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Vibration-driven Systems with Movable Internal Masses: Control and Optimization

1. INTRODUCTION

The subject matter of the paper is the control and optimization of mechanical systems that can move in a resistive medium without specific propelling devices, such as wheels, legs, fins, caterpillars, or screws. Such systems consist of a body with movable masses inside. The internal masses interact with the body by means of the forces generated and controlled by drives. When the control force is applied to an internal mass, the reaction force is applied to the body and changes its velocity, which affects the resistance force exerted on the body by the environment. Thus, the control of motion of the internal masses provides the control of the external force acting on the body and enables one to control the motion of the entire system. This principle of motion can be used in mobile robots, especially in mini- and microrobots designed for the motion inside small-diameter tubes and in vulnerable media. Usually, regular progressive motions of such a system are generated and sustained by periodic vibratory motions of the internal masses. For that reason, it is appropriate to call such mobile systems the vibration-driven systems. In the present paper, we consider a vibration-driven system the body of which moves along a straight line on a rough horizontal plane, while two internal masses move in a vertical plane passing through this line. We construct periodic motions of the internal masses so as to provide a velocity-periodic progressive motion of the body with a maximum speed.

2. THREE-BODY SYSTEM MOVING ALONG A ROUGH PLANE

The system consists of the body and two internal masses. One of the internal masses moves horizontally along the line of motion of the body, while the other mass moves vertically. There is Coulomb's friction force acting between the body and the plane. The friction force can be controlled by only one mass that moves horizontally. However, the horizontal motion of the internal mass does not ensure the control of the normal pressure force that also influences the magnitude of Coulomb's friction force. The introduction of the mass allowed to move vertically provides such a possibility and, hence, increases the control capabilities. For this system, an optimal control problem is solved. The role of the control variables is played by the accelerations of the internal masses relative to the body. The absolute values of these accelerations are constrained due to restricted power of the drives. It is assumed that contact between the body and the plane is not violated, which implies an additional upper constraint on the magnitude of the downward acceleration of the mass moving vertically. Periodic motions of the internal masses are constructed that satisfy the constraints, provide a velocity-periodic motion for the body, and maximize the displacement of the body in the desired direction for a fixed period. It is proven that the period consists of two intervals. The body moves forward during the first interval and remains fixed during the second interval. In the optimal motion, the body never moves backward. On the first interval, each control is of bang-bang type with one switching instant at most. On the second interval both controls are constant. The optimal control problem is reduced to the constrained maximization of a quadratic function. The parameters to be found are the duration of the interval of the forward motion of the body and the switching instants of the controls. This statement of the control problem does not impose constraints on the maximum relative displacements of the internal masses. Such constraints can be taken into account by varying the period of the motion. Detailed solutions are obtained for two limiting cases, where the vertical motion of the mass is prohibited and where the relative acceleration of this motion is constrained only by the condition that the body does not loose contact with the plane. In the second case, the displacement of the body for the period is more than 4 times the displacement provided by the only internal mass moving horizontally.

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