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Zero-energy snow removal system for track switch based on air forced field

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ABSTRACT

With the rapid development of railway traffic in China's alpine regions, real-time self-powered snow removal is an important route for cleaning track switch, which currently still use manual sweeping or electrical heating. These two traditional snow removal methods require large amounts of manpower or electricity. Here we propose a zero-energy snow clearing device that can continuously remove snow for switch only by track vibration. This device mainly contains a motion conversion mechanism and an air compression component. The motion conversion mechanism can amplify the micro-vibration of the rail and act as a mechanical engine (ME) that drives the air compression component to generate high-pressure air to blow off the snow at the track switch. A prototype was manufactured to demonstrate the feasibility of the design. From the high-pressure air generated by rail vibration to the process of snow removal, it is a nature cycle of no external energy consumption.

Keywords: Qinghai-Tibet Railway, Tibet Plateau, Railway snow removal, energy harvesting, self-power

1. INTRODUCTION

In recent years, the global awareness of sustainable development of electricity and energy has become increasingly intense1-3. One of the most promising ways to achieve energy sustainable development is the employment of energy-harvesting technologies from the ambient environment for sustainable operation4. This technology captures the environment's micro-energy sources such as solar, wind, thermal and vibrational mechanical energy, and enables self-powered functions for electrical equipment and distributed energy supplies. Several studies have been working to employ solar energy to drive hydrolysis5-6 and power the wearable electronic device to achieve its continuous self-power supply7-8. And small-scale wind power generation also has been successfully used as a promising sustainable technology to power electronic equipment9. Heat recovery are also known as a viable environmental energy harvesting technology10. Through the collection of environmental waste heat11-12, temperature fluctuations13 and biothermal14, micro-thermal power generation device can be manufactured to achieve sustainable self-powered supply for low-power sensors. However, the collectability of solar, windy and thermal energy sources are greatly affected by environmental weather. Distinguished from others, vibration mechanical energy is the one that is available almost everywhere and at any time, to name a few, gentle airflow, ambient sound, human body motion, ocean waves and so on. Therefore, self-powered concept based on vibration mechanical energy acquisition has become a more excellent sustainable energy utilization strategy. The two main types of vibration mechanical energy harvesting technologies are triboelectrification19-26 and piezoelectricity27-34. Self-powered technique based on triboelectrification could be applied in various fields. Electricity generated by friction between fabrics caused by human motion could serve as power supply for portable wearable devices21-23. Friction between biological tissue inside a living organism can also produce electricity as a source of power for biosensors24. Triboelectric nano-generator (TENG) based on water wave vibrational energy has be studied for the

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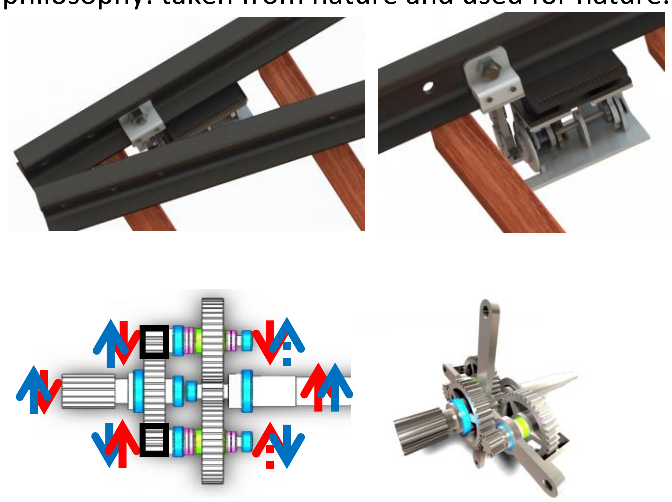
realization of self-powered sea mark and weather monitoring systems25-26. The other piezoelectric vibration energy collecting method also has been widely investigated. Recently, there have been a large number of researches on piezoelectric-based mechanical energy harvesting of human motion for continuously supply low-power wearable electronic devices27-30. Even piezoelectric mechanical energy harvesting using animal motion, such as fishtail swings for power biosensors has become a reality31. The environmental micro-vibration self-power supply technology is not only studied in the movement of organisms, but also in the field of transportation, such as energy-saving shock absorbers35-36, vibration energy collection of speed bump37 and rail vibration energy harvesting38-39. Almost all of the previous researches on rail vibration energy harvesting is to convert vibration into electricity, and then use electricity to drive electrical equipment using electromagnetic generator. As limited by the working mechanism, an electromagnetic generator usually produces a small output voltage when its size is small, so that the output power cannot be effectively matched with the electric load. And in some special cases, collecting vibrational energy and then converting it into electrical energy to power the device is not the best self-powering method. For example, the most effective way to drive an air compressor using rail vibration energy is to directly compress air through rail vibration, rather than converting the vibration into electricity and then driving the air compressor. In this paper, we propose a self-powered air compression system based on rail vibration to remove snow for track switch.

