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Effect of distributive mass of spring on power flow in engineering test

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ABSTRACT

Mass of spring is always neglected in theoretical and simulative analysis, while it may be a significance in practical engineering. This paper is concerned with the distributive mass of a steel spring which is used as an isolator to simulate isolation performance of a water pipe in a heating system. Theoretical derivation of distributive mass effect of steel spring on vibration is presented, and multiple eigenfrequencies are obtained, which manifest that distributive mass results in extra modes and complex impedance properties. Furthermore, numerical simulation visually shows several anti-resonances of the steel spring corresponding to impedance and power flow curves. When anti-resonances emerge, the spring collects large energy which may cause damage and unexpected consequences in practical engineering and needs to be avoided. Finally, experimental tests are conducted and results show consistency with that of the simulation of the spring with distributive mass.
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1. Introduction

Spring is widely used in train buffer, clutch control, coupling vibration absorption, vibration isolator etc. [1]. Usually, it has various configurations, such as steel ring spring, belleville spring and torsional spring. Spring mass is always neglected in practical engineering, whereas multiple modes may emerge due to the mass existence, which may lead to potential high responses for the whole system. Therefore, it is worthwhile noting such problems to avoid negative consequences. In early times, under free vibration circumstance of a spring with one end fixed and another end with a lumped mass M attached, for simplification of the vibration system, the spring's effective mass, i.e. one third of the spring's mass, might be added to the lumped mass, which is described in Refs. [2,3]. Huang [4] gave the vibration solution and effective mass of a massive spring system. Zhang et al. [5,6] presented the effective elastic constant and mass by means of energy method, and obtained the expression of oscillatory period. It should be noted that vibration of the spring-mass system have influences on impedance of an isolation system, or even some other quantities, for example, power flow, which is always used to evaluate the isolation performance of a whole system. While, rare researchers dug deeply in such field.

It is well-known that spring is widely used as vibration isolator in the floating raft isolation system, heating system in a high building, exhaust system in a manufacturing workshop, and vehicles such as automobiles and trucks. And related

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publications can be found in many journals [7–9]. Yan et al. [6] studied the vibration responses and power flow characteristics of an isolation system by exploiting the mobility power flow analysis method. They found that controlling parameters of the base, coupling rigidity and the transmission power flow can be effectively reduced in the raft. Slough et al. [10] presented an approach based on power flow to analyze the vibrational floating raft isolation system. It depicted that proper section of isolation spring stiffness can reduce the transmitted power. Yang et al. [11] investigated vibration power flow of a nonlinear isolator mounted on a base. Cubic damping and stiffness was assumed for the base and isolator. It denoted that softening stiffness nonlinearity is beneficial to the reduction of power transmission. Isolation has significant relation with its impedance which is an important quantity to evaluate the vibration level. Yet few people paid attention to the effect of the spring's mass on the impedance of the spring, let alone the effect on power flow.

Power flow analysis is a powerful approach and capable to evaluate the structural vibration distribution in a manner analogous to fluid flow [12–14], which can be calculated through finite element method [15]. It is always exploited in the evaluation of isolation performance of isolation systems, which always includes classical beams [16], plates, shells [17] and isolators such as steel springs. It is also an effective method to detect structural damage of transportation vehicles [18,19]. Since distributive mass of spring has influence on the vibration response, therefore, on the impedance which is closely related to power flow, it is an urge to investigate how the distributive mass of the spring affects the impedance of the isolator, and then the power flow to give constructive guidance to optimize the system. This work emerges from the interest of the influence of distributive mass of spring on the vibration through an isolator. Analysis of power flow through a steel spring with distributive mass is investigated with indirect power flow analysis. For practical engineering steel isolator, its complex impedance is calculated with four-end parameter method. Due to the distributive mass of the steel isolator, interesting phenomena are found during the test and mass effect on the impedance and power flow is analyzed. Several conclusions are drew for the guidance of future research.

2. Theory and method

2.1. Theory of distributive mass of spring in vibration

As shown in Fig. 1, it is a spring with length of L, distributive mass m and stiffness k, connected to a lumped mass M. Its wave motion can be derived as

$$u_{tt} - \frac{kL^2}{m} u_{xx} = 0 \tag{1}$$

where u_{tt} denotes the temporal second derivative of u with respect to time t, and u_{xx} represents the spatial second derivatives of u with respect to displacement x. It is assumed that end at $x = 0$ is fixed while end at $x = L$ is connected to a lumped mass, which corresponds to the boundary condition of

$$\begin{cases} u(0,t) = 0 \\ Mu_{tt}(L,t) = -kLu_x(L,t) \end{cases} \tag{2}$$

respectively, with u_x the spatial first derivative of u with respect to displacement x. Furthermore, assuming the initial and static tensile displacement of the spring is u_0, then

$$\begin{cases} u(x,0) = \frac{x}{L} u_0 \\ u_t(x,0) = 0 \end{cases} \tag{3}$$

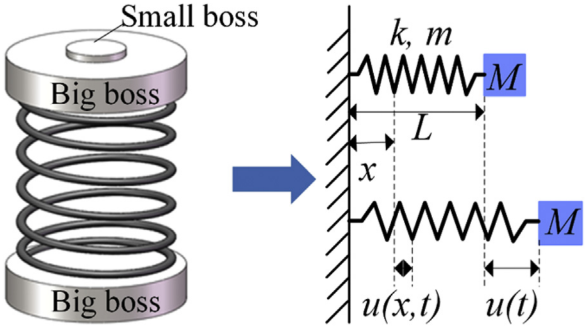

Fig. 1. The steel isolator with distributive mass.

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