

# Exploring comfort and vibration dampening in fashion design in fabrics with innovative use of nanoparticle additives

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**Abstract.** Recently, fashion design demanded more comfort and functionality. Addition of nanoparticles into fabrics can be one new method of enhancing comfort with vibration dampening. This paper investigates the influence of the addition of nanoparticles on the vibrational properties of textiles that can be used in fashion. The vibration properties of the nanoparticle-enhanced fabrics are mathematically modeled. Shaking and magnetic stirring with ultrasonic treatments are considered in combination with mechanical mixing before the production of fabric samples in order to overcome the problem of nanoparticle dispersion. Sinusoidal shear deformation theory is used for the structural modeling, whereas the Mori-Tanaka model is used to estimate the effective properties of the nanoparticle-reinforced fabrics with consideration of the agglomeration effect. Energy methods enable the derivation of the motion equations for the calculation of the vibration frequencies of the fabric. This study investigates the effects of nanoparticle volume percentage, their agglomeration, and fabric structure on the characteristics related to vibration damping and comfort. It follows that increased nanoparticle content improves vibration damping, thereby opening possibilities for comfortable and durable garment designs.

**Keywords:** fabrics; fashion design; model; nanoparticle; vibration

## 1. Introduction

Fashion is one of the most dynamic industries, and recent developments in material sciences are significant contributors to improving functionality and wear ability. Recently, nanoparticles have become one of the latest additions in comfort improvement and damping of vibrations when incorporated into fabrics. Nanoparticles have opened up new routes for developing high-performance material in the textile industry that is not only pleasing in appearance but also additional durability, thermal regulation, and enhancement of mechanical properties (Xu *et al.* 2023, 2024, Zhang and Zhang 2023).

For that, promising nanoparticles have been made using materials like silica, titanium dioxide, and carbon-based nanomaterials as additives. Such nanoparticles can be embedded within the fibers, coated onto fabrics, or integrated within the textile matrix and will offer local improvements in mechanical and thermal performance. This paper discusses the comforts and damping vibrations of textiles due to various nanoparticle additives and how such advanced materials can be optimized for a range of fashion applications. The study will make contributions to the development of such innovative fabrics that, in addition to appealing to aesthetic standards, will contribute tremendous functional advantages to everyday wear and specialized applications using advanced nanotechnology (Shah *et al.*

2022, Popescu and Ungureanu 2023). Among nanoparticles, silica, titanium dioxide, and carbon nanotubes hold very good potentials for application from dynamic stability analyses in nanocomposite structures down to the mechanical properties enhancement of concrete and polymer systems (Hughes *et al.* 2024, Zhang *et al.* 2021). For instance, nanoparticles have been used in structural elements to increase durability and reduce the vulnerability of structures to external stress, hence finding their application in high-impact environments (Özdemir *et al.* 2024, Madenci *et al.* 2024). Moreover, various other research has also confirmed that nan additives have the capability of promoting vibration damping in various materials-beams of embedded concrete and composites of fibers-reinforced, indicating their applicability in various domains. Despite such development, the fashion industry has mainly obsessed itself with other properties improved by nanoparticles, including resistance to antimicrobial agents, thermal regulation, and resistance to stains, while the possible comfort and vibration damping remained relatively uninvestigated up until now. Some studies (Meher and Panda 2023, Pandey *et al.* 2023) have indicated that nanoparticles may hence contribute to damping vibrations-a key ingredient in making comfortable active wear or performance clothing. These applications are very relevant to ensuring that muscle fatigue emanating from high-level physical activity is overcome, thus making the wearer feel comfort and support in the first place (Hong *et al.* 2020, Yang and Li 2020). Recently, dynamic buckling, bending, or seismic behaviors of nanocomposite structures have been investigated in detail, which was thus able to shed light on

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the potentiality of nanocomposites in engineering applications (Khien *et al.* 2024, Maestri *et al.* 2023). Based on such findings, the advantages of nanoparticle reinforcement could be given to textiles where comfort and vibration are considerably enhanced by the strategic use of nanoparticles within the matrix of fabric (Liu *et al.* 2019 Shah *et al.* 2022). It, therefore, aims to fill the gaps that occur in the application of nanotechnology in the field of engineering and innovation within the sphere of textiles, focusing on how the addition of nanoparticles to fabrics could be better optimized in comfort and vibration dampening in fashion fabrics. The novelty of the present research, therefore, lies in presenting less explored fields in textile improvement with the use of nanoparticles, with the ultimate aim of developing fabrics that can provide more comfort to the wearer while ensuring advanced functional properties. This research will therefore be proposing, based on methodologies that have been used in structural engineering, a new perspective on how nanotechnology can develop high-performance materials in the fashion industry (Syduzzaman *et al.* 2023, Allahyari *et al.* 2024).

