Study of Parameter Influence of the Basic Cylinder of Rotary Screw Propulsion Units on Noise Level during Locomotion on Ice

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Abstract: The paper presents deformation calculations of the basic cylinder of the rotary screw propulsion unit under external load. The influence of such basic parameters of the rotary screw propulsion unit as basic cylinder diameter, its length and wall thickness on its deformation area, and, as a consequence, the generated noise level has been demonstrated. The basis for the method development were studies by scientists who were studying the sound wave generation by the deformation of different structural elements, parts and assemblies. The contribution of each of the parameters of the basic cylinder to the general level of the generated sound pressure was analyzed. It was determined that the magnitude of the noise level is mostly dependent on the length of the basic cylinder, then, to a less extent, on the cylinder wall thickness, and, to the least extent, on its diameter. A correlation was revealed between the oscillations power of the propulsion unit and their correlation with their generated noise level. The results and conclusions obtained during the described study allow for a more solid-based approach to the parameter selection of the rotary-screw propulsion unit for improved acoustic comfort, also for improved driver's work conditions, including the relief of his/her nervous system, sharpening of his/her attention during the operation, accident reduction. Beside the design of structures with the least possible noise, the proposed method allows also for selection of a rational propulsion unit design achieving a compromise between vehicle's noise specifications and its off-road ability.

1 INTRODUCTION

Currently, the main way to develop all-terrain vehicles is to ensure their mobility (Belyaeva and Evseev, 2020, Diakov, 2018, Klubnichkin, 2019, Manianin, 2019). However, the study of the noise level generated by all-terrain vehicles was not given sufficient attention.

One of the factors worsening the work condition of all-terrain vehicle drivers is the high noise level in the cabin, which both affects the driver's well-being and detracts him/her. Numerous researchers have proven that the increased noise level (more than 55-65dB) significantly affects human health (Parma Declaration on Environment and Health, 2010) (Fritsch, 2011, Lercher, 2007). Exceeding the noise level by 10-20dB relative to the background leads to panic in fish (Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities, 2012). The same excess of the noise level by 10 relative to the background leads to a decrease in the bird population by 90%. (Harbrow, 2010)

The noise generated by off-road vehicles is mainly generated by the engine, transmission, as well as vibrations caused by the interaction of the propulsion unit with the road surface. The most noisy is the rotary screw propulsion unit. Let us consider in more detail how noise is generated in this propulsion.

The purpose of this study is to develop the requirements for the operation of all-terrain vehicles with a rotary-screw propulsion units and the choice of their design parameters that ensure the movement of vehicles with a generated sound level less than 65dB.

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2 THEORETICAL RESEARCH

A most complete description of the influence of the screw blade on the total noise in a vehicle's cabin can be found in studies by (Nikitin, 2004, Shashurin, 2010, Pokachalov, 2003) providing evidence that the acoustic power of any sound source can be obtained from the following equation:

$$W_i = \rho c s_i v_i^2 S_i, \tag{1}$$

where ρ - is the air density, c – is the sonic speed, ν_i - is the oscillation velocity of the surface radiating the acoustic oscillations, s_i – is the power conversion ratio of the mechanical oscillations to the acoustic ones, whereas S_i – is the acoustic radiant surface. From this equation, it is obvious that the design-stipulated acoustic power U is dependent on the acoustic radiant surface and the surface oscillation velocity:

$$U = KW_i = Kv_i^2 S_i, \tag{2}$$

where K – is the generalized conversion ratio of the mechanical oscillation energy into the acoustic one. Under recognition that the oscillation velocity is related to the amplitude and the locomotion velocity by the following dependency: $\nu_i = 2\,A_{\max}/(L\,V^{-1})$, where $A_{\max}$ is the maximum oscillation amplitude, and $0.5\,L\,V^{-1}$ is the cycling time of such oscillation equal to the rotor length divided by the vehicle's locomotion speed (since the oscillation cycle consists of the maximum displacement of the point under test and its return in its initial position, then, during the rotor travel all-along its length, the surface of the basic cylinder will be displaced by $A_{\max}$, first, to the one side, and then to the other side, that is, the total displacement is $2A_{\max}$, stipulating the presence of the factor 2 in the presented dependency.

In general appearance, the loading diagram of the rotary screw propulsion unit from the travel surface in form of ice (Belyakov, 2020, 2021) leading to the basic cylinder deformation can be presented as shown in Figure 1.

