Vibration mitigation

New Force-Network based granular damping technology

Vibrations permeate our world, serving as the invisible threads that connect us to our surroundings. Sound, the most palpable form of vibration, encompasses a spectrum ranging from the gentle rustle of leaves to the thunderous roar of a waterfall. Beyond sound, vibrations manifest in various forms, from the rhythmic hum of machinery to the soothing resonances of a well-tuned musical instrument.

In general, we can distinguish two main kinds of vibrations: acoustic and structural. Acoustic vibrations primarily involve the transmission of sound waves through a medium, such as air or water. These vibrations result from the oscillation of particles within the medium and are perceived by our ears as sound. Acoustic vibrations can vary in frequency, amplitude, and wavelength, giving rise to a diverse range of auditory experiences.

On the other hand, structural vibrations involve the mechanical oscillations of solid objects or structures. These vibrations occur when a force is applied to a structure, causing it to deform or resonate. Structural vibrations can arise from various sources, including machinery operation, seismic activity, or human activity. Unlike acoustic vibrations, which propagate through a medium, structural vibrations typically occur within a solid material.

THE IMPACT OF VIBRATIONS

While acoustic vibrations primarily affect our auditory perception, structural vibrations can have broader implications, influencing the stability, performance, and safety of mechanical systems and structures. The effects of vibrations on human life and activities are still poorly understood, and they are the subject of an important emerging field of interdisciplinary research, focusing specifically on the biomechanical response of the human body in a variety of situations.

Controlling acoustic vibrations often involves measures such as soundproofing or acoustic design to mitigate noise and enhance acoustic comfort in indoor or outdoor environments. In contrast, excessive structural vibrations can lead to fatigue and damage over time, posing risks to the integrity of buildings, bridges, and other infrastructure.

Several approaches are employed to dampen structural vibrations, aiming to reduce the amplitude and mitigate the potential risks associated with excessive oscillations. These include structural modifications, which can alter the dynamic characteristics of the structure and reduce its susceptibility, and active damping systems, which rely on sensors to detect vibrations and actuators to apply countering forces in real time, effectively suppressing oscillations across a broad frequency range.

VIBRATION-DAMPING MATERIALS

One of the most promising approaches to control the effects of structural vibrations on human activities and health relies on the use of materials specifically engineered to dampen vibrations. New, sustainable, and lightweight vibration-damping materials are, for instance, of crucial importance in the transportation sector, where they can contribute to both vibration and weight reduction. They also have potential to act as support structures in the automotive industry, rail transportation, space industry, and marine transportation.

Previous research has characterised two main groups of vibration-damping materials of potential relevance in this field. The first group includes metal alloys and metal matrix composites, in which a metal matrix is reinforced with one or more secondary materials, including ceramic particles, fibres, or whiskers. The second group includes polymers, such as thermoplastics, which become pliable or mouldable when heated and solidify upon cooling, and thermosets, which undergo chemical transformations upon heating to then solidify into an extremely durable hard form after cooling. Despite their versatility, both metal alloy and polymeric materials may not exhibit the desired performance when both vibration damping and support functions are needed, like in transportation.

GRANULAR DAMPING

To create new materials with an optimal balance between vibration-damping and mechanical properties, such as strength, durability, and low weight, Dr Simon Oman at the University of Ljubljana in Slovenia and his colleagues Igor Ermi, Marko Nagode, Jernej Klemenc, and Aleš Gosar have studied experimentally and with numerical models how polymeric materials develop vibration-damping properties and how these can be made to coexist with high mechanical stability. The study resulted in the production of the first Granular Damping Elements (GDEs).

Their work is based on an innovative approach to prepare polymeric materials with dramatically enhanced damping properties and stiffness developed by Professor Ermi. This method makes it possible to synthesise materials with damping properties up to 100 times higher and stiffnesses up to 10 times higher than those of existing polymers. This theoretical and practical breakthrough has been made possible by careful consideration of the interplay of the different vibration-damping mechanisms which act in a polymeric material with a granular structure. The researchers have been further developing this approach, converting its basic ideas into practical, real-life applications.

Granular materials are collections of discrete, solid particles that interact with each other primarily through contact forces, such as friction, cohesion, and repulsion. Sand, gravel, powders, and grains are common examples of materials with granular structure. In these materials, the constituent particles can vary in size, shape, and composition, and they often exhibit complex behaviours due to their interactions. The key to exploiting granular materials for vibration damping, according to the research team, comes from a microscopic understanding of how these materials can absorb mechanical energy and release it efficiently in the environment, for instance in the form of heat.

FORCE-NETWORK TECHNOLOGY

According to the new so-called ‘high-pressure force-network’ technology first proposed in 2019, the vibration-damping properties of granular materials can be attributed to two energy-dissipation mechanisms which operate at different time scales. The first mechanism involves microscopic interactions between molecules within the granules, and it is regulated by the pressure-frequency (time) superposition principle. This principle states that, in viscoelastic materials like polymers, which display both viscous, or flow-like, and elastic, or spring-like, behaviour, changes in the frequency or rate with which energy is applied to a material have effects equivalent to those caused by changes in temperature. This means that knowing the behaviour of a material at a specific temperature and frequency makes it possible to predict its behaviour at different conditions by applying suitable shifts in time or frequency.

