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Vibration energy generators for low-frequency spectral excitations

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Abstract

The presented study shows determinations of expected values of output power on the basis of the spectral description of the excitation (PSD). The output power of vibration energy generators for different low-frequency spectral excitations is compared for different spring approaches, i.e. linear stiffness with mechanical stops, hardening spring and bi-stable system. Results show that nonlinear springs do not necessarily increase the mean output power.

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Keywords: energy generator; spectral excitation; low-frequency; duffing oscillator; hardening spring; bi-stable system

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1. Introduction

Recently, the application range of energy-autonomous sensor nodes is growing up. In the vicinity of kinetically excited components, the use of vibration energy generators is desirable. Depending on the magnitude of the required output power, the mechanical-electrical conversion is carried out by micro-mechanical or mesoscopic systems. The first energy generators were realized as resonant systems for sinusoidal excitation with fixed excitation frequency [1]. However, practical applications for human devices or in automotive environment usually show broadband or multi-modal excitations. A review of broadband vibration energy harvesting techniques is given in [2].

The aim of the study is to determine optimal system parameters for a customized vibration energy generator using nonlinear springs. Although nonlinear springs can achieve higher bandwidth the example in Section 3 shows that

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higher bandwidth does not necessarily lead to a higher output power. Furthermore, it is shown therein that a reliable prediction of the output power by means of the measured frequency sweep is not possible. Therefore, in Section 4 the target parameter optimization is realized on the basis of simulations in the time domain.

2. Model description

The aim of the study is to determine optimal system parameters for a vibration energy generator which supplies a sensor node located close to a wheel suspension of a car. Fig. 1 shows a measured excitation spectrum at the wheel suspension of a car at 120 km/h. The acceleration spectrum is approximated by a triangular spectrum (Fig. 1b). For comparison, a rectangular excitation spectrum with the same integral PSD value is also considered (Fig. 1c).

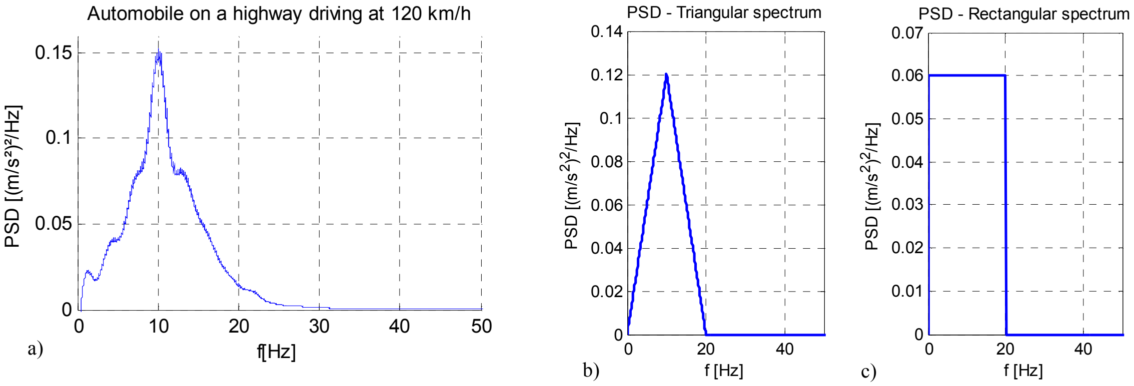

Fig. 1: (a) Sample broadband excitation spectrum of the vertical acceleration of a wheel suspension at highway driving at the speed of 120 km/h; Approximated (b) triangular and (c) rectangular excitation spectra of the study having the same integral PSD value as PSD in (a).

The operation mode of a vibration energy generator can be described as inertial mass-spring-damping system. A seismic mass is connected with the excited housing by a spring. By a mechanical-electrical conversion of the oscillating mass, energy is extracted and converted into electrical energy. Equivalent to the mechanical damping, this can be described by an electrical damping. The adaptation of the converter to the excitation is effected by the choice of the spring characteristic. Based on examinations of linear springs [3], nonlinear and bi-stable spring mechanisms were investigated.

