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Conveyor-type Small Hydropower Plant for Shallow River Waters

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Abstract. **This paper deals with the development of a small conveyor-type hydropower plant intended for operation in shallow river waters without construction of a dam. The proposed design offers a closed-shaped flattened conveyor equipped with flat-shaped blades. The conveyor is oriented perpendicular to the fluid flow. Several identical flat blades interacting with fluid flow are mounted on conveyor belt and move together with the belt in one straight line direction. Then after turning in the reversing mechanism, blades move in the opposite direction. The conveyor system has a built-in energy generator which drive shaft is connected with one of the reversing ends of the plant. Conveyor belt system dynamics analysis is performed on the base of equivalent model with one degree of freedom. The interaction of a moving conveyor flat blade in translation motion with fluid flow is studied by computer simulation with program Mathcad using a superposition principle. In accordance with this approach, a fast-chaotic motion of fluid particles (Brownian motion) is separated from the slow-directed flow motion, with the given average velocity. Optimization of system parameters (blade orientation angle to fluid flow, interaction constants of the braking generator) is performed, using a generated power as criterion. Simulation results confirm the serviceability and operational efficiency of the proposed hydropower plant in shallow river waters.**

Keywords: dynamic analysis, flat blades, hydropower plant, optimization.

I. INTRODUCTION

Hydropower generation is one of the most developed and widely applicable sources of renewable green energy. Operation efficiency of hydropower plant is primarily dependent on the hydraulic head and the rate of fluid flow in the turbine. Due to this, the problem of energetic efficiency of existing power plants is mainly solved by the construction of large dams. Worldwide there are over 58000 dams with the height up to 15 m, and number of dams continues to increase [1]. This trend has a negative environmental impact acting as a barrier to fish migration, fragmenting rivers and degrading habitats [2] – [4].

Other specific feature of existing hydropower plants lies in the practical use of turbines with rotating blades [5] – [7]. To increase generated power, such blades are often made with large radial dimensions. This gives the rise to significant vibration problems due to increased level of dynamic stresses (especially near the blades attachment to the rotor) [8]. Besides, rotating blade can damage fishes and other river species in surrounding water area.

The present paper focuses on the development of a small hydropower plant, which operates without construction of a dam and can be used in areas where water head is even lower than 1 meter. To achieve this goal, it is proposed to realize in the hydropower device a new

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operational principle based on the use of flat blades translational motion excited by fluid flow.

II. Materials, Model and Methods

Instead of conventional turbine models with rotating blades, a new design of wind power plant synthesized on the base of a closed loop conveyor equipped with flat-shaped blades is proposed (Fig. 1).

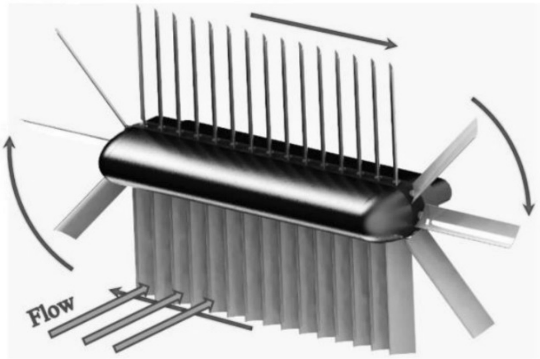

Fig. 1. Three-dimensional design of hydropower plant.

The conveyor belt is equipped with several identical flat blades, which translation motion is excited due to the action of fluid flow. Blades move together in one straight line direction, then turn in the reversing mechanism by 180 degrees and move in the opposite direction. The conveyor system has a built-in energy generator. The drive shaft of the generator can be mounted on one of the axes of the reversing ends of the conveyor belt (in Fig. 1 the drive shaft is not shown). In the proposed device, the fluid flow load is uniformly distributed over the lateral surface of the flat blades. This provides a simple way to increase the operational efficiency of the device, which can be achieved by increasing the area A of blade's lateral surface.

