Dynamics of Machines for the Development of Hard-To-Reach Regions of the World

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Abstract: Rotary screw machine (or a machine on the screw) has been widely used in Russia in 1960-1970. In contrast to vehicles equipped with conventional types of propulsion, the dynamics of screw machines is poor. The uniqueness of the calculation of screw machines in the geometric linear movement of the screw

1 INTRODUCCIÓN

Previous screw-propelled vehicles were designed and built with a rigid or semirigid suspension system. Within the framework of the investigation the design of a screw-propelled vehicle has been proposed with a novel visco-elastic suspension capable of decreasing the dynamic loads on the vehicle's body, which arise due to the unbalance of the screw rotors and the bearing surface.

The author's investigations in this direction have been carried out since 1996 resulting in the articles (Kuklina, 2011; Kuklina, 2013); for the last 20 years the mathematical theories obtained have been improved and put into practice.

2 SCREW GEOMETRY

Analysis of displacements of the screw-propelled vehicle permits one to obtain the scheme of interaction between the vehicle and the environment. Mathematical model displays a geometric line depending on the work front and rear suspensions. This effect is unique only for vehicles with rotor propulsion devices. The linearity of the contact of the bearing surface and the rotors is shown in Fig. 1. (Geometric parameters of the propulsion device of the screw-propelled vehicle when overcoming an obstacle.)

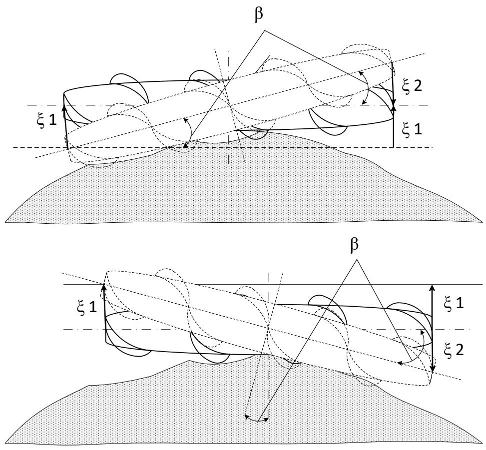

Figure 1: The geometric dependence of the rotor's parameters.

The vertical forces arising from irregularities of the pathway are transmitted to the vehicle's body only through springing elements and dampers, as shown in Fig. 2 (three-mass equivalent system of dynamics of the screw-propelled vehicle).

The coordinates describing the position of the sprung and unsprung masses undervibration conditions are chosen depending on the problem under consideration.Whenstudying the vibrations of the vehicle's body, it is appropriate to choose coordinates $Z_0, \varphi, X_0, \alpha, Y_0, \beta$ i.e., the displacements

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of the center of gravity of the sprung partand the angles of its rotation. It is also necessary to consider:

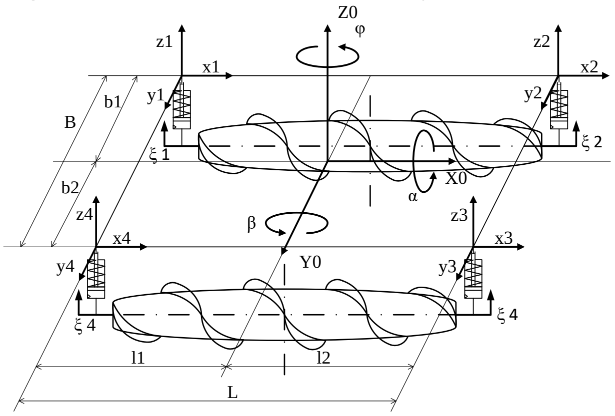

Figure 2: The three-mass vibration system of a screw-propelled vehicle.

- z_1, z_2, z_3, z_4 - the coordinates of displacement of the body's points above the axis of the front or back mountings of the rotor propulsion devices
- x_1, x_2, x_3, x_4 - the coordinates of horizontal lengthwise displacements of the body's points of the front or back mountings of the rotor propulsion devices
- y_1, y_2, y_3, y_4 - the coordinates of horizontal lateral displacements of the body's points of the front or back mountings of the rotor propulsion devices

