Kinematic study of a road power generator for the port transport network

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Abstract. Nowadays, energy-saving applications are based on alternative energy sources that enable autonomous powering of electrical consumers. Within the port transport network, 62% of freight transport is carried by road. One solution for the alternative generation of electrical energy for lighting and power supply of small power consumers is the use of road electromechanical systems such as artificial road bumps with an electromagnetic generator that converts the energy of vehicle movement into electrical energy. This article deals with a road power generator transducer with a slider-rocker kinematic pair for converting translational motion into rotational motion. The authors conducted a kinematic study of the actuating force transducer and analysed its performance at various connecting rod lengths with the required speed and dimensional criteria. They determined the effect of the connecting rod length on the trajectory and speed of the rocker arm. Analysis has shown that a connecting rod length of 100 and 150 mm, providing a working section with a uniform increase in speed of the rocker arm, satisfies the specified requirements. For further investigation of the electromechanical power system, the researchers adopted a 100 mm long connecting rod, as this allows the unit to be realised with reduced dimensions.

1. Introduction

Global energy consumption is rising. While traditional manufacturing and services are becoming increasingly energy efficient, the growth of the world's population and the emergence of new services are increasing overall energy consumption. In 2015, global energy consumption was 20.76 trillion kW·h; according to the International Energy Agency, the forecast for 2030 is 33.4 trillion kW·h, and by 2050 it will reach 41.3 trillion kW·h[1].  

On the other hand, there is a worldwide trend towards alternative sources of electricity. The creation and improvement of existing alternative energy sources is a very relevant topic.  

One such source of electrical power is a road power generator (RPG) in the form of an artificial bump in the road with an electrical power generator, shown in Figure 1.  

These power generators convert the kinetic energy of the vehicle's motion into electrical energy. Considering that 62.1% of cargo is shipped from seaports by road [2], the use of road power generators on the transport network of water transport facilities is of practical and economic interest.  

For example, the dry cargo turnover of seaports in the Azov-Black Sea basin was 111.6 million tonnes in 2020[3], which implies that 73.9 million tonnes were transported by road. With an average
truck capacity of 20 tonnes, 369,500 vehicles entered the ports of the Azov-Black Sea basin in 2020. Considering that a vehicle passes through the port transport network twice (once without cargo and once with cargo) and knowing the average mass of a cargo vehicle ($m_a=12$ t), it is possible to estimate the energy potential of the transport network of the seaports of the Azov-Black Sea basin according to the formula:

$$E_p = mgh + 2m_a gh = (m + 2m_a)n gh$$

where $m = 73.9$ - mass of transported cargo, mt, $g$- acceleration of free fall, $h = 0.07$ - stroke of artificial road unevenness,m [4], $n = 369,500$ - number of vehicles passed through port transport network, pcs.

**Figure 1.** A power-generating artificial bump in the road.

Calculations show that 11164 MJ of energy can be generated per year from vehicle traffic in the ports of the Azov-Black Sea basin. The energy generated by road traffic can provide lighting for seaports and power for small electrical consumers.

**2. Problem statement**

To generate electricity from moving vehicles, scientists in Russia and abroad have developed and researched road power generator designs, which operate based on the following principles [5 - 13]:

- piezoelectric transducers;
- electromagnetic transducers;
- mechanical transducers.

An analysis of the literature shows that the greatest number of publications are devoted to road power generators with a mechanical external load transducer. The transducer is designed as a toothed sector and gear wheel, connected via a drive shaft through an overrunning clutch to an electric generator, as shown in Figure 2.

**Figure 2.** Motion transducer in the form of a toothed sector and toothed wheel.
The main disadvantages of such road power generators are the low load capacity of the toothed kinematic pair of the motion transducer, as the forces in it are transmitted through the small contact areas appearing in the tooth contact areas under the influence of loads and the increased specific pressure on the tooth contact line, which during operation leads to wear of the contact surfaces and material pitting. At the same time, the toothed kinematic coupling has relatively high demands on manufacturing and assembly accuracy, which significantly affects the cost of energy produced.

The authors propose the design of a road power generator with a slider-rocker motion transducer for the pressure platform. In the proposed road power generator shown in Figure 3(a),(b) the pressure platform 1 is connected to stem 2. The stem is fitted with a spring 3 which returns platform 1 to its original position after relieving the load. The motion transducer is designed as a rotating link kinematic pair of rocker 4 and slider 5. Slider 5 is hinged to the spring-loaded stem 2 and rocker 4 is rigidly connected to the drive shaft 6 of motion transducer 3. The drive shaft 6 is connected via an overrunning clutch 7 to the flywheel 8 and the electric generator 9.

![Figure 3. Road power generator.](image)

(a) - structural diagram front view; (b) - structural diagram side view.

