Sound power spectra modelling of the vehicle in motion equipped with rotary-screw propulsion unit

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Abstract: Modelling sound power spectrum results of the vehicles in motion equipped with rotary-screw propulsion unit is considered in this article. Vibroacoustic properties of a vehicle while moving across countryside bad roads have been considered in the paper; expressions to determine sound power spectrum dependence on base cylinder mass and diameter, its rpm and screw blade winding angle have been obtained, as well as such force parameters of rotor-substructure interaction as friction force and screw blade penetration force. Experimental results of rotary-screw vehicle have been analyzed. The research results analysis shows that changing of propulsion unit construction parameters allows to reduce the environment noise impact level by 10 dB. The designed model and the results obtained are applicable when designing cross-country vehicles.

Nowadays Arctic Regions of the Russian Federation are not equally developed in terms of transport. Under conditions of transport network dispersion, the lack of land transport communication between some territories, one of the tasks to enhance mobility of population, and to lower freight transportation costs is to adequately provide Arctic Zone of the Russian Federation with reliable cross-country vehicles comfortable enough to be used (primarily, from the point of view of acoustics) in such conditions. For most structure-borne noise sources, rotary-screw propulsion unit is a physical object, affected by loads from both the vehicle transmission and bearing surface, and transforming them into sonic waves. Depending on the location, method and frequency content of the applied force factor, oscillation forms will be excited in it which, according to the general definition, are characteristic of such a source of the propulsion unit noise.

Modelling sound power spectra of the propulsion unit, generated by oscillating processes when the vehicle is in motion, requires adaptation of the frequency method to solve this task. This method in its pure form can be applied only for a special case of backlash-free pair mating: base cylinder – bearing surface (in case of regular-shaped base cylinder motion along absolutely even bearing surface), when force factor $N(\omega)$ with spectrum $S_N(\omega)$ interacting with the propulsion unit having frequency integrated (mechanical and acoustic) specifications $K(\omega)$, forms sound power spectrum $P_w(\omega)=K(\omega)N(\omega)$. Quality analysis of the force factor time realization, exciting the propulsion unit shows its considerable difference from $N(\omega)$. Basically this fact does not contradict the frequency method idea, however it requires one more member to be introduced in the mathematical model – the element frequency...
characteristic - $X(\omega)$ which can be objectively determined by carrying out the experiment, when the propulsion unit spectrum value $P_\omega(\omega)$ is known from the base cylinder interaction with the substructure, as well as on the basis of well-known methods of determining $K(\omega)$ of the propulsion unit and spectrum analysis of calculated values $N(t)$:

$$X(\omega) = \frac{P_\omega(\omega)}{K(\omega) F[N(t)]]}$$

Model analysis of sound oscillations origin when the vehicles with rotary-screw propulsion unit are in motion shows that product $X(\omega) F[N(t)]$ is in its essence Fourier transform $N_p(t)$, and $N_p(t)$ is a set of force factor $N(t)$ and $\{X(t) \leftarrow F[X(\omega)]\}$. Taking this into consideration, $X(t)$ characteristic properties can be not only experimentally but also mathematically determined by the physical phenomena which take place in the contact area of rotary-screw propulsion unit with the bearing surface. Thus, known from spectrum theory ratio, written for this case allows to conclude that total $N(t)$ can be presented as a set of $N(t)$ and $\{X(t) \leftarrow F[X(\omega)]\}$ (see Figure 1.), which is a short pulse system $t_p << T_M$, its spectrum up to a constant coinciding with a single pulse spectrum. $T_M$ – is rotor spinning single cycle duration, $t_p$ – duration of a single penetration of screw blade into the bearing surface.

![Figure 1. Rotor power load change during its interaction with the bearing surface, where $X_T$ – base cylinder constant force of friction on the bearing surface, $X_p$– the force of screw blade penetration into the substructure.](image)

At ratio $t_p << T_M$ impulse spectrum in low-frequency region within the range of $0 < \omega < 1/t_p$ regardless of its form has the amplitude spectrum constant density proportional to the pulse area. The picture of propulsion unit multi-pulse excitation from the rotor-with-substructure interaction largely coincides with a classical example of white oscillations generation in the form of random successive short pulses [1, 2]. Therefore $X(\omega)$ frequency dependence is expected to be a spectrum function with constant spectral density.

As soon as the major part of the acoustic energy being released when a vehicle with rotary-screw propulsion unit is in motion is concentrated within the frequency range $20 < \Gamma < 4000$ Hz, to reproduce practically identical frequency function in this frequency range, simple time interpretations of the construction force excitation can be used.