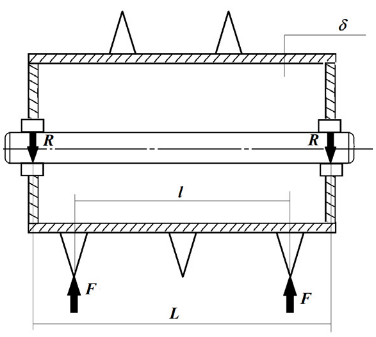

Figure 1: Basic cylinder loading diagram due to external loads.

The problem can be solved by means of Autodesk Simulation Mechanical design software package. The problem was solved in quasi-static statement with linear elastic and plastic material properties.

As material, the basic rotor cylinder adopts St3sp steel grade, see specifications in Table 1.

Table 1: Physical and mechanical properties of St3sp steel grade.

ρ, t/m^3	σ_T, MPa	$\sigma_{0.2}$, MPa	δ_5, %	E, N/mm^2	ν
7,858	245	370	23	200*10^3	0,3

We obtained the sag of the basic cylinder walls as delta of the load value R, the basic cylinder length L, the basic cylinder diameter D and the wall thickness δ. The obtained values are unambiguous evidence of the fact that as the wall thickness δ, and the diameter of the basic cylinder grow, whereas its length get shorter, the deformation magnitude is reduced. In the graphic appearance, the results of the obtained calculations are presented in Figures 2 - 4, whereas the numeric values of the sag are listed in Table 2.

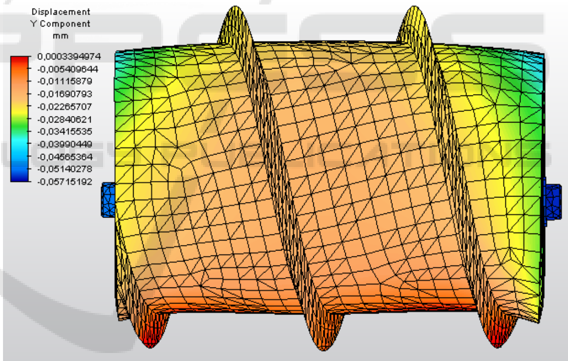

Figure 2: Design case of short basic cylinder loading (1200 mm length) with large diameter (800 mm) and thick wall (5 mm).

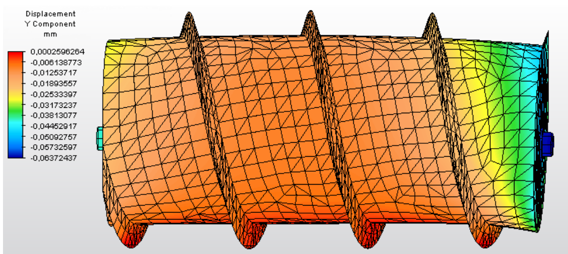

Figure 3: Design case of long basic cylinder loading (1800 mm length) with Large diameter (800 mm) and thick wall (5 mm).

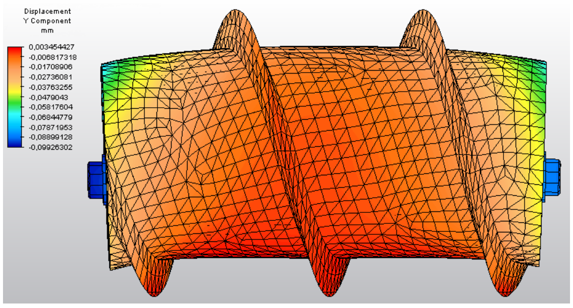

Figure 4: Design case of short basic cylinder loading (1200 mm length) with Average diameter (600 mm) and thin wall (2 mm).

Having obtained the deformation values of the basic cylinder surface, at known speed of locomotion and geometry of the basic cylinder, based on equations 1 and 2 we can easily determine the energy of the mechanical oscillations of the system under analysis. In order to determine the acoustic radiation power, it is important to find out the values of factor *K* from dependency 2. The simplest method of its determining is the comparison of the power of the mechanical oscillations with the actual generated sound power of the experimental propulsion works.

3 EXPERIMENTAL RESEARCH

To determine this parameter, a test bench was developed (Figure 6) consisting of two semi-rotors assembled with a two-shaft counter-rotating gear reducer, with mutually balanced ice penetration of the screw blades, and two adjustable height vertical columns for ice penetration depth adjustment of the screw blades. The rotation of the rotors was obtained via belt transmission generating torque from a vertically traveling weight.

