Comparative study of impression and cutting into ice by helical blade

U Sh Vakhidov¹, I A Yerasov¹, Y I Molev¹,³ and D S Mokerov²

¹Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Minin st., 24, 603950, Nizhny Novgorod, Russia.
²Nizhny Novgorod State Pedagogical University n.a. K. Minin, Uyanova str., 1, 603950, Nizhny Novgorod, Russia
E-mail: ³moleff@yandex.ru

Abstract The paper presents the results of energy efficiency studies of helical blade penetration types into ice. There are two principally different ways of helical groove generation in ice – by cutting and impression. It was found out that at a longer duration of the penetration process of the helical blade with a smaller lead angle the energy demand of the propulsion gets lower due to impression. At blade penetration by cutting, there is an extremum at the angle of cutting of 40-45°, however, the energy demand in such condition is still higher than that of the penetration by impression. Considerable attention is paid in the paper to the measurement of the noise generation during the interaction with the penetrated surface which allows for prompt assessment of the energy efficiency of the considered parameter. The obtained results allow for efficiency improvement of the operation of vehicles with rotary screw propulsion units in real environments, as well as for their increased reliability due to new diagnostics methods.

1. Introduction
One of the most promising development ways of the Russian Federation is currently associated with the exploration of the Arctics which is scarcely possible without construction of appropriate infrastructure, transportation, communications. Thereby, ensuring safety of passengers and cargo transportation at low temperatures, as well as of ensuring the environmental safety of interventions into a vulnerable ecological system is a vital scientific mission. The simplest way to solve the described problem were to use water basin surfaces (also frozen), since this is the only method with the smallest possible environmental impacts produced by transportation vehicles. However, the development of the transportation system in this direction is impeded by problems with ensuring the safety of this process associated with machinery operation at low temperatures, dynamically changing ice conditions (also, occurrence of rain channels where vehicles could fall into), wind loads, icing, prolonged dark periods, remote location of the closest settlements. It means that consequences of emergencies in the Arctics can rapidly take a catastrophic scale. The present paper considers operation of vehicles with rotary screw propulsion units, the distinctive feature of which is the traction generation on ice exceeding the weight of the vehicle. This feature allows both to reduce the tractor weight and to drive it onto the ice out of an ice opening. Thereby, it should be noted that a wide use of such vehicles is impeded due to the high energy demand of their operation. To solve this problem is the objective hereof.
2. Overview of previous studies

The beginning of mobility studies of vehicles with rotary screw propulsion units in severe conditions dates back to the studies of such scientists as: B. Cole [1], A. Soltynski [2], M. Becker [3]. As the last studies of this matter we could consider papers by J. Wong [4]. It should be noted that the principal matter of interest of the above-listed was the locomotion of the subject vehicles on water basins, swamps and other highly humidified terrain. The development of the transportation infrastructure in the Arctic zone has lead to a growth of the number of studies dedicated to the interaction of the rotary screw propulsion unit with the ice and the snow. The development of this scientific research direction has been directly contributed by the research work of Nizhny Novgorod school of all-terrain vehicles [5-17]. The scientists of our school have defined and substantiated areas of us of rotary screw propulsion vehicles; a theory of steady locomotion was developed and systematized; equations were found for all forces acting on a rotary screw propulsion vehicle, also during driving on snow, etc. A thorough analysis of scientific studies associated with rotary screw propulsion units has demonstrated that recommendation on selection of rational geometry parameters of a rotary screw propulsion unit was made based on results of calculations with 4 to 6 considered propulsion unit parameters.

3. Methods

For generation of traction during rotary screw vehicle ride on ice, it is important that the helical blade penetrates into it. Thereby, the penetration depth of the helical blade is selected based on the necessity of generation of the required traction determined by the contact sensor area of the blade with the ice and the ice strength [18]. The required cross-section area of the penetration part of the blade is determined by such geometry parameters as OD of the propulsion element, contact angle of the propulsion element with ice and the lead angle of the helical blade (see figure 1).

![Diagram of geometry parameters of the helical blade penetration into ice](image)

**Figure 1.** Diagram of geometry parameters of the helical blade penetration into ice

Setting the minimum required traction for vehicle propulsion $F_t$, as well as considering that this force should be directed longitudinally the following dependencies are obtained:

$$\frac{F_t}{\cos \alpha} \geq kG \quad \text{and} \quad F_t \leq HB \frac{S}{\cos \alpha}$$

Whence it appears:

$$S \geq \frac{F_t}{HB}$$

on the other hand, the contact area of the helical blade is determined as double difference of the sector area with dia. $D$ and $\nu$ angle and the area of a right triangle with sides $D$ and $D-h$:

$$S_1 = (0.5D)^2 \nu, \quad S_2 = (0.5D - h_\theta)^2 \sin \nu, \quad \nu = \arccos \frac{0.5D - h_\theta}{0.5D}$$

$$S = S_1 - S_2 = (0.5D)^2 \nu - (0.5D - h_\theta)^2 \sin \nu$$

Considering that for small angles the equation $\nu = \sin \nu$ is valid, we obtain:
\[ F_t \leq h_B \{D-h_B\} \arccos\left(\frac{0.5D-h_B}{0.5D}\right)HB \]

presenting the height of the helical blade as part of the basic cylinder diameter \(- h_B = kD\) we obtain:

\[ F_t \leq kD^2 \{1-k\} \arccos(1-2k)HB \]

The solution of the obtained dependency is shown in figure 2.