Investigating the vibration system shown in Fig. 2, we infer the dependencies between the parallel displacement vectors $\vec{z}_1, \vec{z}_2, \vec{z}_3, \vec{z}_4$ and the system's resultant – $\vec{Z}_0$ Fig. 3:

$$Z_0 = \frac{\sum_i l_i z_i}{\sum_i l_i} \tag{1}$$

Using the above-mentioned formula, we obtain the system of dependencies between the geometric parameters of the sprung mass of the vehicle:

$$\left.\begin{aligned} \vec{Z}_0 &= \tfrac{1}{2L}[(\vec{z}_2 l_2 - \vec{z}_1 l_1) + (\vec{z}_3 l_2 - \vec{z}_4 l_1)] \\ \varphi &= \tfrac{1}{B}[(\vec{x}_4 - \vec{x}_1) + (\vec{x}_3 - \vec{x}_2)] + \tfrac{1}{L}[(\vec{y}_1 - \vec{y}_2) + (\vec{y}_4 - \vec{y}_3)] \\ \vec{X}_0 &= \tfrac{1}{B}[(\vec{x}_4 b_2 - \vec{x}_1 b_1) + (\vec{x}_3 b_2 - \vec{x}_2 b_1)] \\ \alpha &= \tfrac{1}{B}[(\vec{z}_1 - \vec{z}_4) + (\vec{z}_2 - \vec{z}_3)] \\ \vec{Y}_0 &= \tfrac{1}{L}[(\vec{y}_1 l_1 - \vec{y}_2 l_2) + (\vec{y}_4 l_1 - \vec{y}_3 l_2)] \\ \beta &= \tfrac{1}{L}[(\vec{z}_2 - \vec{z}_1) + (\vec{z}_3 - \vec{z}_4)] \end{aligned}\right\} \tag{2}$$

The vibrations of the unsprung masses of the vehicle (rotors) are given by the elements of displacements$\vec{\xi}_1, \vec{\xi}_2, \vec{\xi}_3, \vec{\xi}_4$.

The uniqueness of this vibration system isthat the displacements of the end points of the rotors are linearly dependent between themselves. During the collision with an obstacle, not only the front suspension is actuated but also the force is transmitted to the back suspension by the rotor's body, therefore, the quantities $\vec{\xi}_2, \vec{\xi}_3$ influence the quantities of displacements$\vec{\xi}_1, \vec{\xi}_4$ Fig. 2.

The linear dependence of displacements of the end points of the rotors is represented in the system of equations 3.

$$\left.\begin{aligned} \xi_1 &= \sin\beta \cdot L - \xi_2 \\ \xi_4 &= \sin\beta \cdot L - \xi_3 \end{aligned}\right\} \left.\begin{aligned} \vec{\xi}_2 &= \sin\beta \cdot L - \vec{\xi}_1 \\ \vec{\xi}_3 &= \sin\beta \cdot L - \vec{\xi}_4 \end{aligned}\right\} \tag{3}$$

To derive the dynamical equations, one should apply the forcesZ_n, X_n, Y_nacting on the masses of the vehicle (Fig. 2). The force$Z_n$transmitted through the suspension consists of two terms: Z_p - from the springing element andZ_a - from the damper. The forces Z_n, X_n *and* Y_n replace the action of the suspension and their quantities are interdependent.

We obtain the system of equations 4 describing the dependencies of dynamic forces.

$$\left.\begin{aligned} &Z_{n1} = 2C_{p1}(z_1 - \xi_1) + 2k_1(\dot{z}_1 - \dot{\xi}_1);\quad Z_{n2} = 2C_{p2}(z_2 - \xi_2) + 2k_2(\dot{z}_2 - \dot{\xi}_2); \\ &Z_{n3} = 2C_{p3}(z_3 - \xi_3) + 2k_1(\dot{z}_3 - \dot{\xi}_3);\quad Z_{n2} = 2C_{p3}(z_3 - \xi_3) + 2k_3(\dot{z}_3 - \dot{\xi}_3); \\ &X_{n1} = Z_{n1}\tan\beta;\ X_{n2} = Z_{n2}\tan\beta;\ Y_{n1} = Z_{n1}\tan\alpha;\ Y_{n2} = Z_{n2}\tan\alpha; \\ &X_{n3} = Z_{n3}\tan\beta;\ X_{n4} = Z_{n4}\tan\beta;\ Y_{n3} = Z_{n3}\tan\alpha;\ Y_{n4} = Z_{n4}\tan\alpha. \end{aligned}\right\} \tag{4}$$

3 DIFFERENTIAL EQUATION OF OSCILLATIONS

Differential equations of vibrations are obtained by using Lagrange's equations.