For systems with nonlinear springs the value of the mean output power in steady state depends on the phases of the exciting harmonics. Hence a reliable calculation of mean output power requires several simulations with different sets of phases. Assuming uniformly distributed phases mean value and standard deviation of mean output power are evaluated by numerical simulations in the time domain using MATLAB/Simulink®.

The maximum spring deflection also depends on the phases of the harmonics which are used to simulate an excitation according to the requested spectrum. In all analyzed cases, mechanical stops must be implemented to prevent overloading of the spring. The demonstrator with a given mass of 50 g has a limitation of deflection z_m of 1.4 mm. The mechanical damping of the system is assumed to 0.1 kg/s. The electrical damping is optimized for each spring parameter in order to achieve maximum output power.

The descriptions of spring characteristics are specified by Duffing oscillator. The relationship between deflection x and spring force F_{spring} is described by the spring constants k_1 and k_3 as

$$F_{spring} = k_1 x + k_3 x^3. \qquad (1)$$

Corresponding to linear stiffness k_1 the equivalent linear eigenfrequency $f_{e.l.e}$ is defined. For hardening springs the nonlinearity is described by the percentage nl of the linear spring force at maximum deflection z_m. For bi-stable systems the nonlinearity is described by the stable equilibrium position z_{stable}.

$$f_{e.l.e} = \frac{1}{2\pi}\sqrt{|k_1|/m}; \qquad nl = 100\frac{k_3}{k_1}z_m^2; \qquad {z_{stable}}^2 = \frac{|k_1|}{k_3} \tag{2}$$

3. Test of methods for calculation of mean output power

For simplicity in this section we investigate only systems without mechanical stops. For a nonlinear system with hardening spring a frequency sweep with a constant excitation amplitude of a=1 m/s² was calculated by simulation. The result is shown in Fig. 2a. The difference between frequency up- and down-sweep can be seen. Only for comparison a linear system with resonant frequency of 10 Hz is considered. For the linear system the mean output power which is generated by the triangular spectrum given in Fig. 1b can be calculated directly from the transfer function. For the example this is 1.7 mW. Applying the same method for the nonlinear system the calculated mean output power using the frequency up curve equals 2.6 mW and for the frequency down curve equals 0.5 mW. Calculating the mean output power in time domain the mean value of 1000 simulations equals 1.5 mW. Fig. 2b shows the distribution of the mean output power values.

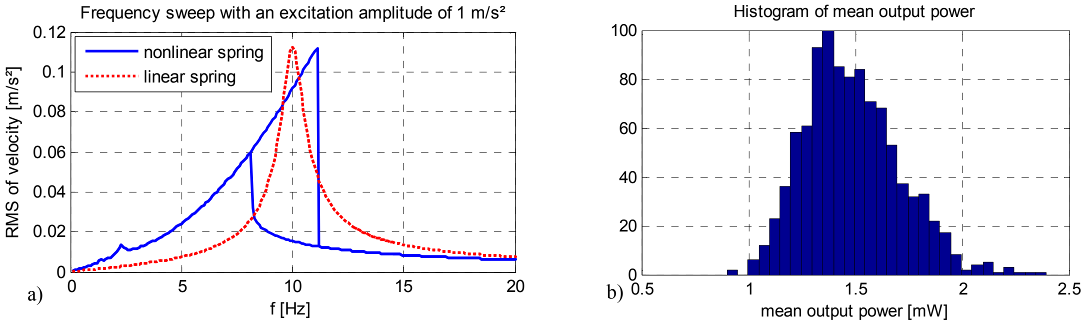

Fig. 2: (a) Frequency sweep of linear and nonlinear system; (b) Histogram of the mean output power for the nonlinear system

The comparison of the output values for the nonlinear system shows that no reliable prediction can be derived from the frequency sweeps. As already shown in numerous references for wideband energy generators, non-linear springs have a higher bandwidth [4], but this does not produce the often expected higher output power. Main reason is that superposition is not applicable for the nonlinear system.

4. Result of time simulations

By means of simulation in time domain optimal parameters for stiffness and damping were searched. For every pair of stiffness parameters the mean value of the mean output power was calculated for different electrical damping values. The mean value was taken from 100 time series. Figs. 3-4 show mean values of the mean output power in steady state for the optimal damping value depending on the stiffness parameters.