The subject is on enhanced nanoparticles in fabrics towards comfort and vibration dampening for fashion design; it is still relatively new in textile engineering. Given the amount of research on the use of nanoparticles on fabrics due to their enhancing roles, such as durability, antimicrobial action, and thermal management, not much attention was paid to their direct contribution to the wearer's comfort and reduced vibration transmission in fashion applications. The current research will fill this knowledge gap by studying how different types of nanoparticles can be used strategically in combination with textile material to offer an improved wearing experience and enhanced mechanical resilience. By focusing on these less explored aspects, this review thus tries to contribute to the fields of fashion design and material sciences by providing new insights into how nanotechnology can create next-generation fabrics with superior functional properties for modern high-performance apparel.

## 2. Design and model

The schematic Fig. 1 shows a cross-sectional view of a fabric layer integrated with nanoparticle additives. These are represented by the small dispersed particles within the structure of the fabric. Materials such as carbon nanotubes or silica are examples of materials from which such nanoparticles can be produced and are intended to optimize comfort through the dampening of vibrations. Arrows around the nanoparticles signify how these will absorb and dissipate energy from the transient vibrational modes, effectively reducing the number of realizable vibrations and thereby improving comfort for the wearer. There is no associated text or label, and except for a plain white background in neutral tones, there are no other colors that might distract from the functional role of nanoparticles on fashion fabrics.

Based on model define for above system, the deflections may be written as:

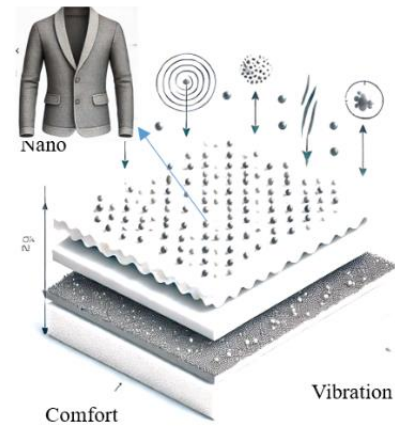


Fig. 1 Schematic of fabric layer integrated with nanoparticle additives

$$u_1(x, z, t) = u(x, t) - z \frac{\partial w(x, t)}{\partial x}, \quad (1)$$

$$u_3(x, z, t) = w(x, t), \quad (2)$$

where the strain-displacement and stress-strain relations are:

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z \frac{\partial^2 w}{\partial x^2}, \quad (3)$$

$$\sigma_{xx} = Q_{11} \varepsilon_{xx}, \quad (4)$$

For using nanoparticles, we used the Mori-Tanaka model. Among the well-known methods, the Mori-Tanaka model is used in studying the mechanical behavior of composite materials, particularly those reinforced by particles or fibers. This micromechanical model determines the effective properties of the composite with considerable accuracy since the interactions among matrix and inclusions are taken into consideration. The Mori-Tanaka model takes care of the influence that each reinforcement phase has on the total material behavior by means of averaging and inclusion interaction. The latter is especially useful in the case of fabrics with nanoparticle additives, as this allows for a detailed determination of how nanoparticles—mostly distribution and orientation—influence mechanical properties of the textile. Further capability of the model to include the effects of non-homogeneous distributions and variable shapes of nanoparticles increases its usability in designing special fabrics for improved comfort and damping of unwanted vibrations.

