



Damping control in a spring and suspension with sign-changing stiffness



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ABSTRACT

Vibration isolation in a range as close to zero frequency as possible is important for human and sensitive high-precision equipment. Springs with variable sign-changing stiffness can cancel the stiffness and provide perfect vibration isolation. However, it is possible in certain damping conditions. This paper presents an approach of damping control in suspensions with such springs. A model of the mode of deformation is formulated and validated for analysis of structural damping in the springs. A vibration model is formulated to estimate a maximum efficiency of a soft suspension in the infra frequency range and predict a reasonable level of slip damping. Novel materials and designs are demonstrated for control and minimization of the damping. Validity of the approach is illustrated with numeric and measured data obtained from development test of the springs and suspensions equipped with such springs.

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1. Introduction and motivation

Vibrations in the infra bandwidth ($f < 10$ Hz) are the most harmful to humans. These vibrations affect workers and have a greater impact on residential areas due to long exposure time [1,2]. Vibration isolation in a range as close to zero frequency as possible and precise position control are needed to support sensitive equipment such as instruments for nano- and microelectronics fabrication, industrial laser and optical systems, and medical and biological research [3–5].

This calls for vibration isolation mechanisms such as pneumatic suspensions, platforms and tables. In combination with automatic control, they are the most effective among conventional systems in certain frequency ranges [6–10]. However, these mechanisms are effective (using, as a rule, external dampers) for reducing resonance peaks rather than for infra frequency vibration isolation of a required level. The reason is the rigid air, metal and other supporting springs, which are deficiently effective in the infra bandwidth when assuming reasonable dimensions.

Suspensions with springs of variable sign-changing stiffness (SCS-springs) have proven most promising for providing infra and low frequency vibration isolation at a reasonable cost. Such springs can operate in parallel with supporting springs or (in some cases) independently to control and minimize the total stiffness k_s of a suspension:

$$\left. \begin{aligned} k_s(q) &= k_{ps}(q) + \Phi \cdot k_{SCS}(q^*) \\ &= k_{SCS}(q^*) \end{aligned} \right\} \rightarrow + \min \quad (1a - b)$$

$$\approx 0$$

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where k_{PS} and k_{SCS} are the stiffness of supporting and SCS springs; q and q^* are the global and local degrees of freedom of the suspension; Φ is the transfer function between the springs. The term k_{SCS} can be “positive,” equal to zero (“quasi-zero”), or “negative” depending on the SCS-spring state of strain, while k_{PS} is “positive” at a certain state of supporting spring.

SCS-springs can provide stiffness control for a suspension and minimize the natural frequency spectrum of a man or engineering vibration isolation system (VIS) up to an arbitrary small value. This kind of elasticity can result from local or global buckling of natural or synthesized springs designed using elastomers such as rubber and metal rods, slender beams, rodless air springs. Many ingenious suspensions have been designed through the use of above mentioned subcases of SCS-springs, as well as the linkages, cams, pneumatic and other mechanisms that produce an SCS-effect [11–14]. Evolution of this concept led to important predictions for practical design, in particular: (a) an SCS-spring element is to be a thin-walled structure, and (b) this element should be in the form of a thin shallow shell or thin plate rather than a slender beam to obtain a wide range of stiffness control without increasing the VIS workspace and losing spring strength [15].

A spring element or a system of such elements provides both a spring force and damping. Reduction in the stiffness magnifies the damping and affects the vibration isolation. Joining the SCS-spring elements to a suspension can increase the damping, in addition. Finally, these worsen the operation and position control of such soft suspension and make impossible vibration isolation in some infra bandwidths. This raises the questions of how significant the damping in SCS-springs can be, and if there is a way to control and reduce the damping to design a soft suspension that provides vibration isolation in a range including close to zero frequencies.

In this paper, we present an approach for analysis, control and minimization of damping in practical design and use of soft suspensions with SCS-springs. First, we formulate a new model in a way that enables an optimal computable scheme for analysis and control the structural damping in such a spring designed as a package of thin-walled structures. Next, we consider a vibration model to estimate the maximum possible efficiency of a suspension in the infra frequency range. Then, we illustrate the effectiveness of novel materials and designs that provide reducing the structural and slip damping. Finally, we demonstrate the feasibility of design of active suspensions with the SCS-springs, which can be effective in the range including close to zero frequencies.

2. Structural damping in the SCS-springs

Packages of thin-walled structures have proven to be the most preferable candidates for SCS-springs. Such springs can be arranged e.g. as a set of elastomeric thin plates spaced around a movable central bush. Packaging n_{pl} thin plates with n_{pl}/n_{set} of them in each lamination gives a compact mechanism and provides stiffness control to design a suspension for a man or engineering VIS [16]. An example of universal configuration of the mechanism is shown in Fig. 1a.

The problem of buckling of thin-walled structures is geometrically nonlinear. The methods of nonlinear theory of elasticity can precisely evaluate the behavior of an elastic structure like a thin shallow spherical or cylindrical shell and thin plates under cylindrical bending [17]. However in practical design, one should prefer approaches that enable reduction of the problem to a sequence of linear boundary value problems. Such an approach considers the final displacement of each finite element (FE) of the structure as the sum of displacements in the large of the FE as a rigid body and a displacement in the small under elastic deformation [18].

This hypothesis allowed for formulating a simple and sufficiently exact iterative procedure for solving the nonlinear problem with acceptable convergence. If the variation of strain energy of an FE is determined by the displacements in the small only, then all FEs are joined into a single structure by these displacements. To evaluate them and determine the modes

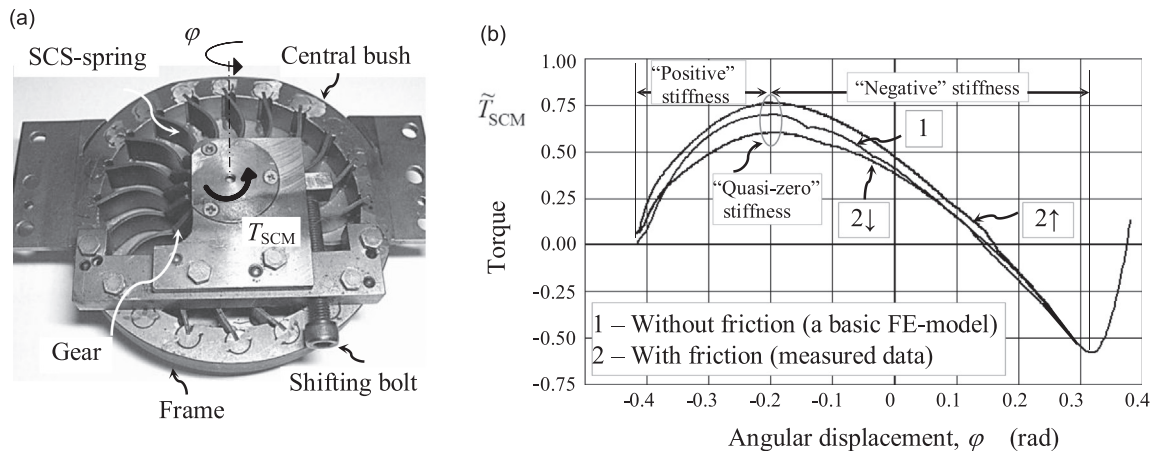


Fig. 1. Damping in an SCS-spring: (a) layout of the spring mechanism; (b) 2↑ and 2↓ are the spring load and unload force–displacement curves.

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