For sprung and unsprung masses M and $m_{1,2}$ the following systems of equations ofequilibrium are derived.

$$\left.\begin{aligned} &(m\ddot{\xi}_1 - 2C_{p1}[z_1 - \xi_1] - 2k_1[\dot{z}_1 - \dot{\xi}_1]) + \\ &+(m\ddot{\xi}_2 - 2C_{p2}[z_2 - \xi_2] - 2k_2[\dot{z}_2 - \dot{\xi}_2]) = H_z(t); \\ &(m\ddot{\xi}_4 - 2C_{p4}[z_4 - \xi_4] - 2k_4[\dot{z}_4 - \dot{\xi}_4]) + \\ &+(m\ddot{\xi}_3 - 2C_{p3}[z_3 - \xi_3] - 2k_3[\dot{z}_3 - \dot{\xi}_3]) = H_z(t) \end{aligned}\right\} \tag{5}$$

The equations of motion for the coordinate systems (Figs. 1 and 2) are derivedusing the formulas of the systems 3 and 4 and the expressions for$Z_n$which are written in terms of the coordinatesz_1, z_2, z_3, z_4.

After substitution of theseexpressions into the differential equations of equilibrium we obtain the systems of differential equations 5 and 6 which represent the most complete and accuratecalculation of (linear and angular) displacements of points of the sprung and unsprungmasses of the screw-propelled vehicle.

$$\left.\begin{gathered}
M\ddot{Z}_0 + \left(2k_1\left[\dot{z}_1 - \dot{\xi}_1\right] + 2C_{p1}[z_1 - \xi_1]\right) + \\
\left(2k_2\left[\dot{z}_2 - \dot{\xi}_2\right] + 2C_{p2}[z_2 - \xi_2]\right) + \left(2k_3\left[\dot{z}_3 - \dot{\xi}_3\right] + 2C_{p3}[z_3 - \xi_3]\right) + \\
+\left(2k_4\left[\dot{z}_4 - \dot{\xi}_4\right] + 2C_{p4}[z_4 - \xi_4]\right) = H_z(t); \\
M\ddot{X}_0 + \tan\beta\left(2k_1\left[\dot{z}_1 - \dot{\xi}_1\right] + 2C_{p1}[z_1 - \xi_1]\right) + \\
+\tan\beta\left(2k_2\left[\dot{z}_2 - \dot{\xi}_2\right] + 2C_{p2}[z_2 - \xi_2]\right) + \\
+\tan\beta\left(2k_3\left[\dot{z}_3 - \dot{\xi}_3\right] + 2C_{p3}[z_3 - \xi_3]\right) + \\
+\tan\beta\left(2k_4\left[\dot{z}_4 - \dot{\xi}_4\right] + 2C_{p4}[z_4 - \xi_4]\right) = H_x(t); \\
M\ddot{Y}_0 + \tan\alpha\left(2k_1\left[\dot{z}_1 - \dot{\xi}_1\right] + 2C_{p1}[z_1 - \xi_1]\right) + \\
+\tan\alpha\left(2k_2\left[\dot{z}_2 - \dot{\xi}_2\right] + 2C_{p2}[z_2 - \xi_2]\right) + \\
+\tan\alpha\left(2k_3\left[\dot{z}_3 - \dot{\xi}_3\right] + 2C_{p3}[z_3 - \xi_3]\right) + \\
+\tan\alpha\left(2k_4\left[\dot{z}_4 - \dot{\xi}_4\right] + 2C_{p4}[z_4 - \xi_4]\right) = H_y(t); \\
M\rho_z^2\ddot{\varphi} + \begin{pmatrix} 2C_{p4}b_2[z_4 - \xi_4] + 2k_4b_2\left[\dot{z}_4 - \dot{\xi}_4\right] + \\ +2C_{p3}b_2[z_3 - \xi_3] + 2k_3b_2\left[\dot{z}_3 - \dot{\xi}_3\right] - \\ -2C_{p1}b_1[z_1 - \xi_1] - 2k_1b_1\left[\dot{z}_1 - \dot{\xi}_1\right] - \\ -2C_{p2}b_1[z_2 - \xi_2] - 2k_2b_1\left[\dot{z}_2 - \dot{\xi}_2\right] \end{pmatrix}\tan\beta + \\
+\begin{pmatrix} 2C_{p1}l_1[z_1 - \xi_1] + 2k_1l_1\left[\dot{z}_1 - \dot{\xi}_1\right] + \\ +2C_{p4}l_1[z_4 - \xi_4] + 2k_4l_1\left[\dot{z}_4 - \dot{\xi}_4\right] - \\ -2C_{p2}l_2[z_2 - \xi_2] - 2k_2l_2\left[\dot{z}_2 - \dot{\xi}_2\right] - \\ -2C_{p3}l_2[z_3 - \xi_3] - 2k_3l_2\left[\dot{z}_3 - \dot{\xi}_3\right] \end{pmatrix}\tan\alpha = M_\varphi(t) \\
M\rho_z^2\ddot{\alpha} + 2C_{p1}b_1[z_1 - \xi_1] + 2k_1b_1\left[\dot{z}_1 - \dot{\xi}_1\right] + 2C_{p2}b_1[z_2 - \xi_2] + \\
+2k_2b_1\left[\dot{z}_2 - \dot{\xi}_2\right] - 2C_{p4}b_2[z_4 - \xi_4] - 2k_4b_2\left[\dot{z}_4 - \dot{\xi}_4\right] - \\
-2C_{p3}b_2[z_3 - \xi_3] - 2k_3b_2\left[\dot{z}_3 - \dot{\xi}_3\right] = M_\alpha(t) \\
M\rho_z^2\ddot{\beta} + 2C_{p1}l_1[z_1 - \xi_1] + 2k_1l_1\left[\dot{z}_1 - \dot{\xi}_1\right] + 2C_{p4}l_1[z_4 - \xi_4] + \\
+2k_4l_1\left[\dot{z}_4 - \dot{\xi}_4\right] - 2C_{p2}l_2[z_2 - \xi_2] - 2k_2l_2\left[\dot{z}_2 - \dot{\xi}_2\right] - \\
-2C_{p3}l_2[z_3 - \xi_3] - 2k_3l_2\left[\dot{z}_3 - \dot{\xi}_3\right] = M_\beta(t)
\end{gathered}\right\} \qquad (6)$$