The principle of operation of the proposed road power generator is as follows: when a car hits platform 1, the latter begins to move down under the influence of the weight of the vehicle, acting on the stem 2, connected to it and compressing the spring 3. Stem 2 moves downwards and drives slider 5. The slider 5 drives the rocker 4 in a rotary motion, which in a partial revolution around its axis rotates the drive shaft 6 and through the overrunning clutch 7 drives the flywheel 8 and the electric generator 9. This generates electricity. The flywheel 9 can store energy from the weight of the vehicle and increase the efficiency of the road power generator.

When the vehicle moves off platform 1, the latter is lifted upwards by the compression force of spring 3. Together with platform 1, stem 2 is lifted upwards, returning the motion transducer links - slider 5 and rocker 4 - to their initial position. During this process, rocker 4 rotates the drive shaft 6 in the opposite direction while flywheel 8 and electric generator 9 continue to rotate in the original direction as they are connected to the drive shaft 6 via an overrunning clutch 7.

The offered road power generator favourably differs from the existing analogues as the design of the impact force transducer in the form of a "slider-rocker mechanism" essentially simplifies the unit design by the transition from the higher cogged kinematic pair of links to the lower rotating kinematic pair "rod-rocker", which reduces the overall design cost and increases the time between failures of the links.

The initial stage in selecting the design parameters of the port road power generator involves a kinematic study of the slider-rocker mechanism of the impact force transducer, with the following constraints:
1. Minimising the overall dimensions of the power unit in the road tunnel:

\[ R + L + H \rightarrow \text{min}, \]

where \( R \) is the length of the RPG transducer rocker arm, \( L \) is the length of the RPG transducer connecting rod, \( H \) is the slider (rod) stroke of the RPG transducer.

2. Accumulation of energy by the flywheel occurs when the slider (stem) moves, transmitting torque from the output shaft of the transducer to the flywheel when the angular velocities are equal.

\[ \omega_{pr} = \omega_{max}, \]

where \( \omega_{pr} \) is the angular velocity of the drive shaft of the motion transducer, \( \omega_{max} \) is the angular velocity of the flywheel.

3. Materials and methods

The study assessed the scientific information sources in the energy potential of port transport systems, alternative sources of electrical energy, and technical solutions for road power generators.

The practical implementation of the morphological synthesis has resulted in a road power generator’s developed design with a slider-rocker of the impact force transducer mechanism.

Within the framework of kinematic research of the slider-rocker mechanism of the impact force transducer, the scheme of which is shown in Figure 4, a mathematical model \( \phi_k = f(\Delta H) \). The model establishes the functional dependence between the angle of rotation of the rocker \( \phi_k \) and the stroke of the slider \( \Delta H \) to determine the position of links and trajectories of its points, as well as the speeds and accelerations of different points and links under the given law of motion of the leading link-slider.

The angle of rotation of the rocker \( \phi_k \) is defined as an inverse trigonometric function expressing in the triangle \( OAA_1 \) the dependence of \( \phi_k \) on the lengths of the sides \( OA_1 \) and \( OA \):

\[
\phi_k = \arccos \left( \frac{OA_1}{OA} \right) = \arccos \left( \frac{OA}{R} \right).
\]

The value of the \( OA_1 \) argument is defined as a function for the lengths of the sides of the right-angled triangles \( OAA_1 \) and \( BAA_1 \).

Find the relationship between the hypotenuse and the legs of the triangles \( OAA_1 \) and \( BAA_1 \), using the Pythagorean theorem:

\[
OA^2 = (OA_1)^2 + (AA_1)^2;
\]

\[
BA^2 = (BA_1)^2 + (AA_1)^2.
\]

**Figure 4.** Schematic diagram of the slider-rocker mechanism:

- \( R \) is the length of the beam of the transducer;
- \( L \) is the length of the rod of the RPG transducer;
- \( \phi_k \) - angle of rotation of the beam;
- \( \Delta H \) - displacement of the slider (rod) of the RPG transducer;
- \( H \) is the stroke of the slider (rod) of the RPG transducer.

Solving the results of the equation in the following formula:
Solving an equation with two unknowns requires you to additionally establish the relationship between the quantities sought. From considering the triangles $ОА_1А_и ВА_1А$, we have:

$BA_1 = BA + OA - OA_1 - \Delta_H$,

or

$\left(BA_1\right)^2 = \left(BA + OA - OA_1 - \Delta_H\right)^2$.

When solving the equations that have been made with respect to the argument $OA_1$, we use the formula for the square of the difference of two numbers:

$OA_1 = \left(BA + AO - \Delta_H\right)^2 + OA^2 - BA^2$

Replacing the notations of the triangle sides lengths in the formula with the accepted notations of the link lengths of the slider-rocker mechanism, we have:

$OA_1 = \frac{\left((L+R) - \Delta_H\right)^2 + R^2 - L^2}{2\left((L+R) - \Delta_H\right)} = \frac{0.5\left((L+R) - \Delta_H\right)^2 + R^2}{\left((L+R) - \Delta_H\right)} - \frac{L^2}{\left((L+R) - \Delta_H\right)}$.

