Modelling of vehicles with rotary-screw propulsion unit along water-flooded substructure

A Strizhak¹, U Vakhidov, A Lipin, R Dorofeev, A V Sogin and L S Mazunova

¹Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Minin st., 24, 603950, Nizhny Novgorod, Russia

E-mail: ¹ strizh-ark@yandex.ru

Abstract. Modelling results of motion of vehicles equipped with a rotary-screw propulsion unit along swamps, swampy ground and beds are given in this article. One of the efficiency criteria of using this type of cross-country vehicles is their maximum speed. The calculation methods and motion modelling results are presented depending on the screw blade pitch angle. For all cases of motion along the substructure with humidity over 40%, the maximum speed value is reached at the screw line pitch angle of 60°. At this the screw blade pitch angle variation allows to 2-3 times vary the maximum speed value.

Nowadays Arctic Regions, Siberia and the Far East of Russia are not equally developed in terms of transport. Under conditions of transport network dispersion, absence of ground transport communication between some territories, the primary task of transport development is to create a uniform ground transport infrastructure. One of the ways of this task realization is to adequately provide underpopulated territories with reliable high performance cross-country vehicles. At present in many countries the work is underway to create new transport and technological vehicles and mobile robotic systems. As soon as swamp areas occupy approximately 10% of Russian territory, one of the key priorities in this field is research, devoted to improve cross-country vehicles trafficability, i.e. their ability to move non-stop and efficiently over different types of ground and a river bed [1-3].

Under these conditions, to ensure normal economic activity and to solve defence problems special attention is paid to all-terrain cross-country vehicles, the ones equipped with rotary-screw propulsion units occupying a special place in this range.

Currently a steady trend is observed in modelling rotary-screw vehicles motion using generic mathematical models of motion in conditions of steady motion, acceleration, breaking and steering modes [4].

However to find only a rectilinear uniform speed it is necessary to accomplish a great number of calculations with exponential motive force dependences approximation to conceive and solve basic differential equation as a trinomial with lengthy coefficients, being parameter functions of mechanical characteristics of the ground, propulsion unit construction and its load mode (external forces). The general purpose of research presented in this chapter is to form the plane-parallel motion pattern of rotary-screw vehicles and to obtain calculated dependences for selecting their design and operation parameters. When modelling the motion the following assumptions are made:
- all TTV rotors move over the grounds of the same characteristics;
- rotors speed is synchronized at the same rate;
- load on screws is distributed equally.

It should be noted that these assumptions are possible as being applied to rectilinear motion modelling. Consequently, in this case we consider that values of the vehicle basic travel time parameters equal the respective values of individual rotor engines. It is noteworthy that if even one of these assumptions is not observed, a turning moment will appear which, in its turn, will lead to TTV turnover maneuver.

It is worth pointing out that swampy ground modelling is a time-consuming task as far as the medium concerned has a heterogeneous structure. For this reason, when developing a computer model averaged parameters were taken according to SNiP 2.02.01-83 [5].

With the help of computer-aided-design system – SolidWorks – RSPU geometrical parameters (Figure 1) impact on speed parameters of rotary-screw propulsion unit at the transport and technological vehicle rectilinear uniform motion with the possibility to discreetly change the screw blade pitch angle (φₜₙ) has been researched. In the process of modelling the pitch angle (φₜₙ) was being changed continuously within the range of 3° to 60° at a pitch of 3°.

![Figure 1. Rotary-screw propulsion unit basic parameters](image_url)

The following parameters of vehicles with rotary-screw propulsion unit and the propulsion unit itself are used in the expressions given in this paper (see. Fig. 1) [6].

Rotary-screw propulsion unit has the following dimensions: 
- \( r_0 = 0.5d_0 \) – rotor base cylinder radius and diameter (m);
- \( L_{ Bíl } \) – rotor base cylinder length (m);
- \( L_p \) – rotor total length (m);
- \( h_3 \) – blade screw blade height (m);
- \( \varphi_A \) – screw blade angle of ascent at its root (rad);
- \( r_H = 0.5d_H \) – rotor nose radius and diameter (m);
- \( t_B \) – screw blade thickness (m);
- \( T \) – screw blade pitch (m);
- \( n_A \) – number of blades;
- \( x_C, y_C, z_C \) – center of mass coordinates of a vehicle with a rotary-screw propulsion unit. Parameters of the vehicle with rotary-screw propulsion unit are the following: 
- \( m \) – vehicle with RSPU mass (kg);
- \( G \) – weight (adhesive weight, H);
- \( m_t \) – rotor mass (kg);
- \( J_x \) – rotary screw vehicle (RSV) inertia moment about axis \( O_x \) of intrinsic (connected) frame of reference;
- \( J_y \) – RSV inertia moment about axis \( O_y \) of intrinsic frame of reference;
- \( J_z \) – RSV inertia moment about axis \( O_z \) of intrinsic frame of reference.

To find the maximum traction it is necessary to determine rotor angle of contact \( A \) by the snow and rotor immersion depth \( z_K \).