The result of the simulations is that nonlinear springs do not increase the mean output power. For the triangular spectrum which approximates the measured excitation at the wheel suspension the maximum mean output power is about 0.95 mW with a standard deviation of about 0.01 mW for the linear system. The maximum results of the nonlinear systems are almost equal with standard deviations up to 0.08 mW. This output power is sufficient to supply a sensor node. The rectangular spectrum with the same energy content generates less power. The maximum value is about 0.61 mW with standard deviations of about 0.04 mW. The sensitivity of the output power to the spring parameters is lower for rectangular spectra in the investigated range.

5. Conclusion

The result of the studies of various non-linear characteristics is that for the investigated excitation spectra no higher output power is achieved compared to the linear spring. In particular, very sharp triangle spectra resemble a sinusoidal excitation and therefore can be converted most effectively by a linear spring. In further work, the tests will be extended to softening springs.

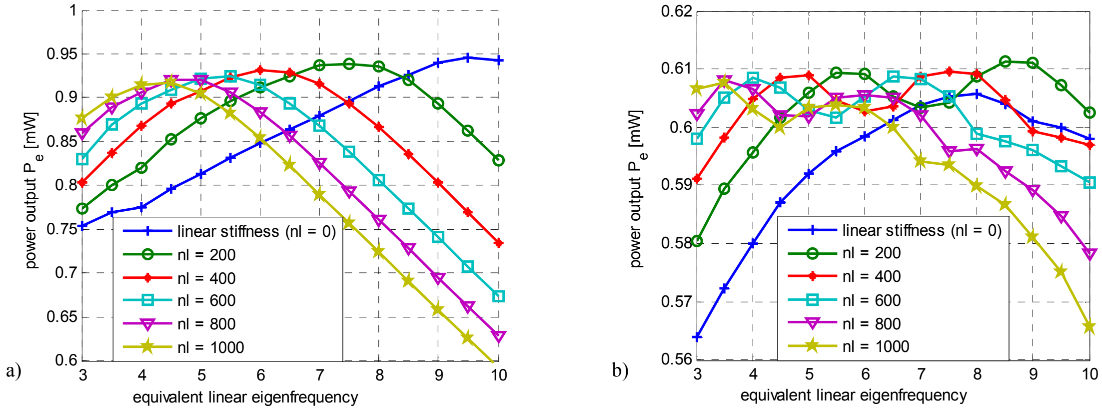

Fig. 3: Mean values of the mean output power for the hardening springs depending on the nonlinearity (nl) for triangular (a) and rectangular (b) spectra.

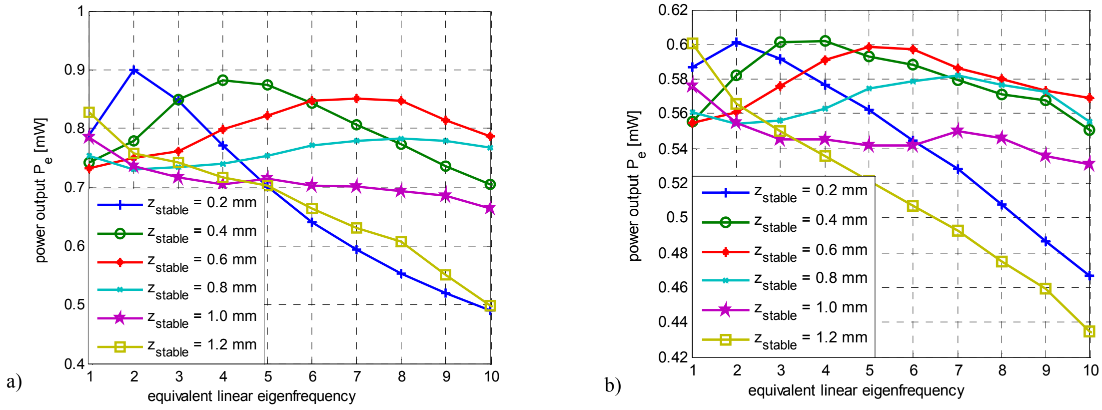

Fig. 4: Mean values of the mean output power for the bi-stable model depending on the stable deflection for triangular (a) and rectangular (b) spectra.

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