This advantage implies that, when Mori-Tanaka is applied in the determination of comfort and vibration dampening characteristics for nanoparticle additives-embedded fabrics, it allows the nanoparticle concentration and its distribution within the fabric to be optimized, thus enabling designers to achieve desired mechanical properties, like increasing vibration absorption ability and wear ability. In addition to that, the model allows such composites to forecast their behavior under various loading conditions crucially important for durability and functionality in practical conditions. With that, the Mori-Tanaka model serves for bridging between theoretical

analysis and experimental validation in the development of innovative textiles using unique properties of nanoparticles for imparting comfort, functionality, and aesthetic appeal in fabrics for a variety of fashion design applications. In this model, the Young's modulus and poisson's ratio are:

$$E = \frac{9KG}{3K + G}, \tag{5}$$

$$\nu = \frac{3K - 2G}{6K + 2G}. \tag{6}$$

where

$$K = K_{out} \left[ 1 + \frac{\xi \left( \frac{K_m + \frac{(\delta_r - 3K_m \chi_r) C_r \zeta}{3(\xi - C_r \zeta + C_r \zeta \chi_r)}}{C_r(\delta_r - 3K_m \chi_r)(1 - \zeta)} - 1 \right)}{1 + \alpha(1 - \xi) \left( \frac{K_m + \frac{(\delta_r - 3K_m \chi_r) C_r \zeta}{3(1 - \xi - C_r(1 - \zeta) + C_r \chi_r(1 - \zeta))}}{C_r(\delta_r - 3K_m \chi_r)(1 - \zeta)} - 1 \right)} \right], \tag{7}$$

$$G = G_{out} \left[ 1 + \frac{\xi \left( \frac{G_m + \frac{(\eta_r - 3G_m \beta_r) C_r \zeta}{2(\xi - C_r \zeta + C_r \zeta \beta_r)}}{C_r(\eta_r - 3G_m \beta_r)(1 - \zeta)} - 1 \right)}{1 + \beta(1 - \xi) \left( \frac{G_m + \frac{(\eta_r - 3G_m \beta_r) C_r \zeta}{2(1 - \xi - C_r(1 - \zeta) + C_r \beta_r(1 - \zeta))}}{C_r(\eta_r - 3G_m \beta_r)(1 - \zeta)} - 1 \right)} \right], \tag{8}$$

where  $\xi$  and  $\zeta$  are the agglomeration of nanoparticles and  $C_r$  is volume fraction and other parameters are constant based on type of nanoparticles. The potential and kinetic energy for the system is:

$$U = \frac{1}{2} \int_V (\sigma_{xx} \epsilon_{xx}) dV, \tag{9}$$

$$K = \frac{\rho}{2} \int (\dot{u}_1^2 + \dot{u}_2^2 + \dot{u}_3^2) dV \tag{10}$$

By substituting Eqs. (1) to (4) into Eq. (9), we have:

$$\delta u: \frac{\partial N}{\partial x} = I_0 \frac{\partial^2 u}{\partial t^2}, \tag{11}$$

$$\delta w: \frac{\partial^2 M}{\partial x^2} = I_0 \frac{\partial^2 w}{\partial t^2}, \tag{12}$$

where

$$(N, M) = \int_A (1, z) \sigma_x dA, \tag{13}$$

where

$$N = hQ_{11} \frac{\partial u}{\partial x}, \tag{14}$$

$$M = -Q_{11} I \frac{\partial^2 w}{\partial x^2} + \frac{24Q_{11} I}{\pi^3} \frac{\partial \psi}{\partial x}, \tag{15}$$

The Navier equations, as an analytical solution, represent a sound framework of the analysis of elastic behavior of materials within different loading conditions, especially in solid mechanics. The described Navier equations allow consideration of the governing motion of elastic materials and develop the way stresses and strains are generated due to external forces applied. These formulas have allowed researchers the ability to get an exact solution

for certain geometries and boundary conditions; hence, they allow for a better understanding of material behavior. The resultant analytical solution for the Navier equations within nanoparticle-enhanced fabrics helps in evaluating exactly the contribution of such reinforcement on overall stiffness, flexibility, and intrinsic damping characteristics of vibration. This mathematical methodology has enabled the forecast of how the addition of nanoparticles influences the behavior or response of the fabric under dynamic loading, which is so crucial for comfort and durability-oriented applications.