Principal model of the hydropower plant synthesized on the base of a closed belt conveyor is shown in Fig. 2.

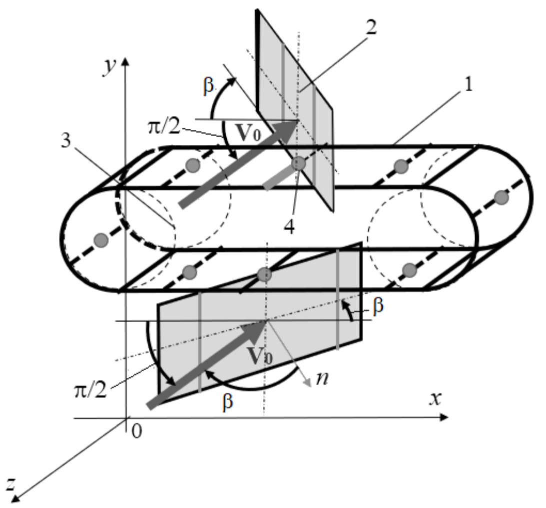

Fig. 2. Principle model of fluid flow power plant on the base of belt conveyor: 1 – closed belt conveyor; 2 – flat blade; 3 – rotor; 4 – fastening element.

Closed belt conveyor 1 forms a central part of the plant, besides the belt has an ability to move parallel to coordinate plane $x0y$. The conveyor is driven by a fluid flow with velocity V_0, acting on the blades 2 in parallel to the $0z$ axis. Power is obtained from a generator connected with rotor 3 of the conveyor 1 (Fig. 2). The flat blades 2 are attached tightly to the conveyor 1 with a fastening element 4 (welded hinge). Besides, the blades 2 are fixed at the angle β toward the x-axis. The model of generator has several flat blades 2. Due to the action of air flow V_0, translation motion of blades 2 along conveyor's straight and circular sections (in final turns) is excited. To obtain useful power, this translation motion of blades 2 is transformed into the rotation of generator's rotor 3.

The interaction of a moving conveyor blade in translation motion with a fluid flow is studied using superposition principle. In accordance with this approach, a fast chaotic motion of fluid particles (Brownian motion) is separated from the slow-directed flow motion, with the given average velocity. In addition, the space around the blade is divided into two zones: one zone is the interaction pressure zone on the front side of the movement, and the other zone is at the rear, or the suction zone [9], [10]. Application of the method makes it possible to study flow – blade interaction without the use of experimental lift and drag coefficients. The applicability of such approach is confirmed by experiments described in [11].

Model of fluid flow interaction with one thin flat blade is shown in Fig. 3. It is assumed that fluid flow has a constant velocity V_0, but blade is turned by angle β relative to flow direction. Due to the action of fluid flow and blade's translational motion along x axis, fluid interaction force N is applied to the blade.

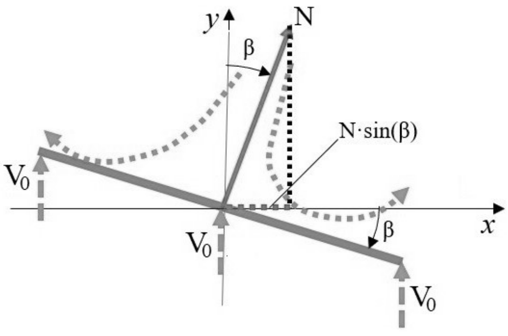

Fig. 3. Model of fluid flow interaction with one moving thin blade.

Basing on fast and slow motions separation principle, it is possible to obtain the differential relations of motion for the interaction of fluid flow with blades. For this purpose, the theorem of classical mechanics for the amount of movement changes in the differential form [12] can be used. As a result, after integration and summation over the entire system of conveyor with one degree of freedom, the following differential equation of blade translation motion is obtained [10]:

$$m\ddot{x} = (1+C)\rho BLK \cdot (V_0 \cos\beta - \dot{x}\sin\beta)^2 \cdot \sin\beta \cdot \mathrm{sign}(V_0 \cos\beta - \dot{x}\sin\beta) + Q, \quad (1)$$

where x is a generalized coordinate (here it is a displacement of conveyor one element); m is a mass of one blade; C is a fluid flow and blade interaction constant; ρ is a density of fluid; B, L are the width and length of one blade; K is number of blades; V_0 is a fluid flow velocity in the direction perpendicular to the x axis; β is a blade positioning angle; Q is a remaining part of the generalized force, including resistance forces and forces of power generator.