It is known that the switch is a very important component, and is a line connection device that makes the rolling stock from one lane to another. In the alpine regions of China, especially in the Qinghai-Tibet Plateau, where the railway transportation is vigorously developed, the roads often affect the normal operation of the trains due to snow accumulation. The most common method of snow removal nowadays is electric heating, which is energy intensive and costly. Another way is to manually sweep the snow, but in the harsh environment of the alpine region, this will definitely pose a threat to the safety of the snow sweepers. In this paper, we propose a new snow removal system for track switch based on air forced field. We directly utilize the micro-vibration energy of the rail to compress air. This device mainly contains a motion conversion mechanism and an air compression component. The motion conversion mechanism can amplify the micro-vibration of the rail and act as a mechanical engine (ME) that drives the air compression component to generate high-pressure air to blow off the snow at the track switch.

2. RESULTS

2.1 Design of the system framework

This paper proposes a zero-energy snow removal system based on air force field. It mainly consists of two major modules: motion conversion mechanism and air compression components. The presented snow removal device absorbs the vibration of the rails generated by a constant stream of passing trains. The motion conversion structure then converts the vertically linear vibration into a rotational motion and pushes the piston of the air compressor to produce a high pressure airflow. Finally, the high pressure air stream blows off the snow that accumulates in the track switch. The working process of absorbing vibration energy from the rails to driving the snow remover to remove snow from the rail switch has no external energy utilized. It is a renewable circulation in line with the philosophy: taken from nature and used for nature.



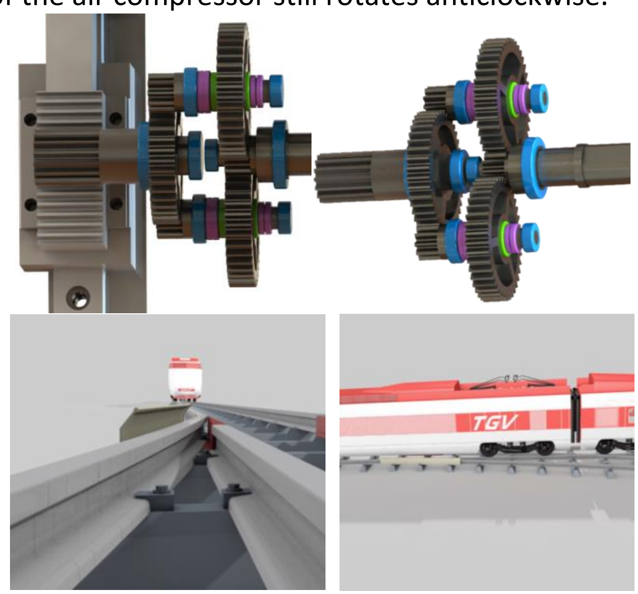
2.2 Design of the system framework

A mechanical motion conversion mechanism is designed to efficiently converting the kinetic energy of the rail tracks into driving energy for air compressor. The motion conversion mechanism primarily consists of pairs of gears and pinions for the purpose of converting the irregular vibration to smooth rotation. During operation, track vibrations are produced by the passing trains and are a source of kinetic energy. Vertical displacements affect the fixed rack with the same amplitude and frequency, and this provides input to the motion conversion mechanism. These displacements are strong in force but small in amplitude, so the motion conversion mechanism increases their amplitude while decreasing their force due to the high-ratio coupling of the gears and pinions. The motion conversion mechanism also converts the bidirectional vibrations of the tracks into unidirectional rotation for the air compressor shaft to eliminate inertia losses due to rotational direction changes.

The system is required to be secure and reliable because of the strict safety demands of railway, and the vibrations from the tracks are usually strong. The track vibrations also change frequency rapidly, which requires components that can respond quickly. Therefore, mechanical components, including gears and pinions, are used to build the energy-harvesting system with high reliability and close meshing. A pure mechanical structure without electronic control decreases the potential for problems with control and extends the durability, which makes the system very reliable. The gears and pinions are mounted steadily with a precise fit, and in this way, the gears can adapt quickly to changing vibrations. Pairs of gears and pinions with large ratios are also used to amplify the small displacements of the track vibrations.