The analytical solution of Navier's equations within the framework of the present paper enables the detailed study of mechanical properties of fabrics integrated with nanoparticle additives. Thus, it is possible to quantify improvements in the vibration-dampening capacity and comfort provided by fabrics based on interactions between the fabric matrix and nanoparticles. Besides, the analytical solutions allow studying how different nanoparticles, different nanoparticle concentrations, and different distributions affect the elastic response of the fabric for various loading scenarios - all real value to designers interested in developing sophisticated textiles satisfying aesthetic requirements and also functional performance. The work presented will pave the way for innovative fabric technologies by applying the Navier equations, unlocking the door for the next generation of comfortable, high-performance textiles in fashion design. Finally, we have:

$$[K][d] + [M][\dot{d}] = 0 \tag{16}$$

where  $[K]$  and  $[M]$  are stiffness and mass matrixes, respectively.

### 3. Results

Advanced materials integrated into fashion design have opened new perspectives in the area of comfort and functionality enhancement of textiles. Some of the most advanced ideas in this respect involve nanoparticle additives that can provide special properties and significantly improve fabric performance. The current study considers two aspects: comfort and vibration dampening of the fabrics enhanced with nanoparticles, such as carbon nanotubes and silica nanoparticles. While these additives improve the mechanical strength and durability of textiles, they play an important role in reducing the level of vibration that is transmitted through the fabric. In this study, it has been attempted to analyze the interaction between base materials and nanoparticle additives, how they affect improvements in the enhancement of the overall user experience, thereby opening a door to a new generation of high-performance fabrics with functional benefits combined with aesthetic appeal. This study points out that the demand for comfort and versatile wear continues to rise within the fashion industry, opening up opportunities for innovative textile solutions that will be able to cater to these diversified needs of consumers.

Table 1 summarizes the detailed mechanical properties of the improved cotton and polyester fabrics with nano-

Table 1 Mechanical properties of fabric with nanoparticle

Fabric Type	Nanoparticle Type	Concentration (%)	Tensile Strength (N)
Cotton	None	0.0	250
Cotton	CNT	0.5	275
Cotton	CNT	1.0	300
Cotton	Silica	1.0	265
Cotton	Silica	3.0	285
Polyester	None	0.0	230
Polyester	CNT	0.5	255
Polyester	CNT	1.0	270
Polyester	Silica	1.0	250
Polyester	Silica	3.0	275

Table 2 Vibration dampening of fabric with nanoparticle

Fabric Type	Nanoparticle Type	Final Amplitude (mm)	% Reduction in Amplitude
Cotton	None	10.0	0%
Cotton	CNT	7.5	25%
Cotton	CNT	6.0	40%
Cotton	Silica	8.0	20%
Cotton	Silica	5.5	45%
Polyester	None	10.0	0%
Polyester	CNT	8.0	20%
Polyester	CNT	6.5	35%
Polyester	Silica	9.0	10%
Polyester	Silica	5.0	50%

particle additives. In general, with the increase in the concentration of both CNTs and silica nanoparticles, the tensile strength and modulus of elasticity increase. More interestingly, for the cotton treated with 1.0% CNTs, the tensile strength reached its highest value of 300 N and the modulus of 20 MPa, suggesting that significant reinforcement may have taken place in the structure of the cotton fabric due to the addition of CNTs. The data obtained for polyester fabrics increased similarly, where the maximum value could be observed at 3.0% silica concentration. Above-test results of an experimental test show that nanoparticles-based additives are effective in textiles' mechanical properties improvement and create a ground for their application in high-performance fashion design.

Table 2 presents the results from vibration dampening performance of fabric samples. In all samples, the starting amplitude of vibrations was 10.0 mm; addition of nanoparticle additives resulted in a significant reduction of amplitudes.

For instance, Cotton fabrics treated with 1.0% CNTs showed an amplitude vibration reduction of 40%, while Cotton fabrics treated with 3.0% silica showed an amplitude vibration reduction of 45%. Similarly, at 3.0% silica concentration in polyester fabrics, the amplitude decreases by 50%. These demonstrate that nanoparticles addition

Table 3 User comfort assessment for fabric with nanoparticle

Fabric Type	Nanoparticle Type	Comfort Rating (1-5)	Softness Rating (1-5)
Cotton	None	3	4
Cotton	CNT	4	4
Cotton	CNT	5	5
Cotton	Silica	4	4
Cotton	Silica	5	5
Polyester	None	3	3
Polyester	CNT	4	4
Polyester	CNT	5	5
Polyester	Silica	4	4
Polyester	Silica	5	5

causes successful damping of vibrations and, hence, have great potential for development of such textiles to enhance comfort by reduced vibration, which can then be exploited in various high-performance applications.

