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Material properties

Vibration isolation behaviour of 3D polymeric knitted spacer fabrics under harmonic vibration testing conditions

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ABSTRACT

The use of 3D knitted spacer fabrics made of polymeric fibre materials as vibration isolators is proposed in this study by considering their spacer monofilaments as Euler springs which have been proved to be excellent vibration isolators. Three types of spacer fabrics with different compression force–displacement characteristics were fabricated by varying monofilament diameter and fabric thickness. Their vibration transmissibility under harmonic vibration testing conditions was measured by an electromagnetic shaker. It is found that the resonant frequency and isolation frequency of these fabrics decrease with increasing acceleration level and load mass, and a thicker fabric has better vibration isolation performance due to its lower resonant and isolation frequencies. The study shows that 3D knitted spacer fabrics can be designed as good human vibration isolators without compromising their comfort.

1. Introduction

The human body is frequently exposed to vibration from power tools and industrial machines and from vehicles like trains and automobiles [1]. Vibration can cause discomfort, reduction of performance, inducement of activity interference and even health and safety risks. Human vibration involves the whole-body vibration (WBV) within frequencies 1–100 Hz when a person stands or sits on a shaking surface, and the hand-transmitted vibration (HTV) between frequencies 8–1000 Hz when holding a vibrating tool [1]. The effects of whole-body vibration include back pain, sciatica, digestive disorders, genitourinary problems and hearing damage. Long-term exposure to hand-transmitted vibration has a risk of developing hand-arm vibration syndrome (HAVS), a well-known example of which is vibration white finger (VWF). At present, preventive efforts have been made by using anti-vibration seat cushions [2] for WBV and gloves [3] for HTV made of damping materials [4,5] like polymeric foams, rubbers, gels and air bladders to reduce the vibration exposure. However, these materials suffer from insurmountable comfort and recycling problems. Therefore, developing breathable and recyclable materials with good vibration isolation performance is highly desirable.

The effective isolation bandwidth of a vibration isolator for reducing the vibration exposure depends on the resonant frequency $\omega = k/m$ of the isolated mass m moving on the isolator of stiffness $k = \delta F/\delta x$ (F-force, x-displacement) [1]. A lower resonant frequency makes the isolator start to mitigate the vibration from a lower frequency, thereby broadening the isolation bandwidth. An ideal isolator should keep the stiffness as low as possible while bearing as great as possible mass load. Hence, low stiffness and high support capacity are the two key factors that should be taken into account at the same time in developing vibration isolators. Since change of supported mass is not usually desirable, the remaining option to achieve a lower frequency of isolation is to reduce the stiffness. However, reducing the stiffness of a linear spring causes a large static deflection which would be prohibitive. Nonlinear springs can overcome this problem by having a high static but low dynamic stiffness (HSLDS) [6–8]. A buckled beam called a Euler spring is a good candidate with the HSLDS characteristic. Prior to buckling, the deflection of an Euler spring is due to axial deformation which results in a high stiffness. Once the critical load is reached, buckling of the Euler spring occurs. Post-buckling of the Euler spring is shortening of its span and offering little resistance to additional deformation, thereby showing a low stiffness. On one hand, this special feature brings about a nonlinear force–displacement relationship which gives rise to a high static load bearing capability in conjunction with a low dynamic stiffness in the post-buckled region [9]. On the other hand, vibrational motion in the presence of gravity requires the dynamic storage of significant amounts of static energy (mgh) to momentarily absorb

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this motion [10]. The large static energy storage necessitates a large mass of linear spring proportional to the total static and dynamic energy to be stored. As the static energy that Euler spring stores below its critical load is negligible, the mass of Euler spring required to support the suspended mass can be minimized, meanwhile keeping the resonant frequency at a low level [10–12]. Therefore, the Euler spring is an excellent vibration isolator that not only satisfies the two key factors as above mentioned but can also be lightweight for wearing comfort. Previous experimental studies have proved that Euler springs made of slender steel struts for seismic application can achieve excellent vibration isolation at a low resonant frequency of about 1 Hz [9,10,12].

In this paper, we propose a novel use of 3D knitted spacer fabrics for human vibration isolation using a similar mechanism. As shown in Fig. 1, a 3D knitted spacer fabric has a sandwich structure in which spacer monofilaments to connect two separate multifilament meshed surface layers can function like parallel Euler springs [13]. This structural feature makes spacer fabrics an ideal textile structure for vibration isolation. In addition, in a spacer fabric, both the multifilament and monofilament yarns can be a single type of polymeric material such as polyester or nylon for recyclable purpose. Nowadays, spacer fabrics have been widely used as cushioning materials to replace polymeric foams for cushion pads, mattresses, impact protectors, etc. due to their excellent compressibility and high air and moisture permeability [14–18]. The main objective of this study is to experimentally investigate the vibration isolation behaviour of this kind of fabrics with a novel vibration testing method in order to understand how the fabric structural parameters and vibration testing conditions affect their vibration isolation performance. It is expected that the study could help design of 3D knitted spacer fabrics for application in human vibration protection.