Determining rotor immersion depth \( z_K \) was carried out by numerical iteration method (stepwise approximation to the required value). The principle of the method is the following. At the first step intentionally little rotor immersion depth into the substructure with the known physical and mechanical parameters is taken. Next, the substructure reaction at the lowest point under rotor is calculated, after that the overall reaction is determined according to the known consistent patterns. At the next
step of calculations the substructure reaction obtained is compared to the vehicle gravity falling on the rotor. If the snow reaction to the rotor is less than gravity, depth of immersion is increased by a small value (pitch) and the calculation is repeated. This continues until the substructure reaction equals gravity. In this case the rotor immersion depth is obtained and the maximum resistance force is calculated.

Motion resistance of the vehicle with a rotary-screw propulsion unit is found by expression

\[ F_f = F_K + F_T1 + F_T2 \]

Force of resistance to rutting \( F_K \) was determined for two cases. At less than a quarter of diameter of rotor immersion, N.F. Kosharny’s expression [7] was used where the front part of the rotor is not taken into account

\[ F_K = QZ \frac{z_k}{L_{BI}} \cdot f_K = \frac{z_k}{L_{BI} (\mu + 1.25)}, \]

\[ QZ = 0.5C(B)L_{BI} J_2 r_0 \frac{0.75 \mu + 0.25 \cos \Phi}{z_k}, \quad J_2 = 1.55 + 1.8 \sqrt{2 - \mu} \]

If the immersion into the snow did not exceed a quarter of rotors diameter, A.P. Kulyashov’s expression for the rotor cone nose piece was used [8]

\[ F_K = 2C(B) \int \varphi(\alpha) d\alpha \quad \left[ \begin{array}{l} \varphi(\alpha) = z_k^{\mu+1} \left| z_k(\mu + 1) + a(\mu + 2) \right| - a^{\mu+2} (\sec \alpha - 1) \frac{\mu+1}{(\mu+1)(\mu + 2)} \right] \]

Range component of base cylinder sliding frictional force \( F_{T1} \) according to N.F. Kosharny’s works [7] is the following

\[ F_{T1} = L_{BI} \sqrt{d_0 z_k} \frac{i_k}{\sqrt{1 + i_k^2}} \left[ \frac{C(B) \tan \Phi J_1 z_k^\mu + 2q}{z_k \leq 0.25r_0} \right] \]

\[ F_{T1} = L_{BI} r_0^{3/4} \frac{z_k^{1/2}}{\sqrt{1 + i_k^2}} \left[ \frac{C(B) \tan \Phi J_2 z_k^\mu + 4q}{z_k > 0.25r_0} \right] \]

\[ J_1 = 2 - 0.66 \sqrt{\mu}, \quad J_2 = 1.55 + 1.8 \sqrt{2 - \mu}, \quad i_k = \frac{\dot{x}}{r_0 \omega}, \]

where \( i_k \) – rotary-screw propulsion unit kinematic number, \( r_0 \) – radius of rotary-screw propulsion unit base cylinder, \( \varphi_3 \) – screw blade pitch angle.

Longitudinal component of screw blades sliding frictional force \( F_{T2} \) according to N.F. Kosharny’s works [7] is the following

\[ F_{T2} = F_{\varphi} \tan \Phi \sin \varphi_3 + \frac{3}{2} \tan \varphi_3 r_0^{1/3} z_k^{2/3} h_3 n_3 q \]

Rotor lateral displacement resistance forces and resistance forces of rotors sidewise rolling movement along the snow, according to the work [9,10,11] are written respectively

\[ F_{\theta} = F_{\theta \max} \left( 1 - e^{-\frac{\lambda_s}{s_{\max}}} \right) F_{\lambda \alpha \alpha} = QZ \frac{z_k^{\mu+1}}{C_{cu} (\mu + 1)} \left( 1 + \kappa_6 s \frac{n_6}{r_0} \right) \]

\[ QZ = 0.5C(B)L_{BI} J_2 r_0 \frac{0.75 \mu + 0.25 \cos \Phi}{z_k} \]
where $F_{\max}$, $s_{\max}$ – shear resistance maximum value and the respective shear; $S$ – shear current value; $\lambda$ – parameter, characterizing the shear process and depending on properties and volume of the sheared snow, $k_{\delta}$ – coefficient, taking into account rotor immersion increase into the snow $z_{\kappa}$ at skidding, $n_{\delta}$ – coefficient, taking into account nonlinearity increase $z_{\kappa}$ at skidding.

Results of computational modelling of the angle change are shown in table 1 and in Figure 2.

