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Efficient Nonlinear Energy Harvesting with Wrinkled Piezoelectric Membranes

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Abstract: We investigate the performance of a piezoelectric energy harvester with nonlinearity induced by wrinkles. Linear and nonlinear regimes are detected in the electric response of the device when sweeping the intensity of the external excitation. Those regimes are related to the activation of a nonlinear mechanical response that appears when increasing the excitation amplitude. The wrinkles have been found to improve the power density and the normalized power density, in a certain noise power range.

Keywords: nonlinear energy harvesting, wrinkled membrane, MEMS

Introduction

Energy Harvesting (EH) has demonstrated to be a good solution for the power needs of the so called Information and Communication Technologies (ICTs) when energy autonomy and wireless communication are required (Seah, Eu, and Tan 2009; Priya and Inman 2009; Paradiso and Starner 2005; Orfei et al. 2013; Ferrari et al. 2008; Vocca et al. 2012). The main goal of EH is to enable electronic devices to be operated without batteries and, to achieve this, a minimum amount of a few mW is needed.

The role of mechanical nonlinearities for energy harvesting purposes has been widely addressed in the last years (Gammaitoni et al. 2012; Guyomar et al. 2005). In particular, many efforts have been devoted to study and characterize the response of bistable systems under wideband mechanical (Ferrari et al. 2010; Soliman et al. 2008; Stanton, McGehee, and Mann 2010; Arrieta et al. 2010) and their capability of increasing the generated electric power in com parisonto the power output of linear oscillators (i.e. resonators). Bi-stability is commonly induced by means of electromagnetic repulsion (Cottone, Vocca, and Gammaitoni 2009) electrostatic interaction (López-Suárez et al. 2013) or mechanical stress (Cottone et al. 2012; López-Suárez et al. 2011). However bi-stability is not the only kind of nonlinearity which could help to increase the performance of energy harvesting devices (Gammaitoni, Neri, and Vocca 2009).

In this paper we present an analysis of a nonlinear energy harvesting device based on a piezoelectric membrane which presents internal mechanical stresses produced during the fabrication process by applying thermal gradients. The consequent mechanical nonlinearity produces an increment in two figure's of merit commonly used to describe the performance of EH devices: power density (PD) and normalized power density (NPD) (Roundy 2005; Beeby et al. 2007).

Material and methods

The considered harvester is an aluminium nitride (AlN), $750\times750\ \mu m^2$, doubly clamped membrane (see Figure 1(a)). A schematic cross section of the device, showing the geometry and thickness of the layer and the position of the electrodes, is given in Figure 1(b). In this configuration the stress generated by the deformation of the piezoelectric layer is transduced to a polarization change along the thickness of the transducer, producing a voltage difference across the electrodes. The electric power generated by the device is evaluated by considering a pure resistive load, R_L, allowing to estimate the root mean square of the power as $P_{rms}=V_{rms}^2/R_L$.

The wrinkled membrane is mechanically excited through an external piezoelectric shaker (Piezo System TS18-H5-202). The membrane is mounted on a PCB board and connected to the shaker though an opto-mechanical support. The setup of the experiment is presented in Figure 1(c). The value of acceleration (a_{rms}) is changed modifying the displacement amplitude at fixed frequency bandwidth, and it is measured by an accelerometer attached to the sample, allowing to record the vibration time series. While the signal generated to drive the shaker is a band-limited ($0-50$ kHz) white Gaussian noise, the support itself acts as a mechanical filter that changes the frequency distribution of the vibrational energy,

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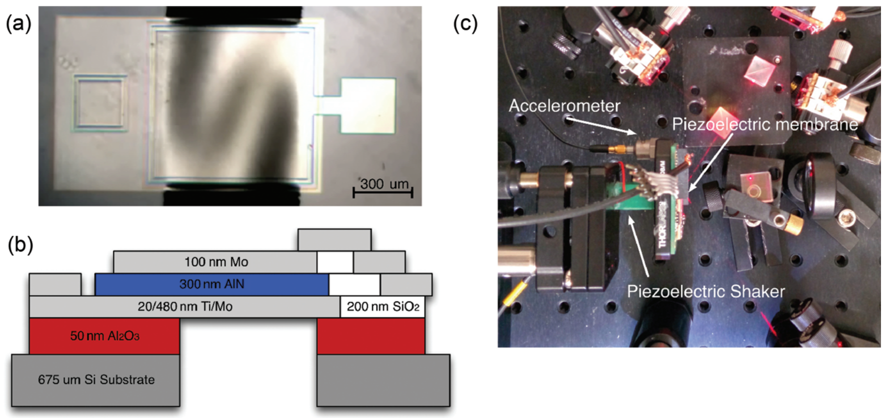

Figure 1: (a) Optical image of the piezoelectric membrane showing the electric paths contacting the upper and lower electrodes. (b) Schematic cross section of the structure showing the materials stack that form the harvester. (c) Schematic of the experimental setup.

producing a coloured noise excitation as showed in Figure 2. The shape of noise PSD does not change modifying the amplitude of the noise.