The system of equations 6 shows the calculation of forces and describes thedynamics of the actuated mechanisms of visco-elastic suspensions. The forces horizontal to$X$and$Y$, are then reduced to the vertical forces via trigonometryequations Z.

The solution to the systems of equations 5 and 6 by numerical methods becomes possible if we know the values of the vibrations, i.e., if the boundary values of the quantities$z_1, z_2, z_3, z_4, Z_0, X_0, Y_0, \varphi$, α, β, $\xi_1, \xi_2, \xi_3, \xi_4$.

Have been obtainedexperimentally, the vehicle's parameters ($L$and$B$), have been specified in advance, and one should determine the drag coefficients of the dampers k_1, k_2, k_3, k_4 andthe spring rate for the elements$C_{p1}, C_{p2}, C_{p3}, C_{p4}$. Having an exact solution to the system of equations 6, we can find numericallyC_p.

Assuming that the screw-propelled vehicle is geometrically symmetric and thecharacteristics of the visco-elastic suspension are completely of the same type, performing mathematical operations permits us to reduce the system of equations 5and 6 to the form of the systems of differential equations 7 and 8.

Thus, the generalized systems of differential equationstake the form for the unsprung masses:

$$\left.\begin{gathered}
m(2\ddot{\xi}_1 + \sin\beta/L) + 2k(2\dot{\xi}_1 - (\dot{z}_1 + \dot{z}_2) + \sin\beta/L) + \\
+2C_p(2\xi_1 - (z_1 + z_2) + \sin\beta/L) = H_z(t); \\
m\left(2\ddot{\xi}_4 + \sin\beta/L\right) + 2k(2\dot{\xi}_4 - (\dot{z}_4 + \dot{z}_3) + \sin\beta/L) + \\
+2C_p(\xi_4 - (z_4 + z_3) + \sin\beta/L) = H_z(t).
\end{gathered}\right\} \qquad (7)$$

And for the sprung body of the vehicle:

$$\left.\begin{aligned}
&M\ddot{Z}_0 + 2k(\dot{z}_1 + \dot{z}_2 + \dot{z}_3 + \dot{z}_4) - 2k(\dot{\xi}_1 + \dot{\xi}_2 + \dot{\xi}_3 + \dot{\xi}_4) + \\
&+2C_p(z_1 + z_2 + z_3 + z_4) - 2C_p(\xi_1 + \xi_2 + \xi_3 + \xi_4) = H_z(t); \\
&M\rho_z^2\ddot{\alpha} + 2C_p b(z_1 + z_2 - z_4 - z_3) - 2C_p b(\xi_1 + \xi_2 - \xi_4 - \xi_3) + \\
&+2kb(\dot{z}_1 + \dot{z}_2 - \dot{z}_4 - \dot{z}_3) - 2kb(\dot{\xi}_1 + \dot{\xi}_2 - \dot{\xi}_4 - \dot{\xi}_3) = M_\alpha(t) \\
&M\rho_z^2\ddot{\beta} + 2C_p l(z_1 + z_4 - z_2 - z_3) - 2C_p l(\xi_1 + \xi_4 - \xi_2 - \xi_3) + \\
&+2kl(\dot{z}_1 + \dot{z}_4 - \dot{z}_2 - \dot{z}_3) - 2kl(\dot{\xi}_1 + \dot{\xi}_4 - \dot{\xi}_2 - \dot{\xi}_3) = M_\beta(t)
\end{aligned}\right\} \qquad (8)$$