Figure 6 shows: 1 – two balanced semi-rotors; 2 – two-shaft counter-rotation gear reducer; 3 – belt transmission; 4 – column; 5 – meter weight; 6 – ice penetration depth adjustment column.

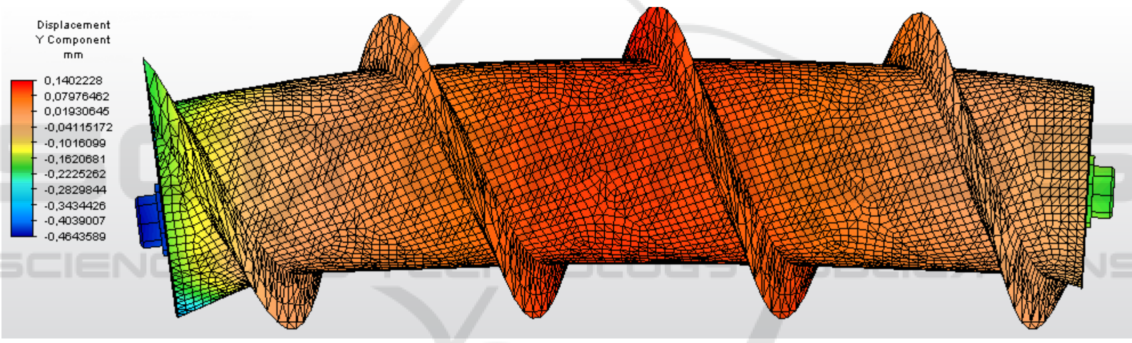

Figure 5: Design case of long basic cylinder loading (1800 mm length) with small diameter (400 mm) and thin wall (2 mm).

Table 2: Test results of sound generated by basic cylinder of rotary screw propulsion unit during its deformation.

<table>
<tr><th>Item No.</th><th>D, mm</th><th>L, mm</th><th>l, mm</th><th>δ, mm</th><th>R, kN</th><th>Δ, mm*10⁻³</th><th>Design level of generated sound, dB</th></tr>
<tr><td>1</td><td>600</td><td>1200</td><td>1000</td><td rowspan="4">3</td><td rowspan="10">100</td><td>48</td><td>20*</td></tr>
<tr><td>2</td><td>600</td><td>1800</td><td>1500</td><td>127</td><td>30</td></tr>
<tr><td>3</td><td>400</td><td>1200</td><td>1000</td><td>125</td><td>30</td></tr>
<tr><td>4</td><td>400</td><td>1800</td><td>1500</td><td>410</td><td>75</td></tr>
<tr><td>5</td><td>600</td><td>1200</td><td>1000</td><td rowspan="4">2</td><td>60</td><td>20</td></tr>
<tr><td>6</td><td>600</td><td>1800</td><td>1500</td><td>180</td><td>40</td></tr>
<tr><td>7</td><td>400</td><td>1200</td><td>1000</td><td>162</td><td>40</td></tr>
<tr><td>8</td><td>400</td><td>1800</td><td>1500</td><td>485</td><td>75</td></tr>
<tr><td>9</td><td>800</td><td>1200</td><td>1000</td><td rowspan="2">5</td><td>18</td><td>10</td></tr>
<tr><td>10</td><td>800</td><td>1800</td><td>1500</td><td>36</td><td>15</td></tr>
</table>

* the sound level equal to 20 dB marked in test No. 1 is not the design value, but an experimental one obtained in the scope of the conducted studies.

Figure 6: Test bench for determining of the relationship between the generated sound level and the deformation force magnitude of the basic cylinder.

The experimental data demonstrate that the re-distribution of the mechanical energy of the basic cylinder oscillations into acoustic oscillations with 1/10 ratio. The obtained data allow for the modification of equation 2 to a dependency of the following appearance:

$$U = 0.4\, A_{max}^{2}\, V^{2}\, \pi\, D. \qquad (3)$$

4 ANALYSIS OF RESULTS

The analysis of the obtained results demonstrates that the design of the rotary screw propulsion units in general and that of the basic cylinder, in particular, will be the less capable of radiating the acoustic energy, the less the deformation magnitude and the locomotion speed of the vehicle are. The rotor length change reduces, on the one side, the oscillation velocity, on the other side, it leads to sag growth. Thereby, in spite of the fact that the power of the generated acoustic radiation (based on dependency 3) is directly proportional to the rotor diameter and inversely proportional to its length, the total noise level will grow with the increase of the length and with the diameter reduction, since these parameters influence the sag magnitude stipulating, in equation 3, the noise level growth not in linear, but in quadratical dependency.