Table 3 summarizes the test results in terms of the assessment on user comfort based on the tested fabric samples. Comfort, breathability, and softness ratings were performed on a scale from 1 to 5, the higher rating being related to better user comfort. The fabrics with 1.0% CNTs and 3.0% silica nanoparticles received the maximum rating in all categories, whereas cotton and polyester samples attained a comfort rating of 5. Thus, it may be believed that the nanoparticle additives enhance not only mechanical properties and vibration dampening but also increase the user comfort by an order of magnitude. This correlation between mechanical properties and user comfort shows that these materials should be used effectively for the development of high-performance textiles suitable for modern fashion design, which at any moment in time must combine comfort with functionality.

Fig. 2 shows the variation of nanoparticle concentration on comfort ratings by two different types of fabrics, namely Cotton and Polyester. The rating of comfort has been quantified between 1 and 5, with larger values which are more indicative of higher comfort degree. From this plot, it can be observed that both types of fabrics exhibit an increasing trend of comfort rating with an increase in the nanoparticle concentration. For Cotton, comfort rating is always 5 at higher concentrations, which range from 1.5% up to 3.0%. This indicates that such fabric treats comfort regardless of whether the quantities of nanoparticle additives in the treatment vary. Whereas for Polyester, an upward trend is also demonstrated, reaching its maximum comfort rating to 5 at 1.5% concentration, but then it plateaus at a lower rating as the test concentrations exceed that amount. This means that, though both fabrics increase their comfort when nanoparticle additives are added, Cotton keeps its comfort level better with a higher concentration of those nanoparticles. The result points to very interesting perspectives for tailoring fabric properties by nanoparticle technology, which brings great advantages in textile design with respect to improving wearer comfort in selected

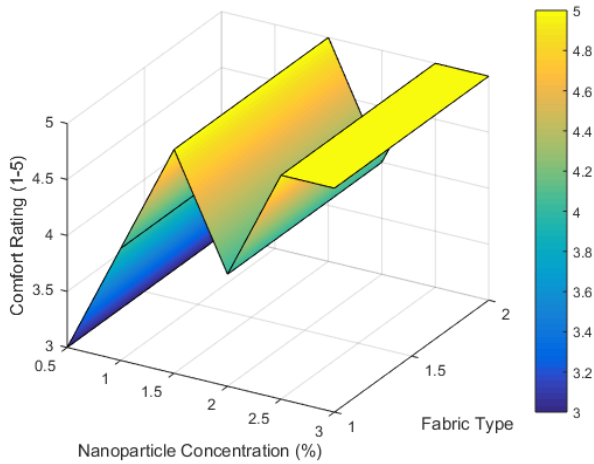


Fig. 2 The variation of nanoparticle concentration

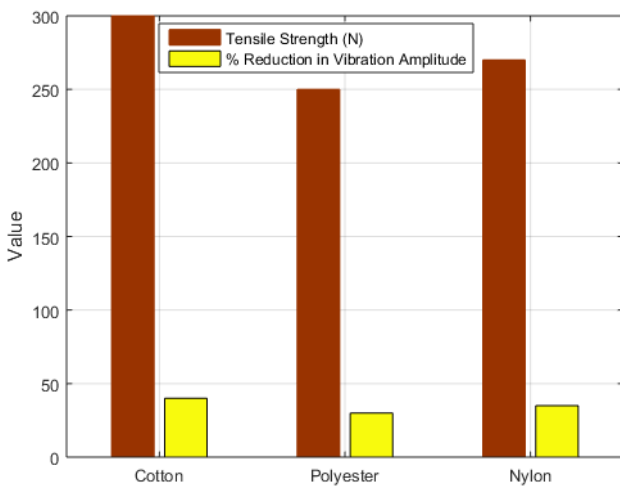


Fig. 3 The tensile strength and the percentage reduction in amplitude of vibration across three types of fabrics

