A Design of Mechanical Frequency Converter Linear and Non-linear Spring Combination for Energy Harvesting

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Abstract In this study, the improvement of energy harvesting from wideband vibration with random change by using a combination of linear and nonlinear spring system is investigated. The system consists of curved beam spring for non-linear buckling, which supports the linear mass-spring resonator. Applying shock acceleration generates a snap through action to the buckling spring. From the FEM analysis, we showed that the snap through acceleration from the buckling action has no relationship with the applied shock amplitude and duration. We use this uniform acceleration as an impulse shock source for the linear resonator. It is easy to obtain the maximum shock response from the uniform snap through acceleration by using a shock response spectrum (SRS) analysis method. At first we investigated the relationship between the snap-through behaviour and an initial curved deflection. Then a time response result for non-linear springs with snap through and minimum force that makes a buckling behaviour were obtained by FEM analysis. By obtaining the optimum SRS frequency for linear resonator, we decided its resonant frequency with the MATLAB simulator.

1. Introduction

The Energy harvesting (EH) technologies have been studied for a wide research region [1]. We are focusing on the vibration type energy harvester (VEH) for human application [2]. In the majority of the previous works, the linear vibration mechanism has been used for large vibration amplitude at resonant situation. However, that kind of ideal resonance can hardly be obtained from an actual ambient vibration e.g. automotive or human movement. Thus, some group try to generate energy from the wideband or unstable vibration with nonlinear spring structures [3] [4].

In this study we propose a novel combination of linear and nonlinear spring structures for VEH fabricated by the MEMS (Micro Electro Mechanical Systems) technology. The nonlinear part that generates shock acceleration is realized by the snap through behaviour of a curved clamped-clamped beam spring. Then the generated shock acceleration is applied to another involved linear resonator system for harvesting energy. By using this combination, we can generate shock acceleration with uniform duration and a high mechanical Q factor linear resonator.

The Q factor for the linear dumped oscillation resonator directly impacts the harvested energy. We can design a high Q factor resonator separately without buckling mechanism. In our previous work, we successfully generated about 10 µW power at the resonance frequency of 433 Hz, and 200 µm amplitude from the electret type harvester with a Q factor of 130. High Q device shows large output however it has very narrow bandwidth to resonance. Thus we consider the combination of our linear electret harvester with additional shock generation mechanism with buckling spring. This method can...
be useful not only to electret type but also any vibration type harvester. On the other hand, the nonlinear spring system shows good performance for the random vibrations. A bistable type VEH can effectively collect mechanical power from the wideband frequency, however it mainly generates energy during snap through behaviour because of its low Q factor. In next section, we explain a design method for nonlinear buckling spring and evaluate a time response of its buckling behaviour.

2 Designs of spring combination

The proposal design of our combination device is shown in figure 1. A pair of clamped-clamped curved beam-spring supports an inner frame. The inner frame contains the linear resonance harvester with high Q factor. By applying external acceleration to the harvester (Fig. 2a), the inner frame shows snap through movement (Fig. 2b). The snap through behaviour generates high and uniform acceleration as shown in Fig. 2(c). It means that the output frequency always constants against various external oscillation. Then from the maximum shock response by SRS (Shock response spectrum) analysis, the resonant frequency of the linear resonator can be obtained.

2.1 Buckling spring design

From the theoretical calculation, buckling beam displacement depends on the applying force and on its stiffness. However the initial shape of our buckling spring is not straight but curved. The beam stiffness and required force for the snap through action are then calculated by the FEM software (ANSYS 15). Figure 3 shows the simulation model, the beam length $L$ is 10 mm, beam width is 60 $\mu$m, beam thickness is 525 and the initial deflection was varied from 50 $\mu$m to 200 $\mu$m. The proof mass size is 10 mm $\times$ 10 mm $\times$ 525 $\mu$m, 0.12 mg. We just considered the simplified mass instead of the inner frame resonator and two curved beam springs for preliminary calculation.
The Simulation result is shown in figure 4. Buckling displacement and required force for snap through were decreased by initial deflection. The initial deflection controls the nonlinear spring stiffness.

We also made the transient analysis of the curved spring model. Figure 5 shows the applied acceleration with frequency of 10 Hz, amplitude of 100 g and the simulated result of displacement for an initial deflection $\delta$ of 100 $\mu$m. Because of the lightweight mass and high spring-stiffness, large amplitude of acceleration was required for the snap-through to occur, however the result shows the snap-through behavior clearly as expected.
2.2 SRS optimized damped oscillation

From a shock acceleration of snap-through action as described above, the curved snap-through displacement and its duration time are extracted. From the response to the applied snap-through shock, we can evaluate the damped oscillation for the inner linear resonator. The vibration waveform was calculated by using the MATLAB software as shown in figure 6. There are two setting parameters of linear spring, the $Q$ factor of 130 and the resonant frequency of 433 Hz. These parameters are decided from our previous work. In the result, the damped oscillation occurred at each snap-through shock acceleration. The response has however not been optimized yet.

3. The shock response method for inner linear spring.

The SRS analysis is a well-known method to evaluate a response for shock. In order to optimize the spring parameter design, we introduce the SRS analysis as a spring combination tool. The simulation flow of SRS is shown in figure 7, which consists of four parts. The first step, the shock acceleration waveform from ANSYS is simulated, and then converted to the MATLAB analysis data. The second, the two parameters of resonant frequency $\omega$ and damping coefficient $\zeta$ are set. Next, the equation of motion is solved for increasing values of $\omega$. The result shows damped oscillation that depends on the parameters $\omega$ and $\zeta$. By recording the maximum displacement of the oscillation, the SRS result can be obtained as Figure 8. Considering the SRS result, it is shown that if we design the linear resonator with a 250 Hz resonant frequency, 3.6 times larger displacement will be applied to the linear resonator than on the nonlinear spring, which will also improve greatly the generated power.
4. Conclusion

We reported the optimum design for mechanical frequency converter by using linear and nonlinear spring combination. The spring stiffness and motion for snap-through behaviour of a nonlinear buckling spring are simulated. From the result, the SRS optimized resonant frequency design of the linear resonator is investigated. Matching the SRS maximum frequency, the linear resonant harvester in damped oscillation mode will be applied 3.6 times larger initial displacement from the wideband applied acceleration.

Reference

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