![Figure 2. The dependence of the traction of one winding of the rotor screw on ice on the helical blade height; 1 - for basic cylinder dia. 0.5 m; 2 - for basic cylinder dia. 1.0 m; 3 - for basic cylinder dia. 1.5 m](image)

For the time being, the profile of the helical blade is usually welded of two inclined flank plates. For such structure, the maximum bending moment can be calculated based on the following equation:

\[ F_t \cdot h_B = \sigma_n W_X, \]

where \(W_X\) is the secant modulus relative to the central axis. For helical blade with triangular profile with height \(h_B\) and height \(b\):

\[ W_X = \frac{bh^2}{24} \quad \text{and} \quad F_t = \frac{S\sigma_n}{48} \quad b = \frac{96F_t}{\sigma_n h} \]

Substituting \(F_t\) values from the equation, we obtain:

\[ b \geq \frac{96\{D-h_B\} \arccos\left(\frac{0.5D-h_B}{0.5D}\right)HB}{\sigma_n h} \]

The obtained results unambiguously determine the geometry parameters of the helical blade allowing for unambiguous determination of the energy parameters of its penetration into the ice. If a flat helical blade is introduced as shown in fig. 3, the energy demand of the penetration will be determined as product of ice strength by single-axis compression of the cross-section of the helical blade and its penetration velocity.

The deformation velocity of the ice is one of the most important specifications determining both the pattern of its deformation and its strength. At low deformation velocities, the ice behaves as plastic medium with low yield strength. The higher the velocity, the higher the yield strength, finally, at a relatively high deformation velocity, the ice begins to behave as brittle-elastic medium. It is considered that the border between the zones of plastic and brittle destruction lies around \(\xi = 10^{-3} \, \text{s}^{-1}\). This border
corresponds to the maximum strength [18]. At 0.2 m blade width in the widest area, the maximum ice strength will be observed at a penetration rate of $2 \times 10^{-4}$ m/s, which is much less than real penetration rates of the helical blade. At a penetration rate above $2 \times 10^{-2}$ m/s, the influence of the penetration rate on the compression resistance of the ice is absent [17]. Then, the penetration power of the helical blade into the ice can be determined as follows:

$$S = \frac{48F_r}{\alpha} \rightarrow N_p = S \cdot HB \cdot V_p = S \cdot HB \cdot V_\chi \cdot \sin \alpha = S \cdot HB \cdot V_\chi \left(1 + \cos \lambda\right) / 2 \sin \alpha,$$

where $V_p$ is the penetration rate of the helical blade, correlating with the travel speed of the vehicle in accordance with the dependence $V_p = V_\chi / \sin \alpha$, where $\alpha$ is the lead angle of the helical blade. Angle $\lambda$ is the penetration angle of the helical blade into the ice, as shown in figure 3. At a penetration angle $\lambda$ above $90^\circ$ the penetration of the helical blade into the ice occurs by impression, at smaller penetration angles cutting prevails.

![Figure 3](image-url)  
**Figure 3.** Ice penetration diagram of the helical blade; a – by impression; b – by cutting

The cutting force are used to be found by formulas suggested by V.F. Kulepov [19-21]:

$$F_n = \frac{P_0}{1 + k \eta} \cdot h \cdot [1 + (b - 1)] \left(1 + k \gamma\right) \left(1 + \xi V\right) \left[1 + \xi (u - 40^\circ)^2\right],$$

where $P_0$ is the reference cutting force obtained during cutting of an ice master of 0.01 m thickness, 0.01 m width, at $0^\circ$C ice temperature, 90 deg. cutting angle, and 0 m/s cutting velocity; $k$ is the coefficient accounting for changing of strength properties of the ice versus temperature, equal to 0.04 N/deg.; $\xi$ is the coefficient accounting for changing of strength properties of the ice at different load accommodation rate equal to 9.87 Ns/m; $\Omega$ is the coefficient accounting for changing of the cutting force vs. cutting thickness, equal to 0.47; $\Gamma$ is the coefficient accounting for changing of the cutting force vs. cutter width, equal to 0.865; $\zeta$ is the coefficient accounting for changing of the cutting force vs. cutting angle, equal to $3.2 \times 10^{-3}$ (deg.$^{-1}$); $\gamma$ is the coefficient of blocked cutting assumed equal to 1.5 for "angular in slot" cutting condition; $h$ is the width of the helical blade; $V$ is the cutting velocity de-
determined by the distance of the cutting point from the rotation axis and rotation speed of the rotor: 
\[ V = \left( h + \frac{D}{2} \right) \omega, \]
where \( D \) is the basic cylinder dia.; \( \omega \) is the angular rotation speed of the rotor.