Analysis of motion dynamics of the conveyor system is performed by the solution of differential equation (1) with program Mathcad.

III. Results and Discussion

Variant of the generator with the linear generalized resistance force Q in the equation (1) is considered:

$$Q = -b_1\dot{x}, \qquad (2)$$

where b_1 is a coefficient of viscous damping in linear generator.

During simulation, power P of linear generator was calculated by formula

$$P = b_1\dot{x}^2. \qquad (3)$$

Mathematical simulation is performed assuming the following values of main system parameters: b_1 = 75 kg/s; m = 10 kg; K = 5; ρ = 1000 kg/m^3; C = 0,5; B = 1 m; L = 1 m; V_0 = 1 m/s; β = 0,039 rad; g = 9,81 m/s^2. Results of dynamics analysis for blade velocity V and for power P obtained in the generator are presented in Fig. 4 and Fig. 5.

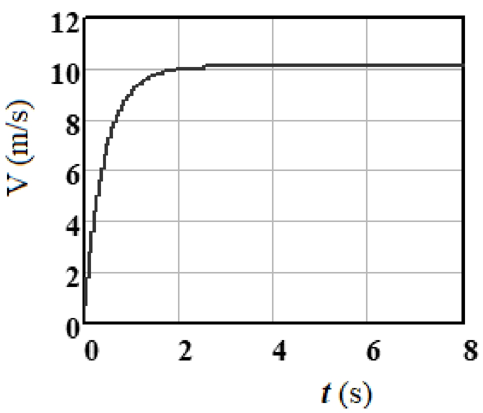

Fig. 4. Velocity V of blade translation motion along x axis versus time t.

By the analysis of diagrams presented (Fig. 4 and Fig. 5), it can be concluded that stationary motion process (when motion velocity along the x axis is almost constant) occurs very quickly (within 1,5 – 2 s), without fluctuations. The power P of the stationary process is dependent on the generator parameter b_1 as well on the flow rate V_0 and blade orientation relative to fluid flow (blade position angle β). For example, in the case studied here, the generated power P reaches up 7500 – 8000 W even at the relatively small fluid flow velocity of V_0 = 1 m/s.

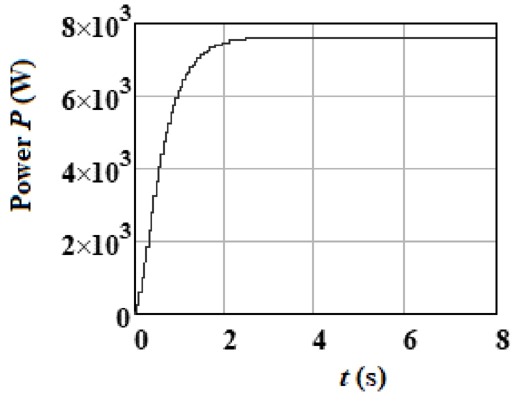

Fig. 5. Power P obtained in the generator (for the system parameters b_1 = 75 kg/s, β = 0,039 rad, V_0 = 1 m/s).

As it is seen from simulation results (for example, Fig. 4), the velocity V of blade stationary motion process is almost constant, and the acceleration is close to zero. Therefore, it is possible to optimize this process.

In solution of optimization problem, the power P is considered as criterion, but the interaction constant b_1 of the braking generator as well as the blade orientation (turning angle β) are taken as variable parameters. Parametric optimization problem is solved with the aid of program Mathcad. The example of response curve for the criterion power P as a function of blade turning angle β is shown in Fig. 6.

