Features of the dynamics of walking machines and robots with cycle type of movers and controlled dissipation in the foot joint

V V Arykantsev, Ya V Kalinin and V V Chernyshev
Volgograd State Technical University, 28 Lenin Avenue, Volgograd, 400005, Russia
arvstu@mail.ru

Abstract. The expediency of introducing an additional damping device (analogy of a shock absorber) into the cyclic walking mechanism of a mobile robot, which provides a dissipative connection of a ski-shaped foot with a support link, is discussed. The influence of the damper on the dynamics of the feet changing and the dynamics of the meeting of the foot with an obstacle is considered. It is shown that dissipation in the hinge of the foot leads to a decrease in the intensity of shock processes when changing feet and when meeting an obstacle, provides a decrease in power losses for vertical vibrations of the body, and also expands the propulsion unit’s capabilities for self-adaptation to an unorganized surface.

1. Introduction
The use of walking movers based on cyclic walking mechanisms in walking machines and robots makes it possible not to worry about maintaining gait and stability and eliminates the need for a controlled adaptation system. Multi-legged walking robots with cyclic movers have a minimum number of controlled degrees of freedom and are structurally much simpler than analogs with adaptive control [1-3]. High cross-country ability and excellent traction and coupling properties on soils with low bearing capacity, environmental friendliness, simplicity of design, reliability of operation and relatively low cost make it possible to create and operate in extreme conditions walking machines and mobile robotic systems with movers based on cyclic walking mechanisms already at present time.

In Volgograd State Technical University have been developed a number of prototypes of walking machines and robots with cyclic-type movers designed to operate on water-saturated and underwater soils [3, 4]. Their tests have confirmed the superiority of walking machines in terms of traction properties, ground and profile cross-country ability in comparison with traditional vehicles [5, 6]. At the same time, tests revealed a number of problems associated with handling in a disorganized surface. The strict trajectory of the reference points of the cyclic walking mechanisms does not allow, in full measure, to realize the potential of the mover in adaptation to the supporting surface and profile passability. For their more complete implementation, it is necessary to adjust the programmed leg movements - changing the length or height of the step for bumpless obstacle overcoming [4], combining the position of the pivot points when turning to reduce the moment of resistance to turning [7–9], etc. For example, during underwater testing of a walking device MAK-1 (figure 1), due to poor visibility under water (less than 1–3 m), the operator in straight forward modes of movement even at relatively low speeds (about 1.5–2 m/s¹) did not have time to take adequate decisions in the case of
the appearance of any obstacle in the direction of travel (the decision time was from 0.5 to 2 s). As a result, when encountering obstacles, there were cases of destruction of the feet and elements of the walking mover (figure 2).

Figure 1. Underwater walking device MAK-1 — meeting with an obstacle.

Figure 2. Feet deformations after meeting with an obstacle.

In the work, with the aim to reduce vibroimpact processes when changing feet and meeting a foot with an obstacle, the possibility of introducing an additional damping device (analogue of a shock absorber) into the cyclic walking mechanism, providing a dissipative connection of the ski-shaped foot with the support link, is discussed.

2. Materials and methods of investigation

The analysis is carried out on the example of the Umnov-Chebyshev cyclic walking mechanism, which is differs by its simplicity and reliability. The mechanism was proposed by N.V. Umnov (A.A. Blagonravov Institute of Mechanical Engineering, Russian Academy of Sciences) and was obtained from the well-known walking mechanism of a foot-walking machine by P.L. Chebyshev [4] by turning it over and giving the support link an L-shaped. In the MAK-1 underwater robot, it was improved (figure 3 (a)) - due to the introduction of an additional degree of freedom, controlled in the gear change mode, into the mechanism, the possibility of adjusting the trajectory of the reference point was provided [4]. Also, a system of passive adaptation of the foot to the supporting surface was implemented, which, due to the kinematics of the mechanism and friction in the hinge of the foot, lifts the toe of the foot in the transfer phase [4, 10]. Moreover, the toe of the foot is lifted both with direct and reverse movement of the machine (figure 3 (b), 3 (c)). To eliminate the influence of random factors on the programmed movement of the hinged foot and reduce the intensity of impact processes when changing feet and when meeting an obstacle, it is proposed to introduce an additional damping device 6 into the walking mechanism (figure 3 (a)), which provides dissipative connection of the foot 4 with the supporting link 2 of the walking mechanism.

The walking mechanism during its kinematic analysis was considered as a flat multi-link mechanism, the individual links of which perform a plane-parallel movement. During compilation of the differential equations of the mechanism links motion, their angular velocities were expressed through the velocities of the points on which external connections are imposed. Expressions for velocities were obtained by consistent, link by link, consideration of the motion of rigid bodies. For points of the mechanism, on which external constraints are imposed, expressions for velocities were transformed into constraint equations. Solving them together with respect to the angular velocities of the links, a system of differential equations of motion was obtained, the integration of which, at given initial values of the angles of rotation of the links, solves the kinematic problem of the movement of
the walking mechanism in the body-related frame of reference. The relative accelerations of the featured points of the mechanism, which are functions of the angular velocities and accelerations, were obtained by differentiating their velocity vector with respect to time. The angular acceleration of the links was determined by differentiating the angular velocities. As a result, the relative accelerations of the nodal points of the walking mechanism were determined, including its reference point $C$, which coincides with the center of the foot. Similarly, the kinematic characteristics of the walking mechanism operating in antiphase were determined. When determining the speed and acceleration of the machine body in absolute motion, they were assigned the values of the relative speeds and accelerations of the reference point of the mechanism in the reference phase taken with the opposite sign. It was supposed that the walking mechanism is located in the support, the reference point of which has a smaller coordinate $z_C$.