Single rectangular power pulse will have the same spectrum, its spectral density $X_0(\omega)$ being fully described by two parameters: $t_p$ - duration and $A$ - amplitude.
\[
S(\omega) = A t_p \left\{ \frac{\sin \omega t_p}{2} \right\} \rightarrow X(\omega) = A \frac{t_p}{T_M} \left\{ \frac{\sin \omega t_p}{2} \right\}
\]

This problem should be solved in such a way that the energy concentrated in spectral function \(X(\omega)\) equals the time realization energy \(X(t)\). Thus, total impulse force \(A t_p\) should be equal to the moment of momentum, acquired by the system at the force factors set, affecting each complete revolution of the rotor (bearing in mind that spectral function \(X(\omega)\) is a dimensionless value, the amplitude value should be averaged by average value of impulse of forces affecting the rotor, that is the sum of the friction force product by a single revolution of rotor duration, product of cutting force by the phase duration of screw blade penetration into the substructure):

\[
A = \frac{M_p n V p T_M}{t_p (X_T T_M + X_p T_p)} = \frac{M_p n V p}{t_p (X_T + X_p T_p / T_M)},
\]

where \(M_p\) – is rotary mass, \(n\) – number of screw blade threads, \(V_p\) – the rate of screw blade penetration into the substructure. Then equation 1 is written in the form of:

\[
X(\omega) = \frac{M_p n V p}{(X_T T_M + X_p T_p)} \left\{ \frac{\sin \omega t_p}{2} \right\}
\]

Mathematical expression for oscillatory occurrences when the vehicle is in motion along the cross-country terrain is conventionally described by equation:

\[
L_{X(\omega)} = L_{N_t(\omega)} - L_F(\omega),
\]

where \(L_{X(\omega)}\) is sound power level of rotary-screw propulsion unit, appearing when the vehicle is in motion, \(L_{F(\omega)}\) – sound power level of force factor, \(L_{N_t(\omega)}\) – level of spectrum interaction of propulsion unit-with-substructure.

Force impact interaction spectrum \(X(\omega)\) of rotor with the bearing surface while in motion will be determined basing on the reverse problem, dependent factors affecting vibroacoustic parameters of the vehicle.

Knowing experimental values \(L_{N_t}, L_F\) and \(L_p\) it is possible to calculate design values [2]:

\[
X(\omega) = 10^{0.1 L_X}, \quad X_0 = X(\omega) = 10^{0.1 L_X} \frac{R_W(\omega)_{k0}}{K(\omega)_{k0} F[N(t)]_{0}} = \frac{M_p n V p}{(X_T T_M + X_p T_p)} \left\{ \frac{\sin \omega t_p}{2} \right\}
\]

Taking into account that the screw blade penetration rate into the substructure is determined by the following geometrical and speed parameters of rotary propulsion unit: base cylinder diameter, screw blade winding angle and base cylinder rpm \([3-5]\):

\[
V_p = \frac{\sigma D}{2 \cos \beta}; \quad L_S = \frac{D}{2} \sin \beta; \quad V = \alpha L_S = \frac{D}{2} \sin \beta; \quad T_M = \frac{2\pi}{\omega};
\]

from where:

\[
L_X(\omega) = 10 \log \frac{M_p n \sigma D}{2 \cos \beta X(\omega)_{k0}} \left( \frac{2\pi}{\omega} X_T + X_p T_p \right) \left\{ \frac{\sin \omega t_p}{2} \right\}
\]

The dependence obtained allows to theoretically determine sound pressure level at the interaction of rotary-screw propulsion unit with the substructure depending on the rotary mass, its diameter, cutting force for different rotary rotations per minute, at different screw blade winding angles.
Solution of the obtained equation is shown in Figure 2. Experimental research showed that deviation of experimental and theoretical data of sound power spectra does not exceed 2 dB (5%), allowing to apply the obtained dependence for designing special cross-country vehicles, i.e. for the required sound-insulating structural calculation, providing comfortable operator environment within the whole range of transport and technological operations. The research was carried out within Federal Target Programme «Research and development of priority areas of Russia’s science and technology sector for 2014-2020» № 14.577.21.0222 on the subject «Creating an experimental model of amphibious autonomous transport and technological complex with intelligence control and navigation system for all-year-round exploratory drilling operations on the Arctic shelf» [6-9].

The designed model of determining sound power spectra, emerging while vehicles with rotary-screw propulsion units are in operation has shown that by changing the propulsion unit geometrical parameters there appears a technical capability to reduce the sound power value by 10 dB.

Figure 2. Theoretical and experimental sound power spectra emerging when the base cylinder of rotary-screw propulsion units rotates at 5 rad/s; 1-theoretical sound power spectrum for rotor with base cylinder of 1,2 m diameter and screw blade winding angle 20°; 2-theoretical sound power spectrum for rotor with base cylinder of 1,2 m diameter and screw blade winding angle 15°; 3-theoretical sound power spectrum for rotor with base cylinder of 0,8 m diameter and screw blade winding angle 20°.

Figure 3. Testing a vehicle with rotary-screw propulsion unit.
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