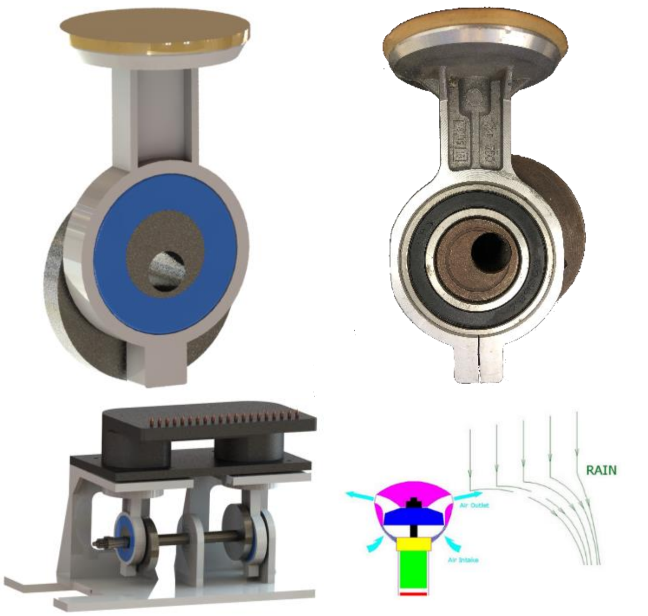
The designed energy harvesting system is 170 mm*120 mm*140 mm, as shown in **Fig**. The detailed structures are depicted in **Fig**. A fixture is designed to be mounted under the track to conduct the vibration to the rack. The rack moves vertically with the same frequency and amplitude as the track. The first gear meshes with the rack and uses pinions to amplify the displacement by different ratios of angular velocity, and the last pinion drives the air compressor shaft to rotate. All the gears and pinions are assembled on the shafts, which are fixed in the shell which is finally installed on the supporter. **Fig** shows the design of the vibration energy harvesting system. There are two one-way bearings installed inside the gears that transform the bidirectional vibration of the rack into the unidirectional rotation of the air compressor shaft. One-way bearings are positioned between the shafts and gears so that torque can be transmitted through the shafts and gears only when the one-way bearings are engaged. When in operation, the two one-way bearings always work alternatingly: when one is engaged, the other is always disengaged. When the one-way bearings are disengaged, the rotations of the shafts and gears can be different.

As shown in **Fig**, when the rack moves upward, the right one-way bearing is engaged, and torque is transmitted by the right shafts. As the left shaft does not transmit any torque, the left gear simply rotates along with the pinion on the other shaft. In this way, the input shaft of the air compressor rotates anti-clockwise. In reverse, when the rack moves downward, the left one-way bearing is engaged, and the left shaft transmits the torque. The input shaft of the air compressor still rotates anticlockwise.



2.3 Design of the air compressor.

The air compressor mainly includes two parts of the push piston and the air flow path. The unidirectional rotary motion transmitted by the motion conversion mechanism drives the piston up and down to compress the air inside the flow channel. Finally the high-pressure air generated by above process is sprayed by the high-pressure nozzle to blow up the snow accumulated in the track switch. Due to the special structure of the flow channel, the inlet cross-sectional area is much larger than the nozzle outlet area, so the air pressure inside the flow channel is very large. Therefore, the air ejected from the nozzle can directly blow off the snow on the one hand. on the other hand. Besides, it can form an umbrella-shaped air force field over the track switch to prevent snow falling into the switch. The air force field can be seen from **Fig.**



2.4 Rail track vibration analysis.

The rail track is excited by the wheels of each passing train. The weight of the train rests on the wheels and leads to the vertical deflection of both the wheels and tracks. A unified model of a train and track has been proposed to describe the vibration of the vehicle and track coupling system[38]. The vehicle is simplified, with two wheels and without bogies, because only the vibration of the tracks is investigated in this paper. This simplification of the vehicle has limited influence on the track vibration. The general model is shown in **Fig**. In this model, the vehicle structures including the bogies are assumed to be a rigid body with mass mv. The mass of vehicle is set to 53.5 tons. The damping and spring come from the suspension of the train. The track is divided into finite elements. Each element consists of a partial mass of track denoted mt, and the deformation of the track is described by the upper and lower sets of damping and spring, denoted ky1, Dy1 and ky2, Dy2, where the model is set as 1300 kN/m, 90 kNs/m, 3300 kN/m, 30 kNs/m. The track is further described by beam structures with elements shown in Fig. 6. The fastenings between the track and road are horizontally expressed by the spring and damping. The mass of the track and vertical deformation are composed of finite elements. Combining the two parts, a global dynamic equation is expressed as Eq. (1),

$$[M]\{\ddot{x}\}+[D]\{\dot{x}\}+[K]\{x\}=[F] \qquad (1)$$

where [M] is the mass matrix of the vehicle, wheels and track, [D] is the damping coefficient matrix, [k] is the spring coefficient matrix, and [F] is the force matrix.

