Insights into the Size Effect of the Dynamic Characteristics of the Perovskite Solar Cell

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Abstract Driven by government policy and incentives, solar power production has soared in the past decade and become a mainstay during the worldwide clean-power transition process. Among the various next-generation photovoltaic technologies, perovskite solar cells (PSCs) are the most important emerging area of research due to their outstanding power conversion efficiency and affordable scale-up operation. We adopted the nonlocal strain gradient theory and the first-order shear deformation plate theory to investigate the size-dependent free vibration behavior of PSCs. The size-dependency in the nanostructure of the PSCs was captured by coupling the nonlocal and strain gradient parameters. In accordance with the Hamilton principle, the governing equations set was derived. Subsequently, the Galerkin procedure was applied to address the dynamic characteristics analysis of PSCs with simply supported and clamped edges. Compared with the size-insensitive traditional continuum plate model, the current multiscale framework revealed a size effect on the free vibration of the PSC. Moreover, some parametric experiments were conducted to explore the impacts of scale length parameter, nonlocal parameter, and boundary conditions on the natural frequency of the PSC.

Keywords Free vibration · Nonlocal strain gradient theory · Perovskite solar cell · Size effect

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1 Introduction

The perovskite solar cell (PSC) has garned tremendous attention from the scientific community over the past few years due to outstanding optical and electronic properties [1]. This new-generation photovoltaic device rose to prominence in 2012 with an energy conversion efficiency of 9.7% and then rapidly achieved a new certified record with 25.7% in 2022 [2]. Although PSCs have proven their competitive power conversion efficiencies and the prospect of further improved performance, their structural response during their operational lifetime still lacks investigation [3]. The study of the free vibration of PSC lays a solid foundation for optimizing the structure, because it is a crucial part of analyzing the dynamic response to various loading scenarios.

For mainstream solar power generation, technologies cannot be deployed in the field without accurately estimating their structural response. Despite the significance in real-life applications, there are few studies on the size-dependent dynamic characteristics of PSCs among the broad spectrum of available scientific reports that emphasize the interest and importance of this topic. Thus, we attempted to fill this gap by using nonlocal strain gradient theory (NSGT) to reveal the size effect of the free vibration behavior of the PSC with both simply supported and clamped boundary conditions.

2 Methods

2.1 Formulations

Grounded on NSGT [4], the internal energy density potential incorporating nonlocality and higher-order strain gradient tensor were formulated as:

$$\begin{aligned} U\left(\varepsilon_{ij}, \varepsilon'_{ij}, \alpha_0, \varepsilon_{ij,m}, \varepsilon'_{ij,m}, \alpha_1\right) = \frac{1}{2}\varepsilon_{ij} C_{ijkl} \int_V \alpha_0\left(\left|x - x'\right|, e_0 a\right)\varepsilon'_{kl} dV' \\ + \frac{1}{2} l^2 \varepsilon_{ij,m} C_{ijkl} \int_V \alpha_1\left(\left|x - x'\right|, e_1 a\right)\varepsilon'_{kl} dV' \end{aligned} \tag{1}$$

where ε_{ij} and ε'_{ij} are the strain tensors at the arbitrary point x and its neighboring point x' in V, respectively; C_{ijkl} denotes the elastic coefficients of the classical elasticity; α_0 and α_1 indicate the nonlocal attenuation function and the additional kernel function, correspondingly, which are related to the nonlocal parameters $e_0 a$ and $e_1 a$, and the distance between the considered points x and x' in V; e_0 and e_1 refer to the material constants; a is the internal characteristic length, l is a material length scale parameter which describes the higher-order strain gradient field.

The constitutive equations in NSGT herein can be described as:

$$\sigma = \int_V \alpha_0\left(x', \mathrm{x}, e_0 a\right) C_{ijkl} \varepsilon'_{kl,m} dV' \tag{2}$$

$$\sigma^{(1)} = l_0^2 \int_V \alpha_1\left(x', \mathrm{x}, e_1 a\right) C_{ijkl} \nabla \varepsilon'_{kl,m} dV' \tag{3}$$

where ∇ represents the Laplacian operator. The total stress tensor predicted by the NSGT can be then expressed as:

$$\mathrm{t} = \sigma - \nabla \sigma^{(1)} \tag{4}$$

Based on the assumption that the same nonlocal attenuation functions and parameters are taken, namely, $e_1 a = e_0 a$, then a general constitutive relation yields:

$$\left[1 - (e_0 a)^2 \nabla^2\right] t_{ij} = \left(1 - l^2 \nabla^2\right) C_{ijkl} \varepsilon_{kl} \tag{5}$$