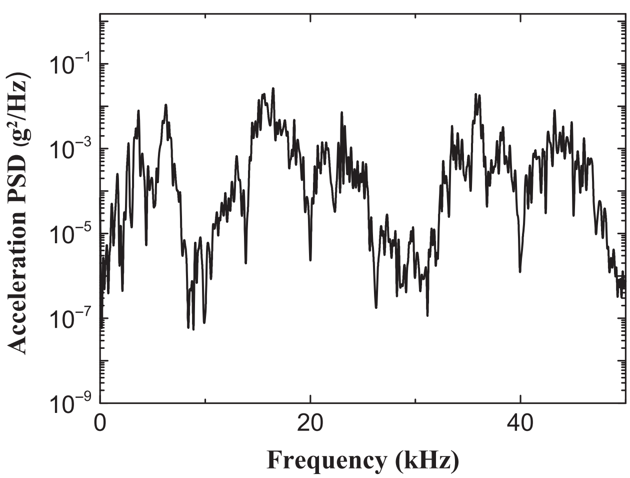

Figure 2: Power spectral density of acceleration with 8.6g of standard deviation used for the measurement. It is evident that the action of the mechanical support modifies the frequency spectra of the original signal.

The performances of the harvester are evaluated in terms of PD, defined as

$$PD_{rms} = \frac{P_{rms}}{volume} \left(\mu W\, cm^{-3}\right)$$

and in terms of NPD, defined as

$$NPD_{rms} = \frac{P_{rms}}{volume \times {a_{rms}}^2} \left(\mu W\, cm^{-3}\, g^{-2}\right)$$

The volume is computed considering the dimension of the active part of the membrane.

Notice that the PD does not take into account the value of acceleration under which the harvester is subjected, while the NPD accounts only on the value of acceleration but does not consider the frequency content.

Electrical Response

The optimal load, R_L, was estimated by exciting the wrinkled membrane with low acceleration white noise, resulting in an optimal value of 20 kΩ. This value is then used for all the results presented in this work. The electrical response of the harvester when sweeping the vibration intensity is shown in Figure 3. Three different regimes can be identified in terms of PD (squares). Since stresses from the membrane cannot be removed it is not possible to compare directly the device under test with the corresponding linear device. However for small accelerations the system can be approximated to a linear system. This is confirmed considering low intensity accelerations, i.e. up to 4 g, where the PD increases proportional to ${a_{rms}}^2$ (see inset of Figure 3) following the trend

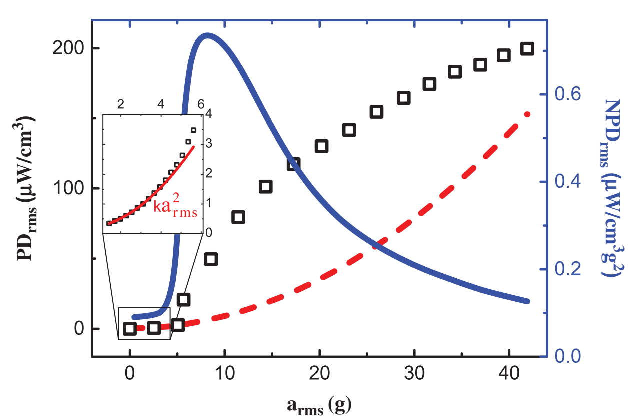

Figure 3: Generated PD (squares) and NPD (solid line) under a broadband mechanical excitation. The red dashed-line represents the trend of the PD for a linear system (i.e. proportional to ${a_{rms}}^2$). The NPD shows a peak indicating the existence of an optimal region (~8 g) of work for the energy harvesting device. Inset: Trend of the generated power density for the system at low acceleration excitation following the typical trend of linear systems.The presence of nonlinearities is more evident evaluating the NPD (blue line). The expected value for this metric is constant for a linear system while in this case a maximum is present for $a_{rms} = 8g$.

expected for linear systems (Beeby et al. 2007).This trend is used as reference for comparing the linear behaviour with the nonlinear. For accelerations ranging from 4 g to 8 g the nonlinearities start playing an important role, increasing the performance of the harvester in comparison to the trend for a linear system represented by the red dashed line. For higher accelerations the generated PD increases more slowly. The PD and NPD show different trends since PD is defined as the harvested power per volume unit, while NPD is expressed as PD normalized by the mean square of the input acceleration.