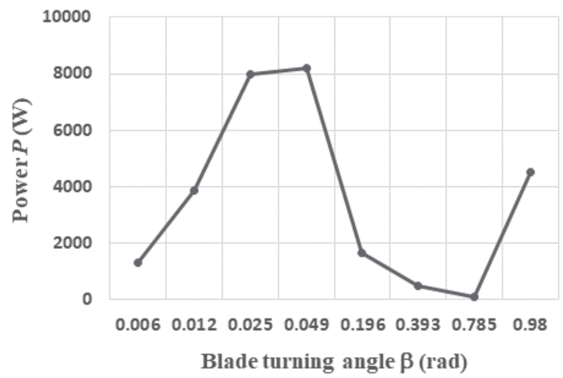

Fig. 6. Response curve for the optimization criterion P as a function of blade turning angle β (for the case of V_0 = 1 m/s and b_1 = 5,5 kg/s).

As it is seen from the diagram presented (Fig. 6), the generated power P reaches maximal values of 7-8 kW under the relatively small blade's turning angle (β = 0,025 – 0,050 rad).

Other example of a response surface for the optimization criterion power P is shown in Fig. 7. In solution of this problem, variation of linear generator parameter b_1 was held (under the constant turning angle β = 0,039 rad).

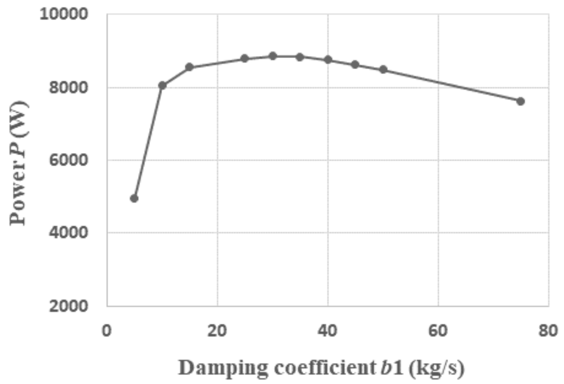

Fig. 7. Response curve for the optimization criterion P as a function of interaction constant b_1 of the braking generator (for the case of $V_0 = 1$ m/s and $\beta = 0{,}039$ rad).

The renewable power P of linear genarator is dependent on its viscous damping force $-b_1\dot{x}$, which can be varied by changing of interaction constant b_1 (e.g., by changing the design of generator elements). As it is seen from the diagram presented (Fig. 7), the generated power P reaches maximal values of 8-9 kW, if damping contant b_1 of braking generator lies within the range from 10 till 60 kg/s. And what is practically important, such relatively high power can be obtained under the quite a small fluid flow velocity of 1 m/s, characteristic for shallow river waters.

IV. Conclusions

A conveyor-type turbine for small hydropower plants (<100 kW), which can operate in shallow river waters without construction of a dam, is developed. Instead of conventional turbines with rotating blades, the proposed model generates useful power from translational motion of flat blades excited by fluid flow.

Due to excluding dams from the structure of the proposed hydropower plant, the ecological situation in surrounding aqua system will improve significantly (no barrier to fish migration, no negative influence on river fragmenting and degrading habitats, etc.). Besides, compared to turbine with rotating blades, there will be a lower risk to damage fish or other river species around the translatory moving blade in the proposed device.

The operational advantage of the conveyor-type hydropower device lies in the fact that velocities of all points of the lateral surface of the flat blade are the same (as opposed to conventional rotary-type devices, in which the speeds of the blade ends are sufficiently higher). Due to this, the side surface of the blade in the proposed device can be used more effectively than in known rotary devices [13]. By the results of computer simulation, a generated power reaches about 8-9 kW even under the quite small fluid flow velocity of 1 m/s.

Optimization of system parameters (blade orientation angle to fluid flow, interaction constant of the braking generator) is performed, using a generated power as criterion. Simulation results confirm the serviceability and operational efficiency of the proposed hydropower plant in shallow river waters.

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