Integrating by parts, then collecting the coefficients of δu_0, δv_0, δw_0, $\delta \theta_x$, and $\delta \theta_y$ to zero, the governing equations of the size-dependent PSC can be obtained. Then, corresponding to the investigated boundary conditions, the generalized displacements $\left[u_0, v_0, w_0, \theta_x, \theta_y\right]$ can be expanded in double trigonometric series. With the aid of the Galerkin method, the governing equations can be derived in the following form:

$$\mathbf{K} - \omega^2 \mathbf{M} = 0 \tag{6}$$

By solving the above eigenvalue problem, the natural frequency of the nanostructures ω_{nl} can be resolved from the smallest eigenvalue.

3 Numerical Results

In NSGT the size-dependency of the nanostructure is characterized as nonlocal parameters $e_0 a$ and material length scale parameters l_0. It should be noted that the current NSGT can degenerate into other lower-order continuum models by adjusting the related coefficients. Specifically, a pure NET model, $l_0 = 0$ is taken to eliminate the strain gradient term. In terms of the system not including stress nonlocality, $e_0 a = 0$. For the classical continuum model, herein the first-order shear deformation plate theory (FSDT), without considering the nonlocality and higher-order strain gradient, $e_0 a = l_0 = 0$.

The PSC is fabricated with a layer stack sequence of FTO/TiO_2/Perovskite/Spiro-MeOTAD/Au. The total thickness, length, and width of a PSC are $h = 1587.5$nm and $L_a = L_b = 0.2$mm, respectively. The related material properties can be found in [5]. The dimensionless parameters are introduced as $\overline{e_0 a} = \frac{e_0 a}{L_a}$, $\overline{l_0} = \frac{l_0}{L_a}$.

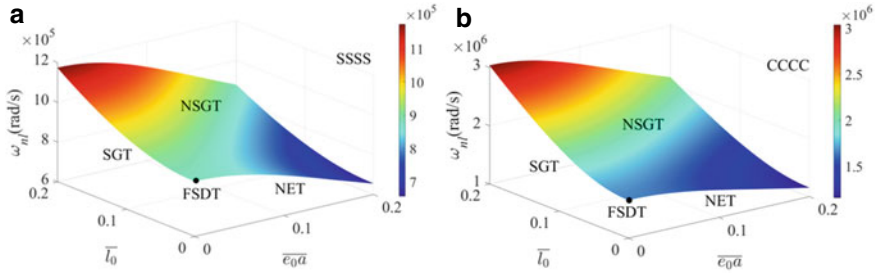

Fig. 1 Size effect on the natural frequency of **a** PSC with simply supported edges (SSSS); **b** PSC with clamped restraint (CCCC). NSGT, nonlocal strain gradient theory; PSC, perovskite solar cell

The natural frequency of the simply supported and clamped PSCs with various dimensionless nonlocal and material length parameters is shown in Fig. 1. It can be seen that, for both boundary conditions, the increase of the two size effect parameters results in distinct variations in the natural frequency of the PSC. With the attendance of the nonlocal parameter, the natural frequency of the PSC demonstrates a declined trend. However, the material length scale parameter tends to enhance ω_{nl} in the considered range. One possible explanation is that the nonlocal parameter addresses the effect of stiffness-softening, whereas the material length scale parameter addresses the effect of stiffness-hardening. In particular, the effects induced by the size-dependent coefficients become more prominent when their values approach the geometric size of the structure. Moreover, under two boundary restraints, as predicted, the clamped PSC possessed greater natural frequency than the supported plate due to the additional constraints.

4 Conclusions

In the present study, the size-dependency on the dynamic characteristics behavior of the PSC wasinvestigated based on NSGT. By introducing the nonlocal parameter and the material length scale parameter, the size-tendency of the nanostructure was captured in a complicated mix of stiffness-softening and stiffness-hardening. It was revealed that both scale parameters play crucial roles in the free vibration of the PSC. Moreover, it should be noted that the size-dependent model showed its characteristics as the scale parameters approached the dimensions of the structure.

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