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Harvesting energy from the vibration of a passing train using a single-degree-of-freedom oscillator

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ABSTRACT

With the advent of wireless sensors, there has been an increasing amount of research in the area of energy harvesting, particularly from vibration, to power these devices. An interesting application is the possibility of harvesting energy from the track-side vibration due to a passing train, as this energy could be used to power remote sensors mounted on the track for strutural health monitoring, for example. This paper describes a fundamental study to determine how much energy could be harvested from a passing train. Using a time history of vertical vibration measured on a sleeper, the optimum mechanical parameters of a linear energy harvesting device are determined. Numerical and analytical investigations are both carried out. It is found that the optimum amount of energy harvested per unit mass is proportional to the product of the square of the input acceleration amplitude and the square of the input duration. For the specific case studied, it was found that the maximum energy that could be harvested per unit mass of the oscillator is about 0.25 J/kg at a frequency of about 17 Hz. The damping ratio for the optimum harvester was found to be about 0.0045, and the corresponding amplitude of the relative displacement of the mass is approximately 5 mm.

1. Introduction

Energy harvesting devices used to scavenge energy from ambient vibrations have been intensively studied during the past few years, mainly because of the need to power wireless devices, or to have autonomous solutions to augment the use of batteries [1,2]. A linear spring–mass–damper system has been the most common type of energy harvesting device, due to its simplicity. For harmonic excitation, good performance is achieved when the device is tuned so that its natural frequency coincides with the frequency of excitation [3].

Most of the previous studies in energy harvesting from vibrations have focussed on situations where the energy is harvested for a period of time long enough such that the initial transient response of the oscillator is negligible compared to the steady-state response [4–8]. If the damping in the harvester is low, however, which may be the case to increase the energy harvested in each cycle, the result would be that a relatively long initial transient would occur before the system

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reaches its steady-state. This is a major limitation in some practical cases where there is time-limited excitation [9]. The initial transient may have a detrimental effect on the harvester performance if a classical design approach based on steady-state behaviour is considered.

In this paper, the energy harvested from the track-side vibration induced by the passage of a train is studied, as a specific practical application of time-limited excitation, where there is only significant vibration input for the duration of the train passage. A preliminary but not comprehensive investigation on this topic was recently presented by the authors in [10]. Such energy could be used to power or recharge batteries of rail-side equipment, such as wireless sensors for monitoring railway track health and temperature, warning light systems etc. Such applications are of particular importance in remote areas, where there is a lack of electrical infrastructure. A related area is the harvesting of energy from train suspensions [11], but this is considered to be a more classic case of harvesting energy from steady-state vibration and is well-covered in the literature.

Some research work in the area of scavenging energy from trains has recently focused on the design of specific harvesting devices from the technological and electro-mechanical point of view. For instance, an electromagnetic mechanism converting pulse-like linear vibration into regulated rotational motion was presented in [12]; a wide-band piezoelectric harvester was designed in [13] to generate power in various frequency regions; a piezoelectric generator installed under the sleeper, was used to scavenge energy from vertical vibrations of the track [14]; a device mounted on rail-ties (sleepers) was used to converted the vertical displacement of the rail into electrical energy through mechanical amplification and rectification [15]; a comparison between an inductive coil device driven by the vertical rail displacement, and a piezoelectric device driven by the longitudinal strain produced by rail bending was presented in [16]. Several other power harvesting devices capable of scavenging power from the vertical deflection of railroad track are discussed in [17], and simulations on the maximum power potential for different prototypes along with their optimal number and location are presented in [18]. However, in all work cited above, no insight is given regarding the fundamental theory of vibration energy harvesting from time-limited excitation, which is the basis for the development of physical prototypes and devices.

The aim of this paper is thus to present a fundamental investigation on the maximum available energy that could be potentially harvested from a passing train using a linear single-degree-of-freedom oscillator. Using an acceleration time history of vertical vibration measured on a sleeper during the passage of an Inter-city 125 train in the United Kingdom, passing at a speed of about 195 km/h, the optimum mechanical parameters of a linear energy harvesting device are determined. Since the operational frequency range of the harvester is below 35 Hz, the dynamics of the railway track are ignored. This would not be the case, however, when the train passes over a bridge, for example, where bridge dynamics could be exploited as well [19].

A preliminary numerical simulation is first performed to determine the optimum mechanical parameters. A theoretical study is then presented in which an approximate analytical formulation is proposed taking into consideration the optimal design of a linear single degree-of-freedom oscillator to scavenge energy from time-limited harmonic oscillations. The analytical study facilitates some general guidelines for the mechanical design of a harvester for train-induced vibrations.

2. Optimal parameters of an energy harvester – numerical study

The vertical acceleration of a sleeper was measured at Steventon on the Great Western Main Line in the UK as an Inter-city 125 train at a speed of 195 km/h (54.2 m/s) passed by. The track consists of continuously welded rail attached by spring clips and supported via rubber pads on concrete monoblock sleepers in ballast. The accelerometer was located at the center of the sleeper, but it may be noted that in the low frequency range below 50 Hz the whole sleeper vibrates as a rigid body. The track is raised on a shallow embankment, approximately 0.7 m above the level of the surrounding fields. The ground at the site consists of deep layers of clay; for more details see [20]. The train consists of two diesel power cars, one at each end, with seven passenger coaches between them. Each vehicle is supported by four wheel-sets arranged in two bogies, each of which has a wheelbase of 2.6 m. The power cars are about 18 m long, while the passenger coaches are about 23 m long. Seven seconds of data were recorded at a sampling frequency of 1 kHz as the train passed by, and the resulting acceleration signal is shown in Fig. 1(a). The power spectral density of the acceleration signal is shown in Fig. 1(b) up to a frequency of 35 Hz. At the top of this figure, another frequency axis is shown, which is the actual frequency normalized by S/L, where S is the train speed and L is the length of the passenger carriages. It can be seen that the peaks in the spectrum appear to be integer numbers of the ratio S/L, which were referred to as the trainload dominant frequencies in [21]. It can also be seen that the maximum acceleration occurs when the non-dimensional frequency is equal to 7, which corresponds to a frequency of about 17 Hz for this speed.

The acceleration signal shown in Fig. 1(a) is considered to be the base input to the energy harvesting device shown in Fig. 2, which is a single-degree-of-freedom mass–spring–damper system encased in a rigid housing. It is assumed that the vibration of the energy harvesting device does not affect the vibration of the sleeper. For the sake of simplicity in this fundamental study, it is further assumed that the energy harvested is the same as the energy dissipated by the damper, and this identifies the ideal upper-limit case where no mechanical loss is considered. As the harvester is encased in a rigid housing, the maximum relative displacement of the mass is limited to $|z|_{max}$, where $z=x-y$ is the relative displacement between that of the mass x, and the casing y. The equation of motion for the energy harvesting device is given by

$$m\ddot{z}+c\dot{z}+kz=-m\ddot{y} \tag{1}$$