In order to maximize the electrical power generated by the harvester, it is necessary to maximize the mechanical power of the system. The mechanical power is dissipated partially through the mechanical-electrical coupling mechanism (i.e. piezoelectric effect), and partially by the structural and viscous damping. The viscous damping is usually produced by the interaction with the surroundings (i.e. air), thus it is quite common to consider energy harvester operating in partial vacuum (Cavallier et al. 2005; Stephen 2006; Elfrink et al. 2009). The magnitude of the output power for piezoelectric linear generators is given by:

$$|P| = \frac{m\zeta_e\omega_0\omega^2\left(\frac{\omega}{\omega_0}\right)^3 Y^2}{\left(2\zeta_T\frac{\omega}{\omega_0}+1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2}$$

where ζ_e is the electrical damping, ω_0 is the angular resonance frequency, m is the mass, Y the amplitude of external excitation and ζ_T is the combined damping ratio (mechanical and electrical). The mechanical damping, or its counterpart the quality factor, depends on various factors (e.g. viscous damping, the clamp recoil losses, thermoelastic damping and so on). To evaluate the impact of damping induced by air in the considered harvester the whole system is mounted in a vacuum chamber. Due to the wrinkles on the membrane it is not possible to optically measure the motion of the structure, and thus it is not feasible to evaluate the quality factor from the mechanical response. However the quality factor Q has been evaluated considering the electrical response of the system and has been estimated with the ring-down method, fitting the envelope of the ring-down after removing the driving excitation with an exponential law. The measured quality factor in air and vacuum ($1.8 \cdot 10^{-5}$ mbar) are respectively $Q_{air} = 110$ and $Q_{vacuum} = 244$, demonstrating that the mechanical energy of the system is increased when vacuum is produced in the chamber. Since the mechanical power is higher in vacuum, the performance of the harvester on vacuum

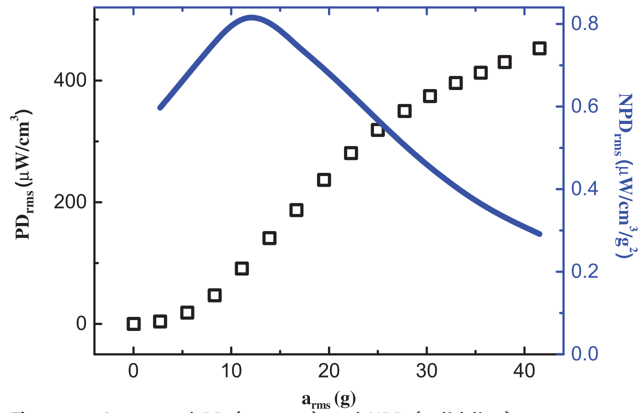

Figure 4: Generated PD (squares) and NPD (solid line) at $1.8 \cdot 10^{-5}$ mbar. The device stills show the peak, reaching a value of 0.8 $\mu W/cm^3 g^2$, on the NPD representation although it is shifted towards ~12 g. The maximum value of the PD, 450 $\mu W/cm^3$, represents an increase by more than a factor of 2 compared to the outcome in air.

will be notably increased as reported in Figure 4. In this scenario the PD increases from $\sim 200\,\mu W/cm^3$ to $\sim 500\,\mu W/cm^3$, The increase of the maximum in the NPD is less noticeable, approximately 14%, in this case the maximum is located at different values of acceleration, slightly greater for the vacuum case.

Higher Order Spectral Analysis

To investigate the nonlinear behavior in more detail, we perform a higher order spectral analysis, using the HOSA toolbox (MathWorks et al. 1998) in Matlab. In particular bispectrum and bicoherence analysis can give information on Gaussianity and linearity of the signal respectively. Similar information can be extracted by statistical test like the Hinich's Gaussianity and linearity tests (Hinich 1982). Three different electrical signal responses have been selected for the Gaussianity and linearity tests. The first one refers to the harvester subjected to an acceleration of 2.9 g, where the system is in the linear regime, according to the trend highlighted in the inset of Figure 3. The second and the third refer respectively to acceleration of 8.6 g and 17.2 g, both in the nonlinear regime.