**Table 1** Blade height change (h) in relation to blade angle change ($\varphi_{\lambda}$).

| Angle of pitch ($\varphi_{\lambda}$) degrees | 3  | 6  | 9  | 12 | 15 | 18 | 21 | 24 | 27 | 30 |
|-------------------------------------------|----|----|----|----|----|----|----|----|----|----|
| Blade height h, mm                        | 231| 230| 228| 226| 223| 220| 216| 211| 206| 200|
| Pitch angle ($\varphi_{\lambda}$) degrees | 33 | 36 | 39 | 42 | 45 | 48 | 51 | 54 | 57 | 60 |
| Blade height h, mm                        | 194| 187| 179| 172| 163| 155| 145| 136| 126| 115|

Basing on the results of mathematical modelling, computational modelling was carried out, as a result of which speed values at TTV with RSPU motion at different blade pitch angles have been obtained. These results prove that within the screw blade winding angles range of 12 to 45 degrees, motion of vehicles with rotary-screw propulsion units have stable characteristics. Reduction of winding angle by less than 10 degrees results in the vehicle’s sharp speed drop, and increase by more than 45 degrees results in a simultaneous speed and resistance increase. When the peak value of the screw blade pitch angle is reached, the vehicle stops because the resistance force of motion exceeds the motive force. This can happen at any moment due to the substructure physical and mechanical properties change. It means that regardless of the speed increase, this mode is not stable, which makes the guaranteed vehicle operation with the above-mentioned screw blade parameters impossible in the whole range of water-flooded substructures.

This work is one of the recent studies of Nizhny Novgorod Scientific School of Cross-country Vehicles and Scientific School of Bauman Moscow State Technical University [12-17].

**Figure 2.** Graph of RSPU speed dependence on the blade pitch angle for swampy ground

**Conclusion**

A model of vehicles with rotary-screw propulsion units rectilinear motion in swamps, swampy ground and beds has been developed. Calculated analysis of rotary-screw transport and technological vehicle rectilinear motion has shown that at the blade pitch angle change of up to 60° (compared with base
pitch angle of 30°) the maximum speed increases 2 – 3 times, but operation conditions stability worsens (probability of loss of mobility increases at the substructure physical and mechanical properties change).

References

[1] Makarov V, Zeziulin D and Belyakov V 2014 Prediction of all-terrain vehicles mobility in snowscape scenes 18th International Conference of the International Society for Terrain-Vehicle Systems, ISTVS 2014 Code 111443

[2] Belyakov V, Kurkin A, Makarov V and Zeziulin D 2015 Multifunctional vehicle for coastal areas The Twelfth International Conference on the Mediterranean Coastal Environment (MED-CAOST 2015) 945-951

[3] Belyakov V, Kurkin A, Makarov V, Zeziulin D, Minaev D, Zaytsev A and Teslenko D 2017 Ground vehicle for ice conditions monitoring Proceedings of the Thirteenth International MEDCAOST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation, MEDCOAST 2017 775-785

[4] Donato I O, Zhuk V A and Kuznetsov B V 2000 Rotary-screw vehicles. Fundamentals of motion theory N. Novgorod: TALAN 451

[5] SNiP 2.02.01-83 Footing of buildings and constructions

[6] Shapkin V A 2001 Fundamentals of vehicles with rotary-screw propulsion units movement along snowscape areas Doctoral thesis in Engineering Science. N. Novgorod

[7] Kosharny N F 1981 Technological and performance characteristics of cross-country vehicles Kiev: Visheish.shk 208

[8] Kulyashov A P 1986 Special road-building machines with a rotary-screw propulsion unit Doctor of Engineering Science thesis. Gorky 327

[9] Naumov V N, Mashkov K Y and Bakov K E 2011 Modelling a rectilinear motion of a transport and technological vehicle with a rotary-screw propulsion unit Bauman MSTU Vestnik. Ser. Mashinostroenie 31–35

[10] Sherbakov Y V 2000 Developing calculation methods and selecting rational parameters of motion of underwater transport and technological vehicle with rotary-screw propulsion unit Ph.D. thesis in Engineering Science, N. Novgorod, NSTU 167

[11] Cole B N 1961 Inquiry into amphibious screw traction Proceedings of the Institution of Mechanical Engineers 19 (175) 919-940

[12] Krasheninnikov M., Kulashov A., Shapkin V., Koshurina A. The concept and methodology of creating the universal life-saver with rotary-screw mover // Lecture Notes in Electrical Engineering. 2013. – T. 195 LNEE. – № VOL. 7 «Proceedings of the FISITA 2012 World Automotive Congress».

[13] Krasheninnikov M, Koshurina A, Vasilyev I and Smirnova E 2015 Use mobile robots groups for rescue missions in extreme climatic conditions Procedia Engineering 100 1242–1246 doi: 10.1016/j.proeng.2015.01.489

[14] Koroshova J V, Krasheninnikov M S, Koshurina A A and Lyakhmanov D A 2018 Multifunctional mobile complex of transport-technological machines for the Arctic IOP Conf. Ser.: Mater. Sci. Eng. 393 012119

[15] Erasov I A, Molev Yu I, Mokerov D S, Shetulova T G 2018 Determining friction coefficient between the base cylinder of rotary screw propulsion unit and various ice types in different daylight surface IOP Conference Series: Materials Science and Engineering 386 012006

[16] Tyugin D, Zeziulin D, Kurkin A, Belyakov V and Makarov V 2018 Development of a mobile robot group for coastal monitoring IOP Conference Series: Materials Science and Engineering 386 012009

[17] Papunin A, Belyakov V, Makarov V, Anikin A and Vahidov U 2018 A dynamic model of unsupported pit traversal by a vehicle with 6×6 wheel arrangement IOP Conference Series: Materials Science and Engineering 386 012001