Dynamic of the wind powered walking vehicle

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Summary. This paper presents the modelling of novel walking vehicle which aims to move against the wind flow using only the energy of the wind. The vehicle consist of the body, four legs, and wind propeller installed on it. When it is situated in a wind flow, propeller begins to rotate and transmits the energy to the main crank of the legs.
A mathematical model of the system is constructed. Aerodynamics of the propeller is described using a quasi-steady approach basing on available experimental data. It is shown that for certain values of parameters the apparatus can perform motion in upwind direction. Sufficient conditions of existence of periodic regimes are obtained. It is shown that the system can possess two types of periodic regimes corresponding to upwind motion. The average velocity of the body depending on the geometrical parameters is investigated. Evolution of attracting and repelling regimes of motion is analyzed. To demonstrate the possibility of motion against the wind, the plastic prototype of the vehicle is constructed and tested.

Introduction

The problem statement of a straight motion against the flow due to the energy of this flow for walking robots is unique. Nowadays Theo Jansen's mechanical devices are widely known, which are able to walk and get energy from the wind [1, 2]. Such mechanisms can perform motion in downwind direction with a help of sails, or in perpendicular to the wind direction, using a propeller.
In present work, we introduce the novel wind powered walking vehicle based on the Chebyshev plantigrade machine [3,4]. To realize the upwind motion, we upgraded mechanical scheme and supplemented a wind propeller on the body.

Description of the mechanical system

Scheme of the mechanical system is represented in Fig.1. The base of the walking mechanism consists of the body and four legs which are installed on it. This base is equipped with a wind turbine so that the shaft of the propeller is connected with the main shaft of legs by a warm gear. We suppose that this vehicle is located in the horizontal steady wind flow with the speed v_0. The vehicle moves straight along the wind over an absolutely rough plane in the gravity field.

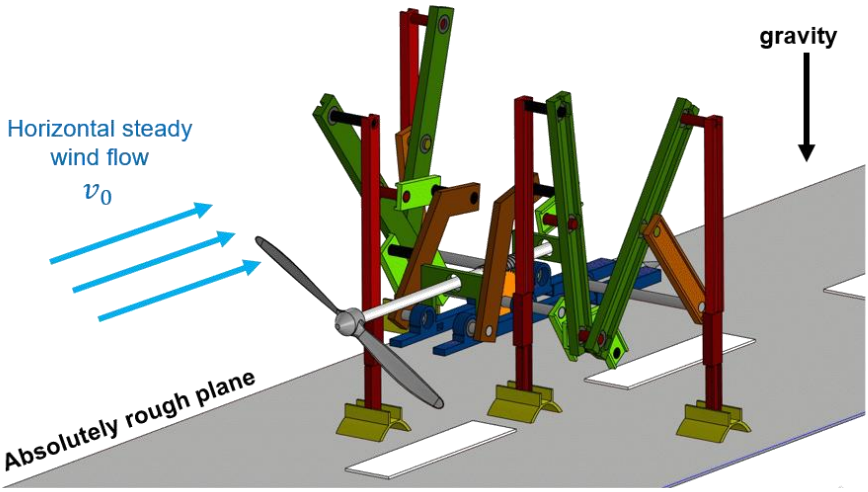

Figure 1: The scheme of the mechanism.

We assume that there is no slipping of the supporting legs and there is no tilting of the body. With these assumptions, the vehicle has one degree of freedom. The angle φ of rotation of the leg's crank shaft is chosen as a generalized coordinate. Equations of motion of the system are derived using the Lagrange formalism:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right) - \left(\frac{\partial L}{\partial \varphi}\right) = n \cdot M_{aero} - \frac{v}{\dot{\varphi}}\left(F_{aero} + k(v + v_0)\right).$$

Here $L(\varphi, \dot{\varphi})$ is the Lagrange function, n is a gear ratio between propeller and cranks, v is a horizontal velocity of the body, k is the aerodynamic drag coefficient of the body. M_{aero} and F_{aero} are the aerodynamic torque and the drag force acting on the propeller, correspondently. These functions are described according a quasi-steady model and have the following form:

$$M_{aero} = \frac{1}{2}\rho_a S \cdot r_a (v + v_0)^2 C_T(\lambda), \qquad F_{aero} = \frac{1}{2}\rho_a S \cdot (v + v_0)^2 C_D(\lambda),$$

where $\lambda = n r_a \dot{\varphi}\,(v + v_0)^{-1}$ is a tip speed ratio of the propeller, ρ_a is the air density, S and r_a are the characteristic area and the radius of the propeller. $C_T(\lambda)$ and $C_D(\lambda)$ are non-dimensional coefficients of torque and drag force, correspondingly. These coefficients are approximated using experimental data [5].

Right hand side of the system is π-periodic with respect to φ. Therefore, the phase space of the system is cylindrical. An attracting limit cycle with a positive value of $\dot{\varphi}$ enclosing the phase cylinder corresponds to desired upwind motion regime.
The following parameter is introduced: $\varepsilon =$. It is supposed to be a small value. This means that characteristic values of aerodynamic loads are significantly smaller than characteristic values of inertial forces.

Main results

We obtained sufficient conditions of existence of periodic upwind motion regimes using the Andronov-Pontryagin asymptotic method [6]. This method involves the averaging procedure. Notice that averaging is widely used in most powerful and demanded approaches of nonlinear dynamics [7, 8]. We performed analysis of limit cycles depending on parameters of the vehicle. The attraction properties of the regimes are studied.

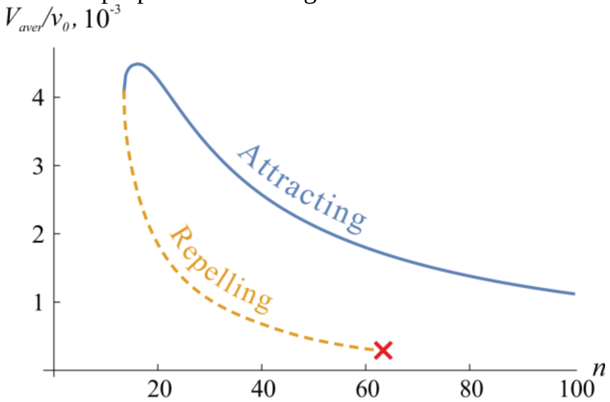

Figure 2: Bifurcation diagram for periodical trajectories.

An example of bifurcation diagram is shown in Fig. 2 for the case $\varepsilon \to 0$ with other parameters of the system corresponding to the laboratory prototype constructed and tested in the Institute of Mechanics of Lomonosov Moscow State University. The description of the prototype and the video of its upwind motion are available [9]. In particular, the total length of the prototype is 225 mm. Fig. 2 illustrates how the average velocity the body depends on gear ratio n. Upper branch of diagram corresponds to attracting trajectories, and lower to repelling ones. Red cross corresponds to the bifurcation when a repelling periodic trajectory enclosing a phase cylinder merges with a separatrix and is destroyed as a result. Accuracy of asymptotic bifurcation diagram was checked by direct numerical integration of the system for the case $\varepsilon = 0.76$. In particular, the value of parameter n for which repelling trajectory is destroyed is determined with 6% precession.

Conclusion

The mathematical model of a wind powered walking vehicle is constructed. Results of parametrical analysis of the model are used to adjust constructive parameters of the first prototype. Experimental testing of the prototype demonstrated the possibility of motion against the wind for a walking mechanism.

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