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Design study on magnetic springs with low resonance frequency

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ABSTRACT

Passive magnetic gravity compensation may be a very feasible alternative to commonly used mechanical or pneumatic solutions for vibration isolation systems. The final paper discusses a study on the optimal design of a magnetic spring with passive gravity compensation. For vibration isolation systems it is often preferred to combine a certain force level with very low spring stiffness to achieve a low resonance frequency. Several optimization methods are used in the paper to optimize the dimensions of planar magnet structures to exhibit a certain vertical force with low stiffness and the optimized results are compared. The results from this study give insight in the influence of topology choice on the achievable vibration isolation performance of permanent-magnet based springs.

1 INTRODUCTION

Many industrial and academic applications require an advanced form of vibration isolation. In such applications a table or platform needs to be isolated from all vibration sources, viz. floor vibrations, acoustical noise or forces acting on the isolated platform itself. These applications are often characterized by a heavy mass which remains vibration-free in a predefined position, with minimized energy consumption, minimal movement and a vibration rejection up to hundreds of Hertz. As a result, the suspension should exhibit a low stroke, a high static force with minimized energy consumption, a low intrinsic spring stiffness and a high isolation bandwidth.

As an alternative to the commonly used pneumatic actuators, this paper proposes electromagnetic suspension to perform these tasks. In the electromagnetic mount the isolated platform is passively supported by a magnetic spring which is based on interaction between permanent magnets and as such provides a high passive vertical force. Active actuators, which are not considered in this paper, firstly stabilize this inherently unstable system and secondly provide the advanced vibration isolation. In order to prevent a mechanical path for floor vibrations to travel to the isolated platform a contactless magnetic solution is chosen.

Permanent magnet devices are often designed to exert a very high force density as for example is seen in magnetic couplings [1, 2] or in the magnetic springs shown in [3, 4]. In such designs a small relative movement often leads to a significant change in reaction force, i.e. a high stiffness. This disadvantageous in terms of vibration isolation because such systems are designed to exhibit resonance frequencies as low as 0.5 Hz. To achieve such a low resonance frequency, a compromise in terms of reduced

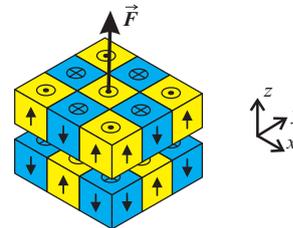


Figure 1: Schematic representation of a 3×3 permanent-magnet spring with checkerboard magnetization. The magnets are oriented such that the top array is repelled.

force and force density is eminent. This paper researches the relationship between this force and the achievable resonance frequency.

2 THE PASSIVE MAGNETIC SPRING

An impression of the magnetic spring that is considered in this paper is shown in Fig. 1. It comprises of two horizontal permanent magnet arrays which both have a vertical checkerboard magnetization. The orientation of both arrays is in this case such, that the upper array is repelled by the lower array. The number of magnets along the horizontal directions, n , is chosen odd because of symmetry reasons. With such odd number of magnets the responses when moving in positive or negative direction along one of the horizontal axes are equal.

It was shown in [3] that high force densities can be achieved with such topology, up to 6000 kN/m^3 . Because further research of these topologies has shown that the vertical spring stiffness in such case is extremely high, the focus in the article is on a significant reduction of this vertical spring stiffness. In order to achieve this goal, a variable pole pitch and a variable magnet pitch are introduced in the magnet arrays. This is shown schematically in Fig. 2.

Two optimization methods are used to optimize the respective dimensions of the permanent magnet arrays. The first method optimizes analytical models of the interaction force obtained by the surface charge model [5] with nonlinear constrained multivariable optimization `fmincon` in Matlab. Although the force computation is fully analytical, this gradient-based optimization SQP algorithm computes a quasi-Newton approximation to obtain the Hessian. The main risk of such a deterministic algorithm is that it may become trapped in local minima. On the other hand, metaheuristic algorithms such as genetic algorithms or particle swarm may have troubles converging to an optimum with the given set of constraints. The second optimization method which is used is therefore a hybrid method which combines both types of algorithms. This method uses

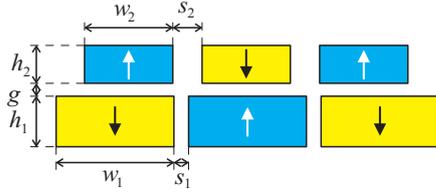


Figure 2: Dimensions used in the optimization shown for a topology where the number of magnets along the sides, n , is equal to 3.

semi-analytical force computation together with a true gradient optimization [6, 7].

3 OPTIMIZATION GOALS

Although in Fig. 2 the number of magnets in horizontal direction, n , equals 3, this integer number is varied in the final paper and always kept odd because of symmetry reasons. Each optimization is now carried out in two steps: The first step maximizes the vertical force exhibited by the magnetic spring within the set of constraints. The second optimization step then tries to bring the spring stiffness as close to 0.5 Hz as possible while maintaining a minimum vertical force level. This minimum force is given as a non-linear constraint to the optimization routine and is varied between 100 N and 10 kN. The resonance frequency is obtained with the assumption that the vertical spring force is in equilibrium with the vertical gravity force, or

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{k}{F_{ver}/g}} = \frac{1}{2\pi} \sqrt{\frac{gk}{F_{ver}}}, \quad (1)$$

where g is the gravitational acceleration of 9.81 m/s² and k is the vertical spring stiffness. The final publication will discuss the optimization methods in more detail.

4 RESULTS

The optimization of the various topologies shows that the number of magnets is of significant influence on the spring stiffness. Figure 3 clearly shows a relationship between number of magnets in the arrays, force levels and achievable resonance frequencies. The optimization results are further elaborated on in the final paper.

5 CONCLUSION

This paper investigates the feasibility of permanent-magnet based topologies for vibration isolation applications. For such applications a low resonance frequency combined with a high vertical spring force is an advantageous property and therefore the research is focused on achieving these goals.

Several optimization methodologies are utilized to optimize the dimensions of two arrays with rectangular magnets which together form a magnetic spring as a result of repulsion force. The optimum number of permanent magnets in these arrays is also part of the research. With these results this paper presents some novel topologies which exhibit large vertical forces and low stiffness based on passive permanent magnet interaction.

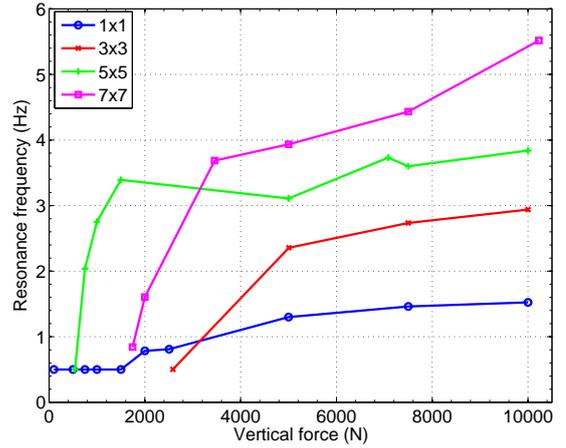


Figure 3: Relation between the vertical force and the achievable resonance frequency of the magnetic spring. Each line represents a different number of magnets ($n \in [1, 3, 5, 7]$).

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