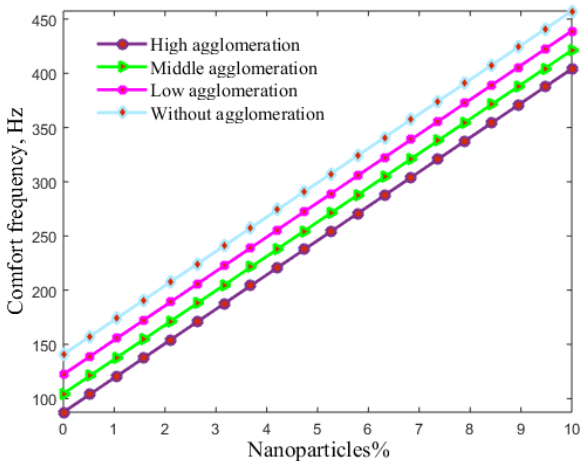


Fig. 4 The agglomeration on the vibrational frequency of the fabric structures embedded with nanoparticles

applications and providing a reduction of vibration impacts. Taken together, these figures illustrate how the addition of nanoparticles can enhance the physical-comfort related properties of fabrics. Generally speaking, it would now

appear that Cotton becomes the better choice in those applications focusing on strength and damping of vibration.

Fig. 3 shows the tensile strength and the percentage reduction in amplitude of vibration across three types of fabrics, namely Cotton, Polyester, and Nylon. It has been found that Cotton is the strongest among them-300 N, followed by Nylon at 270 N and Polyester at 250 N, respectively. From these results, one may state that Cotton is more structurally solid and hence more favorable in areas where the material is required to be strong.

For the vibrational damping characteristics, Cotton takes the lead, assuming a 40% reduction in vibration amplitude, while Polyester and Nylon take up 30% and 35%, respectively. From this, it can be deduced that the addition of nanoparticle additives greatly enhances the vibrational damping properties of Cotton fabric relative to the other materials analyzed. This is probably due to the fact that each fabric possesses unique physical and chemical interactions with the nanoparticle additives. Thus, Cotton outperforms other fabrics in many respects: tensile strength, comfort, and control of vibration make it a fascinating candidate for applications in fashion design, which is interested in enhanced comfort and performance.

Fig. 4 shows the effects of the agglomeration on the vibrational frequency of the fabric structures embedded with nanoparticles. All data show that the vibrational frequency decreases considerably at high volume percentages of nanoparticles when the agglomeration effect is taken into consideration. The phenomenon can be explained by the fact that agglomeration prevents the homogeneous dispersion of nanoparticles throughout the fabric matrix. These nanoparticles, upon agglomeration, develop points of stress concentration that might weaken the overall material properties. The rigidity in the fabric structure reduces, and hence, the frequency response to vibrational loading is lower. This also becomes very important in the design of fabrics where comfort and mechanical performance are closely associated with the structural integrity at a material level.

Furthermore, it is obtained from this study that with the increase in nanoparticles concentration, the vibrational frequency, after attaining a critical value, shows a trend which is exactly opposite. In other words, the increased volume fraction of nanoparticles increases the overall bending rigidity of the fabric structure and hence accounts for the vibrational frequency increase. This effect is especially important in the case of those types of nanoparticles that can serve as effective mechanical property reinforcement of the fabric upon proper dispersion. The greater the bending rigidity, the greater the ability of the fabric to absorb and dissipate energy; thus, it has improved vibration-damping characteristics. Therefore, the optimal dispersion of nanoparticles in the fabric matrix is a matter of prime importance for performance management by fabric designers. This balance is highly important not only in raising comfort and damping vibrations in fashion design but also for the final product to retain aesthetic and functional properties. The knowledge obtained from this study underlines the relevance of nanoparticle distribution and its direct influence on the vibrational mode of advanced

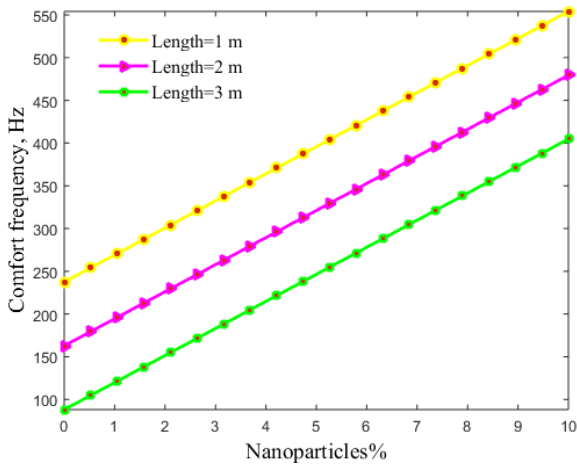


Fig. 5 fabric length changes the vibrational frequency as a function of volume percentage of nanoparticles

