interaction normal force; Rt – fluid interactions tangential force

Accordingly, to classical mechanics there can be found out reduction forces and moment of forces in the center O_2 in the following Eqs. (5-7) [5, 6]:

$$RN = Dn \int_{-L}^{L} \text{sign1} \left[V\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - \xi\frac{\omega}{2} - r\omega\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 d\xi, \tag{5}$$

$$RT = -\int_{-L}^{L} \text{sign2}\, Dt \left[V\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - r\omega\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 \cdot d\xi, \tag{6}$$

$$MO_2 = Dn \int_{-L}^{L} sign1 \left[V\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - \xi\frac{\omega}{2} - r\omega\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 \xi d\xi$$

$$-\frac{\Delta}{2} Dt \int_{-L}^{L} sign2 \left[V\sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - r\omega\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right]^2 \xi d\xi, \tag{7}$$

where RN, RT, MO_2 – components of forces vector and forces moment in point O_2; $2L$ – length of blade; sign1, sign2 – +1 or –1, that depends of local interactions directions (see Fig. 3); Δ – width of blade.

Here problem exists to find integrals Eq. (5-7) because sign1 and sign2 switch functions depend of systems parameters (L, Δ, R, V) and motion parameters (ω, φ).

In this report the simple case is observed when width of plate is small ($\Delta \to 0$) and sign1 = +1. Then from Eq. (5), (7) can be find out:

$$RN = Dn \left[2L \left(V\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - r\omega\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right)^2 + \frac{L^3\omega^2}{6} \right], \quad RT \approx 0, \tag{8}$$

$$MO_2 \approx \frac{2}{3} DnL^3\omega\sin\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)(V - R\omega). \tag{9}$$

Formulas Eq. (8), (9) can be used for rotor rotation motion investigations.

1.2. Differential equation of rotor motion with one blade

For system with one degree of freedom (angle φ) by using kinetics energy exchange theorem can be find out differential equation of motion [5, 6]:
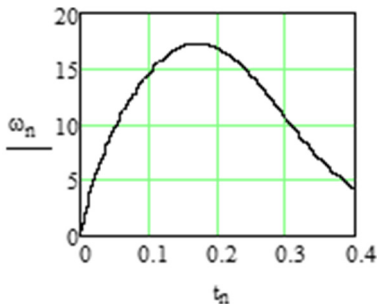
$$\ddot{\varphi} = \frac{1}{JO_1}\left(RNr\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) + MO_2 - M(\varphi, \dot{\varphi}) - C_g r\cos(\varphi) \right), \tag{10}$$

where: JO_1 – constant including system mass, moments of inertia rotor and blade; $M(\varphi, \dot{\varphi})$ – moment of generator and of resistant forces; C_g – constant of gravitation interaction which takes into account rotation axis orientation and location of center mass.
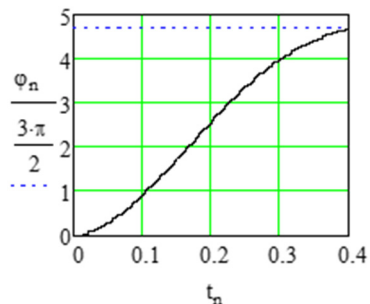
Eq. (10) may be investigated by computer, checking parameters sign1 = +1. If C_g is large, system does not rotate but starts to move in pendulum vibration regime.

1.3. One blade systems modelling with Math CAD

Some diagrams of modelling with explanations are shown in Fig. 4, Fig. 5.

a) Angular velocity ω_n in time t_n domain   b) Turn angle φ_n in time domain
Fig. 4. Results of modelling with MathCAD with sign1 = +1 (from rest position till angle $\varphi = 3\pi/2$)

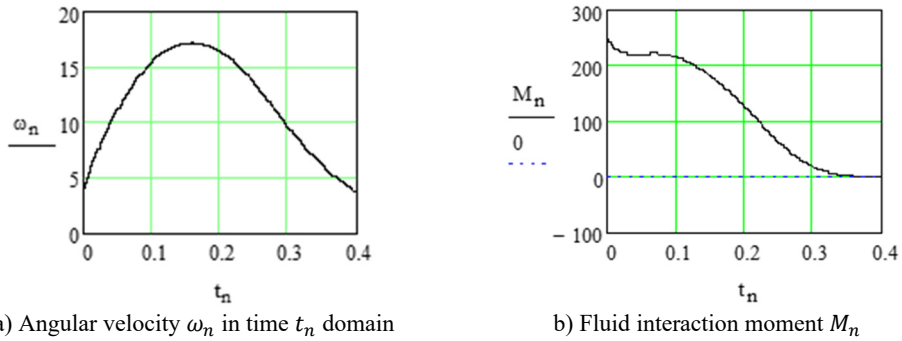a) Angular velocity ω_n in time t_n domain   b) Fluid interaction moment M_n

Fig. 5. Results of modelling in stationary rotation with sign1 = +1 by angle $\varphi = 0$ till $3\pi/2$

2. Conclusions

The possibility to use double pendulum system with additional constraint for energy extraction from fluid is established. The analytical formulas for fluid interaction with rotating blade are given. In future it allows investigated more complicated system with different number of blades and different positioning angles. Results of this report can be used for systems parameters optimization.

References

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