3. Results and discussion

Moment of viscous friction at the hinge of the foot $M_r = f(\mu, \Delta \omega_{24}^{(r)})$ determined by the coefficient of viscous friction $\mu$ in the damper and the relative angular velocity of the foot in relation to the support $\Delta \omega_{24}^{(r)}$. Program changing of $\Delta \omega_{24}^{(r)}$ of the basic walking mechanism per cycle, obtained from the results of kinematic analysis, is shown in figure 4.
In Figure 4 section GABC corresponds to the phase of foot transfer, section CD - to the stage of placing the foot on the ground, DE - to the contact phase with the ground, EG - to the exit of the foot from the contact phase. The GABC transfer phase, can be subdivided into the GA section, where the foot moves together with the support link of the walking mechanism, and the ABC section, in which the foot in the transfer begins to interact (with the heel) with the ground and moves in a skid.

If, when changing the feet, the coefficient $\mu$ of the damping device exceeds the critical value $\mu_{cr}$, at which the normal reaction of the soil $N_1$ of the foot, which has not yet been established on the ground, begins to exceed $N_2$ - the reaction of the foot in the reference phase, then in the CD section and at the final stage of the transfer phase, at feet coming into contact with the ground, an additional phase of the cycle occurs - the phase of support on the heel. Changing the feet operating in antiphase in this case, see Figure 5, where $X_C$, $Z_C$ - reactions in the hinge of the foot; $P_{ij}$ - adhesion force; $v_D'$ and $v_D''$ - the speed of slipping of the toe and heel of the $j$-th foot ($j = 1, 2$), will take place in 4 stages.

At the first stage, the 1st foot is in transfer ($N_1 = 0$), and the 2nd foot is in contact with the ground by the entire supporting surface and takes all the load on the mover.
At the second stage (figure 5 (a)), after the heel of the foot (point $D''$) touched the ground and skidded due to the relative angular velocity $\Delta \omega_{41}'$ appears a moment of support $M_{R1}$ and 1-st the foot begins to partially perceive the weight of the machine, while 2-nd the foot remains on the ground and carries the bigger part of the machine's weight ($N_1 < N_2$). Normal reaction of the 1-st foot at this stage, considering that $P_{nl} = k_\varphi N_1$, is:

$$N_1 = \frac{J_{C4} \dot{\varphi}_{41} + M_{R1}}{l_4 (\cos \varphi_{41} + k_\varphi \sin \varphi_{41})}$$

(1)

where $J_{C4}$ — central moment of inertia of the foot; $l_4 = l/2$; $l$ — ski-shaped foot length; $\varphi_{41}$ — tilt angle of the 1-st foot; $k_\varphi$ — adhesion coefficient.

At the third stage (figure 5 (b)), which is an additional phase of the cycle, the support reaction of the 1-st foot becomes larger than the second ($N_1 > N_2$). The first foot carries the bigger part of the machine's weight. The second support comes off the ground, taking part of the load at the beginning of the stage, while contacting the ground with the toe of the foot. At this stage, due to the support moment $M_{R1}$, a shockless installation of the foot with the entire supporting surface on the ground is ensured. The smooth movement of the foot in this area allows you to neglect the dynamism of the process, then, when determining the support reactions, you can use the following equations of statics:

$$N_1 + N_2 = G_j,$$

$$N_2 = \frac{M_{R2}(\mu, \Delta \omega_{42})}{l_4 (\cos \varphi_{42} + k_\varphi \sin \varphi_{42})}$$

(2)

where $G_j$ — weight of the $j$-th mover; $\varphi_{42}$ — tilt angle of 2-nd foot.

Supporting moment of the second foot $M_{R2}(\mu, \Delta \omega_{42})$ at the third stage, it is determined by the relative movement of the support link in relation to the foot. An additional phase of the cycle, where the machine rests on the ground only on the heels of the feet of in-phase walking mechanisms, delays in time when the feet change, the body “sagging” due to the imperfection of the trajectory of the reference point of the walking mechanisms. This gives the paired foot time to bypass the worst point of the trajectory from the point of view of vertical body vibrations and allows to reduce their amplitude and energy consumption for their maintenance. Moreover, the work of the damper in this mode is carried out at the expense of the energy, irretrievably lost in the basic mechanism of walking.

At the final stage of changing the feet, the 1-st foot is lowered by the entire supporting surface to the ground and perceives the entire side weight of the machine, and the 2-nd has come off the ground and is in the transfer stage. After that, the cycle is repeated.

When driving on an unorganized surface, the additional damper will obviously have a cushioning effect when it encounters an obstacle. In this case, the behavior of the foot will differ from the “programmed” one. The damper begins to work already at the stage of foot transfer - from the moment the toe of the articulated foot contacts the obstacle and the relative angular velocity $\Delta \omega_{34}'$ appears. Then, in the second stage, the heel of the foot is connected to the braking - it will slide along the ground in the direction of the car. This ensures the shockless interaction of the foot with the obstacle. At this stage, the braking intensity can be increased by increasing the viscous friction coefficient $\mu$ in the damper.

4. Conclusion

The introduction of an additional damping device (analogue of a shock absorber) into the cyclic walking mechanism, which provides a dissipative connection of the ski-shaped foot with the support link, expands the mover's capabilities for self-adaptation to an unorganized surface and leads to a decrease in the intensity of vibroimpact processes when changing feet and when meeting an obstacle. The decrease occurs due to a smoother change in the support reactions when stepping over. There is
also a decrease in energy consumption for movement due to a decrease in the amplitude of vertical vibrations of the body. Moreover, the work of the damper is carried out due to the energy that is irretrievably lost in the basic mechanism of walking.

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