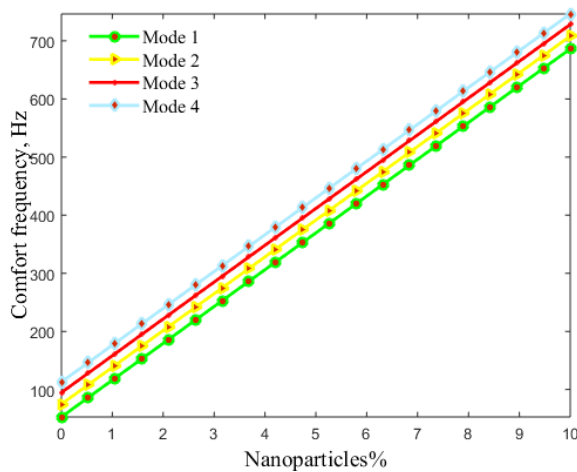


Fig. 6 The vibrational frequency dependence on mode number

fabrics, hence opening new perspectives in fashionable and wearable applications.

Fig. 5 shows how fabric length changes the vibrational frequency as a function of volume percentage of nanoparticles. Indeed, from this data, it is evident that the increase in the length of the structure is directly increasing the vibrational frequency. The reason for this trend may be because a longer fabric structure has more stiffness compared to the shorter ones. A longer fabric would tend to enjoy a greater distribution of tensile forces, and this usually reflects positively on its bearing load and stiffness. Due to the increased stiffness, the fabric would stand in a better position to properly respond to vibrational stimuli, hence producing higher frequencies.

Also, the interaction of fabric length and volume percentage of nanoparticles is a critical factor for general mechanical performance. As the volume percentage of the nanoparticles is increased, the added stiffness from the nanoparticles further acts to increase the frequency. The relationship among these points out the importance of an optimized fabric length-nanoparticle content approach for vibrational characteristics. It is in these parameters,

balanced appropriately, that designers are able to develop improved fabrics from both comfort and aesthetic perspectives but also with better mechanical properties, which are of interest for fashion and wearable technology applications. Better understanding of this dynamic may lead to innovations that will enhance the functionality of fabrics while maintaining their lightweight and flexible nature, thus changing the face of modern textile design.

The vibrational frequency dependence on mode number, concerning the volume percentage of nanoparticles in the fabric structure, is shown in Fig. 6. These results show that by increasing the mode number, the vibrational frequency increases. This is in good agreement with the basic principles of vibrational analysis, in which larger mode number means larger and higher-energy states of a material vibration. With the increased mode number, the deforming ability of the fabric and the response to applied forces improve; hence, frequency increases.

This relationship between mode number and frequency has a particular importance in advanced application fabrics like wearable technology and performance textiles. The incorporation of nanoparticles into a fabric matrix is one means whereby designers can influence vibrational characteristics, thereby permitting the fabrication of fabrics which, while providing comfort, can also be engineered to exhibit mechanical properties according to needs. It allows them to tune mode numbers and volume percentages, creating the vibrational response.

#### 4. Conclusions

This present study highlights that the addition of nanoparticles can result in significant modification to comfort and damping vibration properties of fabrics. This analysis showed that agglomeration causes the nanoparticle additives to experience a decline in the vibrational frequency resulting from decreased stiffness within the fabric structure. This underlines the prime importance of proper distribution of nanoparticles, since it forms the basis for achieving improved mechanical properties of the fabric. Moreover, the results indicated that higher volume percentages and lengths lead to higher frequencies, which are in agreement with the improved bending rigidity. These suggest that for the best performance of advanced textiles, great consideration must be taken of nanoparticle dispersion and concentration. The mode number effect study on frequency involved higher modes giving rise to increased frequencies that enhance the vibrational response of the fabric. This therefore forms the relationship whereby tailored designs for fabrics could meet certain performance requirements, especially those involving the aspect of comfort and durability. As the textile industry is moving to innovative and functional designs, the incorporation of nanoparticle additives is one avenue through which a smart fabric can be developed. These developments, besides enhancing user experience, also open new frontiers in fashion technology, including clothes that are fashionable yet high-performing, featuring vibration damping and overall comfort.

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