By performing Gaussianity and linearity tests on the time-domain signals, using the respective functions from the HOSA toolbox, we find that for 2.9 g the system behaves linearly. The Hinich's test reports a high probability of false alarm ($Pfa = 1$) on the Gaussianity test meaning that the Gaussian hypothesis cannot be rejected. In this case, the data are Gaussian, hence, also linear. For the higher accelerations clear signatures of nonlinearity are observed. In fact the Hinich's test for the two signals reports a very low *Pfa* equal to 0 and 0.14, respectively for the Gaussianity test. In this case we can reject the Gaussian hypothesis for both signals and thus we can consider the linearity test. In the linearity test the range $R_{estimated}$ of values of the estimated bicoherence is computed and compared to theoretical range R_{theory} of a chi-squared with two degrees of freedom and non-centrality parameter *lambda*. For the second signal the test reports $R_{estimated} = 1.0432$, $lambda = 1.7155$ and $R_{theory} = 3.919$. The test on the third signal reports $R_{estimated} = 1.1203$, $lambda = 1.5296$, $R_{theory} = 3.7524$. Since the estimated and theory R values are quite different for both signals we can conclude that the signals are also nonlinear.

We now turn our attention to a more quantitative analysis of these nonlinearities, which appear to play a crucial role in the enhancement of the harvester response. The nonlinear interactions are examined by calculating the bicoherence of the generated piezoelectric signal under noise excitation, in the time-domain. In Figure 5 the bicoherence of three signals is presented. The first panel of Figure 5 is relative to the electrical output of the harvester subjected to an acceleration of 2.9 g. In this regime the system acts as a linear system and in fact the bicoherence analysis shows only one peak on the diagonal at the resonant frequency of the system. The second and third panels of Figure 5 reefer to the electrical signal generated for a driving excitation of 8.6 g and 17.2 g, respectively. In those cases the signals are not Gaussian and bicoherence is used to confirm nonlinearity. In those scenarios the bicoherence analysis shows a coupling between different modes of the system, that appears as an off-diagonal signal, indicating coupling, and thus energy transfer, between different frequencies. This behaviour is common in doubly clamped structures (Westra et al. 2010). In a harvester, this means that the response is enhanced as multiple modes participate in the transduction.

Conclusions

In conclusion we have measured the performance of a wrinkled piezoelectric energy harvester. We used two figures of merit to evaluate the response in linear and in the nonlinear regime. An optimum working point is found, by exploiting the nonlinearity that arises from the wrinkles. We investigated this nonlinearity in detail by measuring bicoherence, and found that the enhanced transduction can be explained by a significant coupling between the modes in the nonlinear regime. Our work suggests that wrinkled membranes offer an improved performance. It may have also consequences for energy harvesters based on 2-D materials, in which wrinkles occur naturally during fabrication.

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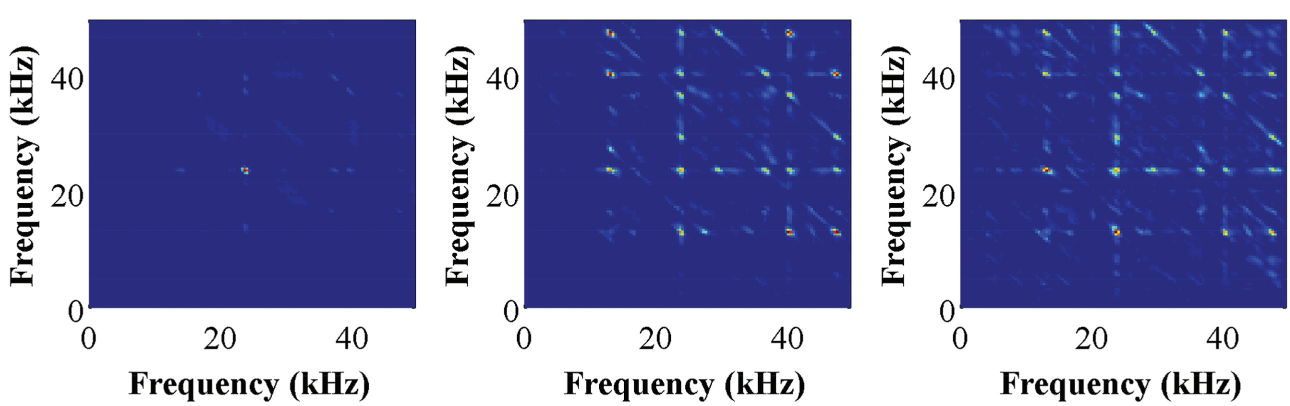

Figure 5: Bicoherence of three electric responses of the energy harvester. The first panel is relative to the electrical output of the harvester subjected to an acceleration of 2.9 g. This signal linear and only the resonant frequency is present on the plot. The second and third panels reefer to the electrical signal generated for a driving excitation of 8.6 g and 17.2 g, respectively. In those cases the signals are nonlinear and the plots show peaks out of the diagonal, indicating coupling, and thus energy transfer, between different frequencies.

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