Evaluation of solutions to the systems of differential equations was performedusing the software for modern mathematical calculations MathCAD in solving theCauchy problem. The result of the solution was the amplitude-frequency characteristicof the visco-elastic suspension.

The amplitude-frequency characteristics are shown in Fig. 3 (amplitude-frequencycharacteristics at point 2 of attachment of the visco-elastic suspension and the rotorpropulsion devices for various values of the spring rates and drag coefficients ofdampers).

The analysis and construction of many amplitude-frequency characteristics willallow theorists and practitioners to choose the best values for the spring rates anddrag coefficients of dampers. Depending on the requirements, one can manipulate theparameters of the visco-elastic suspension and specify the comfort characteristics ofthe driver's operation.

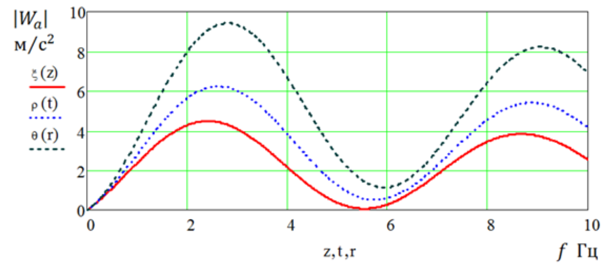

Figure 3: The amplitude-frequency characteristic for the visco-elastic suspension of the screw–propelled vehicle.

4 MACHINE DESIGN SOLUTIONS

To ensure the best possible contact between the propulsion devices and thebearing surface, a new design of the screw-propelled vehicle (Fig. 4) is developedwithin the framework of this study. This design comprises a body (1), a rotorpropulsion device (5), a visco-elastic suspension (12) of rotors with springs anddampers, wherein the dampers (13) and springs (14) of the visco-elastic suspensionare aligned and rigidly attached to the vehicle's frame and coupling elements (15) installed on a fixed spindle (6) bearing electric motors (7) and harmonic driveunits (8), the latter are rigidly connected with the rotor (5) through the bushes (9) towhich trapezoidal roddings (11, 16) hinged to the frame (10) elements are attached.

This vehicle has not two but four rotor propulsion devices, which, by virtue ofthe visco-elastic suspension, provide the greatest tractive force due to an increasedcontact point between the rotors and the bearing surface.

For the purpose of increasing the vehicle's vibroprotection and the comfort ofthe driver, quite a number of design concepts for hydraulic vibratory bearings (Gordeev, Kuklina, 2023; Kuklina, 2022) have been proposed. Evaluation of the quantities of vibration displacements of rotorpropulsion devices in the bearings by the method of measurement without contactbecomes possible through the application of an ultrasonic phase vibrationtransducer (Gordeev, Kuklina, 2020). The design concept was awarded the bronze medal in Seoul.

Thus, significant practical and theoretical experience has been gained ininvestigating and adjusting the parameters of the visco-elastic suspension of vehicleshaving a linear contact between the propulsion devices and the bearing surface.

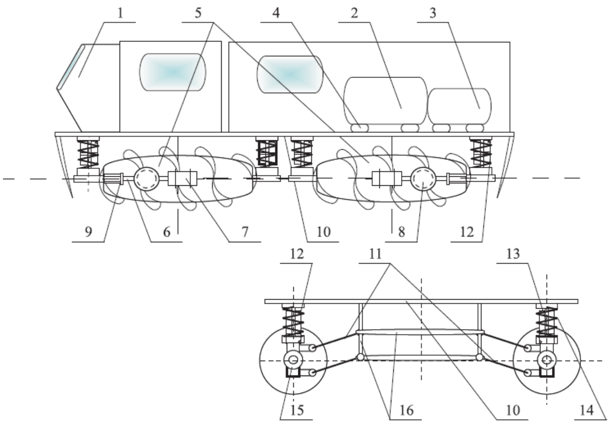

Figure 4: The design of the screw-propelled vehicle with four propulsion devices.

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