It is convenient to define the function $\varphi_k = f(\Delta_H)$ as

$\varphi_k = \arccos\left(\frac{K_1}{R}\right)$,

where

$K_1 = 0.5\left(K_2 + \frac{R^2}{K_2} - \frac{L^2}{K_2}\right)$;

$K_2 = R + L - \Delta_H$.

On the basis of the developed mathematical model, we calculate the angle of rotation of the rocker as a function of the movement of the slider.

The data provides the basis for constructing position plans for the slider-rocker mechanism. The relative positions of the moving slider and rocker are constantly changing, but at any given time the individual links have a defined position.

The construction of the plan starts with the depiction of fixed links and guides using the given coordinates[14]. This is followed by an illustration of the position of the slider at the set position. Then we determine the position of the rocker arm. There are several successive plans for the rocker arm to determine its trajectory.

4. Discussion of the results

Using the developed mathematical model we make calculations for the following conditions: rocker arm length $R=50$ mm, connecting rod displacement $\Delta_H=100$ mm, connecting rod length $L=50$, 100 and 150 mm.

Table 1 shows the results of the calculation.

| Table 1. Value of rocker angle $\varphi_k$ as a function of slider movement $\Delta_H$ |
|-----------------------------------------------|
| Moving slider | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| Connecting rod length | 50 | 0.0 | 25.8 | 36.9 | 45.6 | 53.1 | 60.0 | 66.4 | 72.5 | 78.5 | 84.3 | 180.0 |
| | 100 | 0.0 | 30.2 | 43.7 | 54.9 | 65.3 | 75.5 | 86.2 | 97.9 | 111.8 | 130.5 | 180.0 |
| | 150 | 0.0 | 32.1 | 46.5 | 58.4 | 69.5 | 80.4 | 91.6 | 103.8 | 117.8 | 135.9 | 180.0 |

Based on the data in Table 1, draw the position plans for the slider-rocker mechanism.
The resulting position plans are shown in Fig. 5 ((a) for a 50mm connecting rod, (b) for a 100mm connecting rod, (c) for a 150mm connecting rod).

We plotted the rocker arm motion over a full cycle for different connecting rod sizes from these position plans, as shown in Figure 6.

**Figure 5.** Position plan for the slider-rocker mechanism
(a) - connecting rod length 50 mm; (b) - connecting rod length 100 mm; (c) - connecting rod length 150 mm

Analysis of the position plans and the rocker motion graph shows that the rocker motion is equally accelerated at $b_3-b_9$, irrespective of the size of the connecting rod.
If the connecting rod size is $L=50$ mm (Fig. 5. (a)), when point $b_{10}$ is reached there is an uncertainty zone, i.e. when the slider moves from point $a_9$ to point $a_{10}$ it is impossible to predict the behaviour of the rocker arm. At this point when the slider reaches point $a_{10}$ the rocker may be at one of the points in the uncertainty zone: either $b_{10}^1$ or $b_{10}^V$.

When the connecting rod size is $L=100$ mm and $L=150$ mm (Fig. 5. (b) and (c)) there is no uncertainty zone set in the mechanism with connecting rod size $L=50$ mm. Also, with these connecting rod dimensions, the rocker arm motion trajectory differs only slightly. Therefore, based on the condition $R + L + H \rightarrow \text{min}$, for further investigation of the road power generator, a slider-rocker mechanism with the following link length ratios is adopted:

$L = 1.43H; R = 0.71H; \varphi_{k_0} = 54.9^0$

![Figure 6. Diagrams of rocker motion over a full cycle for connecting rod sizes 50, 100 and 150 mm](image)

**5. Conclusion**

1. The energy potential of the transport networks of the seaports of the Azov-Black Sea basin, as alternative sources of energy using road power generators, is estimated at 11164 MJ of energy.

2. A road power generator is proposed for generating electric power while driving a car through an artificial bump, which favourably differs from existing analogues in that the design of the impact force transducer as a slider-rocker mechanism significantly simplifies the unit design and increases its MTBF due to the use of links of the lower rotating kinematic pair "rod-rocker".

3. The study has developed a mathematical model of the slider-rocker mechanism, establishing functional dependence $\varphi_k = f(\Delta_H)$ between the angle of rotation of the rocker $\varphi_k$ and the stroke of the slider $\Delta_H$. It allows modelling the positions of links and trajectories of its points, as well as determining the speeds and accelerations of different points and links on a given law of motion of the leading link - slider.
4. The kinematic research of the slider-rocker mechanism of the impact force transducer of the port transport network road power generator has resulted in the determined correlation of the length of the mechanism links with the piston stroke, as well as the initial value of the setting angle and the final value of the angle of rotation of the rocker arm.

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