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柔性悬臂梁的振动特性与等效线性化方法的局限性

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Vibration Characteristics of a Flexible Cantilever Beam and Limitations of Equivalent Linearized Method

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摘要

等效线性化方法是大变形柔性梁振动特性分析的一种高效近似处理方法,其成立前提是必须满足小振幅假设。传统完全非线性分析方法通常难以定量表征几何非线性效应对结构参量的影响,不利于开展定性分析,也无法满足降阶建模的需要。以大变形柔性悬臂梁为研究对象,将静态大变形对梁振动特性的影响直接等效为对截面惯性矩和质量密度分布变化的影响,构造了一种物理指示意义更加明确的等效线性化方法,并通过对比验证了该方法的有效性。为进一步讨论等效线性化方法的局限性,设计制作了一根大变形柔性悬臂梁,采用定响应幅的定频稳态激励法测量了悬臂梁在3种不同振幅水平下的频率响应函数(FRF)曲线。计算与试验结果的对比分析表明:静态大变形条件下,当悬臂尖端的动态位移振幅与静态变形幅值的比值低于10%时,结构的FRF曲线变化非常小,系统可视做线性系统,等效线性化方法的计算误差≤6%,算法有效;当悬臂尖端的动态位移振幅与静态变形幅值的比值达到20%时,测试FRF的幅值在共振点明显降低,等效线性化理论的计算结果误差偏高50%以上,等效线性化理论将不再适用;试验悬臂梁的振动非线性效应主要受阻尼的非线性特性控制。

关键词： 振动 等效线性化法 小振幅假设 非线性 柔性悬臂梁

Abstract:

The equivalent linearization method is an efficient and approximate method in analyzing the vibration characteristics of a flexible beam with large deformation, but the small amplitude hypothesis is the precondition of this method. The traditional fully nonlinear methods are usually incapable of characterizing explicitly the influence of geometric nonlinear properties on structure parameters; neither can it satisfy the requirements of the reduced-order models. The present paper considers the vibrating behaviors of a flexible cantilever beam with large deformation, and developes an equivalent linearization method to calculate the vibrating response of this beam. The proposed method can equivalently consider the effects of large static deformation on the vibration properties of a beam as the variations of the cross section moment of inertia and mass density distribution. In order to further determine the limitation of the small amplitude hypothesis, a flexible cantilever beam with large deformation is designed and manufactured, and three frequency response function (FRF) curves under three different vibrating amplitude levels are measured by the fixed frequency steady state exciting method. The comparisons between simulation and experimental results show that, when the ratio of tip dynamic displacement amplitude to static deformation amplitude is less than 10%, the changes of measured FRF curves are very small. So the system can be regarded as a linear system, and the relative error of the proposed equivalent linearization method is equal to or less than 6%, and the approximate method is effective. But when the ratio of tip dynamic displacement amplitude to static deformation amplitude is more than 20%, the value of the measured FRF at a resonant frequency point is significantly decreased, and the relative error of the equivalent linearization method is more than 50%, and this method is no longer suitable. And the nonlinear vibration behavior of the experimental flexible cantilever beam is dominated by the structural damping nonlinear property.

Keywords: vibration equivalent linearization method small amplitude hypothesis nonlinearity flexible cantilever

beam

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