2.5 Dynamic analysis of the MVR.

The MVR consists of gears and pinions in which friction is produced by meshing, and elasticity is one of the properties of the materials. Damping and elasticity also occur between the shafts and gears. Based on the two main considerations, a simple dynamic model of gears and pinions is established, as shown in Fig. 7 in a frontal view. The transmission is equivalently modelled as two meshing gears. The equivalent rotational inertias, spring and damping, should be derived from the ratio of the driveline. The gears and pinions are simplified with the inertia and number of gears. The meshing between them is represented as a spring and damping, and the damping and elasticity between shafts and gears are also drawn in this model. This model is described by Eqs. (2) and (3).

$$T(t)=J_1[d^2\theta_1(t)/dt^2]+(D_1+D_g)[d\theta_1(t)/dt]+T_1(t)$$

(2)

$$T_2(t)=J_2[d^2\theta_2(t)/dt^2]+D_2[d\theta_2(t)/dt] \qquad (3)$$

where J1 and J2 represent the rotational inertias of the two gears, D1, D2 and Dg are the damping forces on the shafts and the gears, h1 and h2 represent the rotational angles of the two gears, and T1 and T2 represent the torques acting on the gears. Considering the ratio r between the gears and ratio, the dynamics can be drawn as

$$T(t)=(J_1+r^2J_2)[d^2\theta_1(t)/dt^2]+[D_1+D_g+(z_1/z_2)^2D_2][d\theta_1(t)/dt]$$

(4)

The one-way bearings change only the direction of one shaft. In this model, the dynamics are ignored.

2.6 Compress air flow analysis.

To facilitate this research, the following assumptions were made: (1) The working fluid (air) of the system follows all ideal gas laws. (2) There is no leakage between the chambers, the area of the piston rod end is too small to be considered, and the effective areas of all intake and exhaust ports are the same. (3) Supply temperature is equal to atmosphere temperature. (4) The flow of air moving into and out of the chambers is a stable one-dimensional flow that is equivalent to the flow of air through the nozzle contraction.

Because there is no leakage in either chamber, the chambers do not charge and exhaust air simultaneously. Consequently, the energy equation for the discharge and charge side of each chamber can be illustrated by the following equations:

Energy equation:

$$C_vW\frac{d\theta}{dt}=(S\cdot h_c+C_v\cdot G)(\theta_a-\theta)+RG\theta_a-PAu \qquad (5)$$

$$C_vW\frac{d\theta}{dt}=S\cdot h_d(\theta_a-\theta)+RG\theta_a-PAu \qquad (6)$$

Equation of continuity:

From the law of mass conservation, air mass can be given as:

$$\frac{dW}{dt}=G$$

Air mass flow is calculated from the flow equation, which is described later on.

Flow equation:

According to the ratio P_l/P_h, the flow equation for the flow through a restriction can be written as follows:

$$G=\begin{cases}\frac{A_e P_h B}{\sqrt{\theta_h}}\varphi(P_h,P_l);\frac{P_l}{P_h}>0.528\\ \frac{A_e P_h D}{\sqrt{\theta_h}};\frac{P_l}{P_h}\le 0.528\end{cases} \quad (7)$$

where

$$\varphi(P_h,P_l)=[(\frac{P_l}{P_h})^{\frac{2}{k}}-(\frac{P_l}{P_h})^{\frac{k+1}{k}}] \quad (8)$$

$$B=\sqrt{\frac{2k}{R(k-1)}} \quad (9)$$

$$D=(\frac{2}{k+1})^{\frac{1}{k-1}}\sqrt{\frac{2k}{R(k+1)}} \quad (10)$$

Motion equation:

The velocity of the piston is calculated from Newton's second law of motion. In this paper, the friction force model is considered to be the sum of the Coulomb friction and viscous friction. The viscous friction force is considered to be a linear function of piston velocity. The forces on the piston of the booster are shown in Fig. 3. The right side was considered to be the positive direction of the vector. The motion equation of the piston can be given by the following equation:

$$\frac{d^2x}{dt^2}=\begin{cases}\frac{1}{M}(P_{dA}\cdot A_d-P_{dB}\cdot A_d+P_{bA}\cdot A_b-P_{bB}\cdot A_b-F_f),x\neq 0,L\\ 0,x=0,L\end{cases} \quad (11)$$

where

$$F_f=\begin{cases}F_s,v=0\\ F_c+C_u,v\neq 0\end{cases} \quad (12)$$

State equation:

Pressure changes in the air in each chamber can be obtained by deriving the state equation of ideal gases:

$$\frac{dP}{dt}=\frac{1}{V}[\frac{PV}{\theta}\cdot\frac{d\theta}{dt}+R\theta G-PAu] \quad (13)$$

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