2. Experimental

2.1. Fabrics

Three types of spacer fabrics, namely S1, S2 and S3, were used for this study. They were knitted on a Karl Mayer double-needle bar Raschel warp knitting machine by varying their spacer monofilament diameter and fabric thickness. While the surface layers of the fabrics were knitted with polyester multifilaments, the spacer layers were knitted with polyester monofilaments. The specifications of both the filaments used and fabrics produced are listed in Table 1.

As shown in Fig. 1, the as-fabricated 3D knitted spacer fabrics have a sandwich structure consisting of two hexagonal mesh surface layers (Fig. 1a–c) connected by countless spacer monofilaments (Fig. 1d). This open structure allows the air free-circulation, making the spacer fabrics very comfortable. As mentioned before, an Euler spring is a column of spring material that has been compressed elastically beyond its buckling load [12]. The countless buckled spacer monofilaments having different lengths, diameters, geometric arrangements and initial deflections (Fig. 1d) are just like parallel Euler springs, which have been successfully applied as vibration isolators [9–12].

2.2. Measurements

Both quasi-static and vibration tests were conducted in order to get a better understanding of vibration isolation behaviour of spacer fabrics. For the quasi-static compression tests, an INSTRON 5566 set up with two 150 mm diameter circular compression plates, as shown in Fig. 2, was used. The quasi-static tests were performed following the principles of ISO 7743 with a compression speed of 10 mm/min up to 80% deformation of the fabric initial thickness in an environment of 20 °C and 65% relative humidity. The dimensions of each specimen were 90 mm × 90 mm. Three specimens were tested for each kind of fabric.

The vibration tests were conducted on an electromagnetic shaker EM-400F3K-30N80 manufactured by the King Design Industrial Co., Ltd., Taiwan following the standard BS EN ISO 13753:2008. As shown in Fig. 3, the specimen of the same dimensions as used in quasi-static compression tests was placed on the shaker platform and loaded with a steel mass of the same surface dimensions. Four L-shaped steel fixtures glued with PTFE

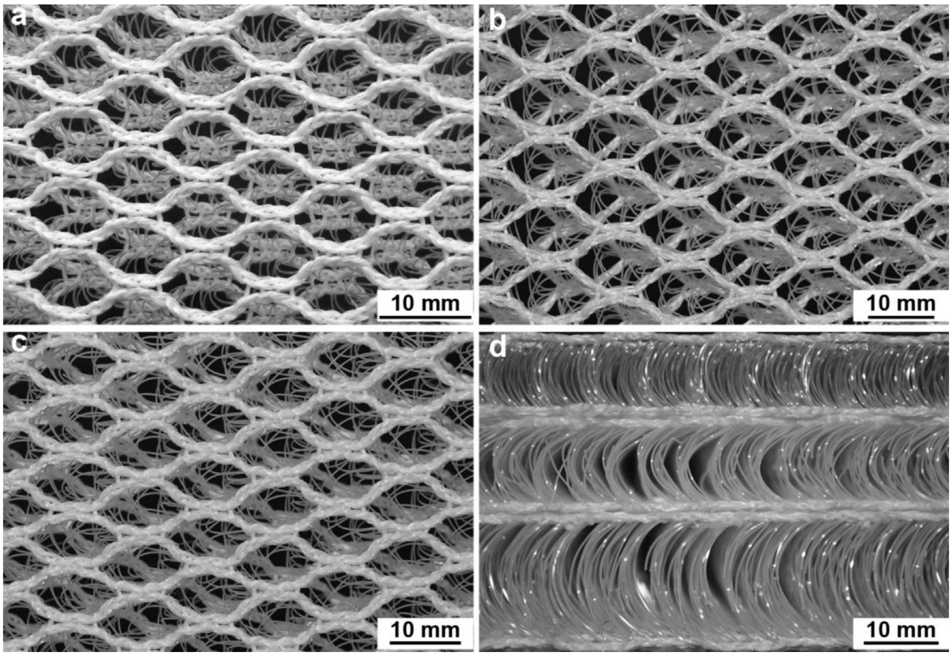

Fig. 1. Photographs of 3D spacer fabrics: top view of S1 (a), S2 (b), S3 (c) and side view of S1, S2, S3 (d).