The reduction in the length of the base cylinder is limited by the need to ensure such a length of contact of the screw blade with the ice, at which the necessary reserve of thrust force of the vehicle under study would be provided. The diameter of the rotor is limited exclusively by the dimensions of the vehicle.

In papers (Vakhidov, 2020a, Vakhidov, 2020b, Lipin, 2019, Mokerov, 2019), noises generated by rotary screw propulsion units were analyzed, the structure of which is shown in Figure 7.

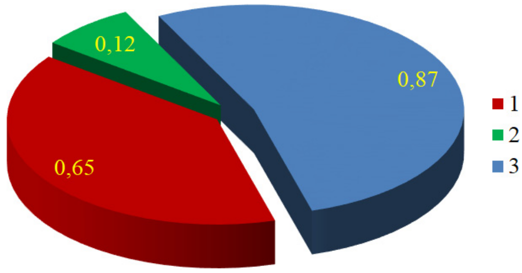

Figure 7: Components of noise generated by rotary screw propulsion unit during all-terrain vehicle locomotion on ice (see paper (Vakhidov, 2020a)). 1 – noise generated by screw blade penetration into ice; 2 – noise generated by base cylinder shell deformation; 3 – noise generated by base cylinder friction over ice surface.

Thereby, in previous works, no difference based on the basic cylinder sag and shell deformation was made. The data provided herein allow for finalizing the contribution of the processes associated exactly with the basic cylinder shell deformation of the rotary screw propulsion unit to the total noise level. As a result, it was found out that it is exactly the deformation under analysis which is "liable" for 80% of the generated acoustic radiation, and it is exactly the basic cylinder wall thickness change and the reduction of the radiant area (e.g. by means of the basic cylinder internal surface sound insulation for single-time radiant area and the radiated noise reduction by 50%) is the most promising development direction of low-noise rotary screw propulsion units.

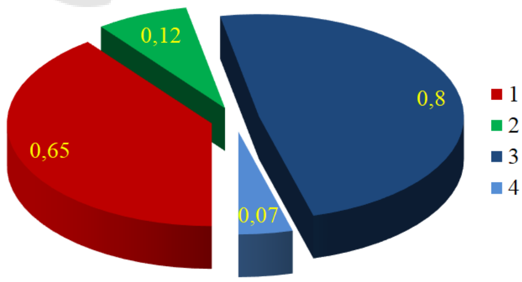

Figure 8: Finalized components of noise generated by rotary screw propulsion unit during all-terrain vehicle locomotion on ice. 1– noise generated by screw blade penetration into ice; 2 – noise generated by base cylinder shell deformation; 3 – noise generated by basic cylinder deflection; 4 – noise generated by basic cylinder friction over ice surface.

5 CONCLUSIONS

The obtained data made it possible to develop requirements to rotary screw propulsion units to provide for its proper operation on ice with acoustic radiation level. It was found out that the basic cylinder should have as large diameter as possible (restricted only by the overall vehicle dimensions) and as less length as possible (restricted by the necessity of the presence of at least two turns of the screw blade winding). The basic cylinder wall should feature a wall thickness of at least 5 mm.

The results obtained in this work clearly indicate that the use of 4 short rotors from the point of view of acoustic radiation is the most promising way to develop vehicles of this class.

The difference in the designs of these vehicles is shown in Figure 9 and 10.

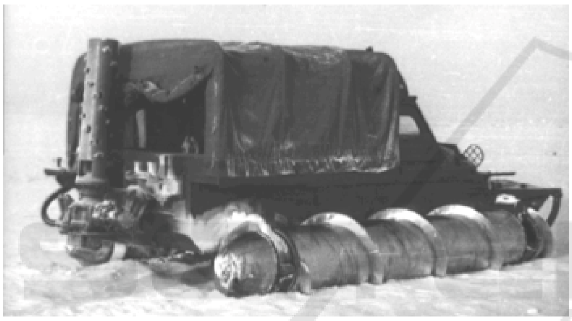

Figure 9: Classic line-up of a special all-terrain vehicle.

Figure 10: The proposed design, which provides noise reduction when driving a special all-terrain vehicle.

A further direction to reduce the noise of the machine is to replace the front rotors with skis or skates. However, this approach significantly reduces the scope of this technique, including making it impossible for it to move on water.

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