Then, the power absorbed for the helical furrow cutting can be calculated from the following equation:
\[ N_p = \frac{V_P}{1 + k t_o} \left( \Gamma ( t_n - 1 ) ( 1 + \zeta ( H ) ) \right), \]

The influence of the shape of the helical blade can be determined by substitution of \( h_B \) and \( V_P \) values in the obtained dependencies as mathematical functions of traction. Then, the energy absorption by the penetration of the helical blade into ice versus the inclination angle of the helical blade edge penetration into ice will appear like the dependency illustrated in figure 4.

**Figure 4.** Energy absorption of the ice penetration of a helical blade of 0.1 m height at 0°C ice temperature (with 0.3 MPa one-axis compression strength) versus front edge inclination angle; 1 – for 1 m/s penetration velocity; 2 – for 10 m/s penetration velocity

### 4. Conclusions
The obtained results unambiguously demonstrate that the minimum power absorption during the locomotion of a rotary-screw propelled vehicle on ice is provided by the ice penetration of the helical blade by impression. Thereby, the less is the inclination angle of the front edge of the helical blade the less is the power absorption of the penetration, however, the time required for the blade penetration is thereby longer. That is, the energy demand of the helical blade penetration by impression with kW*h dimension remains the same. On the other hand, since the energy demand of the ice penetration of the helical blade by cutting remains almost unchanged, the growth of the inclination angle of the front edge of the helical blade will be followed by a longer cutting process and its increased energy absorption.

### References
[1] Cole B N 1961 Inquiry into amphibious screw traction *University of Birmingham* **175** p 19
[2] Soltyński A 1963 Ocena "Piszktadni glebowej" modelowego pojazdu tere-nowego *Technika motorzacyjna* **13 - 10** pp 321-329
[3] Bekker M G 1986 Parametric analyses of tracks and tracklayers update-sample of engineering problems and their solutions in off road locomotion *SAE Technical Papers*
[4] Wong J Y, Jayakumar P, Toma E, Preston-Thomas J 2020 A review of mobility metrics for next generation vehicle mobility models *Journal of Terramechanics* **87** pp 11-20
[5] Kulyashov A P and Kuklina I G 2011 Estimation of the Rotor Screw Machine Vibration Depending on Suspension Parameters and the Mover Line Contact with the Ground *Journal of Road and Construction Vehicles* **7** p 45
[6] Krasheninnikov M et al. 2013 The concept and methodology of creating the universal life-saver with rotary-screw mover *Lecture Notes in Electrical Engineering* **195 - 7**
[7] Molev Y et al. 2019 Sound power spectra modeling of the vehicle in motion equipped with rotary-screw propulsion unit IOP Conf. Series: Journal of Physics: Conf. Series 1177 012034
[8] Belyakov V et al. 2017 Ground vehicle for ice conditions monitoring Thirteenth International MEDCOAST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation (MEDCOAST 2017) pp 775-785
[9] Strizhak A et al. 2019 Modelling of vehicles with rotary-screw propulsion unit along waterflooded substructure Journal of Physics: Conference Series 1177 012039
[10] Abramova E et al. 2018 The simulations of helical blade interaction with ice MATEC Web of Conferences 245
[11] Vahidov U et al. 2020 Case study: Regulation of noise produced by a rotary-screw propulsion unit in an all-terrain vehicle 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2020) pp 548-551
[12] Kurkin A et al. 2015 Autonomous Robotic System for Coastal Monitoring Twelfth International conference on the Mediterranean coastal environment (MEDCOAST 15) 1 and 2 pp 933-943
[13] Kurkin A et al. 2017 Unmanned Ground Vehicles for Coastal Monitoring International Journal of Imaging and Robotics 17-1 pp 64-75
[14] Tyugin, D Yu 2018 Development of a mobile robot group for coastal monitoring IOP Conference Series: Materials Science and Engineering 386 012009 doi:10.1088/1757-899X/386/1/012009
[15] Zaytsev A et al. 2017 Coastal monitoring of the Okhotsk sea using an autonomous mobile robot Science of Tsunami Hazards 36-1 pp 1-12
[16] Zeziulin D et al. 2017 Development of a ground mobile robot for motion in conditions of coastal zones 19th International and 14th European-African Regional Conference of the ISTVS
[17] Erasov I A et al. 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 doi:10.1088/1757-899X/386/1/012006
[18] Stepanyuk I A 2001 Testing and modeling technique of sea ice St. Petersburg: Hydrometeoizdat p 78
[19] Kulepov V 2002 Development of a parametric series of disk-mill ice cutters Journal Road and Construction Vehicles 11 pp 16-24
[20] Kulepov V 2002 Determining the loads imposed on the attachments of ice-cutting machines to cut slots in the ice cover Journal Road and Construction Vehicles 10 pp 42-48
[21] Kulepov V F 2002 Development and creation of ice-cutting machine of new generation Mekhanizatsiya Stroitels'va 9 pp 20-22