By employing a combination of these approaches, engineers can effectively dampen structural vibrations and enhance the performance, safety, and comfort of buildings, bridges, and other mechanical systems. The specific method chosen depends on factors such as the magnitude of vibrations, frequency range, structural characteristics, and budget constraints.

Excessive structural vibrations can lead to fatigue and damage over time, posing risks to the integrity of buildings, bridges, and other infrastructure. For instance, changes in the pressure-frequency (time) superposition principle of heat.
Granular damping elements offer the ability to achieve vibration-damping performances many times higher than those of the best damping materials currently available.

In a real material, the two dissipation mechanisms complement each other, and drive its response to different levels of energy absorption/dissipation. When the pressure applied to the material is low, the macro-scale force-chain network mechanism is dominant. However, when the pressure is high, microscopic molecular-driven dissipation within the granules prevails. This model of vibrational energy dissipation provides guidelines on how to choose optimal materials for creating granular damping elements, the basic components of vibration control exploiting the force-network technology. ‘The key to create a good granular vibration-damping element’, says Oman, ‘is to use materials for which the internal stress parallel to the cross section, or shear stress, decreases faster than the stress applied perpendicular to the element’s cross section, or normal stress, as the size of the granules decreases.’

Hence, Granular damping performance up to four times larger than that of the bulk material. The approach they have been using is currently covered by two patents in the United States and in the European Union. This elegant work has shown that GDEs offer the unique ability to achieve extreme damping performances, which are many times higher than those of the best damping materials/systems currently available on the market.

The second energy dissipation mechanism, which is specific to granular materials and occurs at the macro-scale, is related to the rearrangement of granules when a material is subjected to an external force. In granular materials, particles interact primarily through contact forces. In the presence of external forces, like those exerted by mechanical vibrations, these contact forces redistribute to form force chains that can transmit the applied forces efficiently through the material.

In a real material, the two dissipation mechanisms complement each other, and drive its response to different levels of energy absorption/dissipation. When the pressure applied to the material is low, the macro-scale force-chain network mechanism is dominant. However, when the pressure is high, microscopic molecular-driven dissipation within the granules prevails. This model of vibrational energy dissipation provides guidelines on how to choose optimal materials for creating granular damping elements, the basic components of vibration control exploiting the force-network technology. ‘The key to create a good granular vibration-damping element’, says Oman, ‘is to use materials for which the internal stress parallel to the cross section, or shear stress, decreases faster than the stress applied perpendicular to the element’s cross section, or normal stress, as the size of the granules decreases.’

POLYURETHANE GRANULAR MATERIALS

Oman and his collaborators applied these ideas to engineer a vibration-damping element based on thermoplastic polyurethane in granular form. This material combines the flexibility and elasticity of rubber with the ability to retain its chemical structure even after being repeatedly melted and solidified. They have developed a method for preparing and characterising tubular elements containing thermoplastic polyurethane granules and have shown that this material exhibits vibration damping performance up to four times larger than that of the bulk material. The approach they have been using is currently covered by two patents in the United States and in the European Union. This elegant work has shown that GDEs offer the unique ability to achieve extreme damping performances, which are many times higher than those of the best damping materials/systems currently available on the market.

One important finding described in the patent ‘Sound Insulating Element’ is that, in suitable conditions, granular materials can flow like liquids, but they retain the physical and chemical properties of the bulk material. This phenomenon is known as ‘flowability’ and occurs when the forces between granules and their packing make it possible for them to move and rearrange freely, resembling the behaviour of a fluid. According to the researchers’ analysis, this liquid-like behaviour is observed when a stress larger than a given threshold is applied to a granular material. Flowability in turn enhances vibration damping by redistributing vibrational energy within the material and promoting its dissipation.

Emri has also shown that optimal flowability can be achieved when the granule sizes display a multimodal distribution, characterised by the coexistence of multiple size ranges. Other granule parameters, including their shape and size, and the initial stress applied to the material, or preload, can also influence flowability, and provide additional means to tune and optimise the vibration-damping ability of novel materials.

**POLYURETHANE GRANULAR MATERIALS**

**Materials**

Oman and his collaborators applied these ideas to engineer a vibration-damping element based on thermoplastic polyurethane in granular form. This material combines the flexibility and elasticity of rubber with the ability to retain its chemical structure even after being repeatedly melted and solidified. They have developed a method for preparing and characterising tubular elements containing thermoplastic polyurethane granules and have shown that this material exhibits vibration damping performance up to four times larger than that of the bulk material. The approach they have been using is currently covered by two patents in the United States and in the European Union. This elegant work has shown that GDEs offer the unique ability to achieve extreme damping performances, which are many times higher than those of the best damping materials/systems currently available on the market.

One important finding described in the patent ‘Sound Insulating Element’ is that, in suitable conditions, granular materials can flow like liquids, but they retain the physical and chemical properties of the bulk material. This phenomenon is known as ‘flowability’ and occurs when the forces between granules and their packing make it possible for them to move and rearrange freely, resembling the behaviour of a fluid. According to the researchers’ analysis, this liquid-like behaviour is observed when a stress larger than a given threshold is applied to a granular material. Flowability in turn enhances vibration damping by redistributing vibrational energy within the material and promoting its dissipation.

Emri has also shown that optimal flowability can be achieved when the granule sizes display a multimodal distribution, characterised by the coexistence of multiple size ranges. Other granule parameters, including their shape and size, and the initial stress applied to the material, or preload, can also influence flowability, and provide additional means to tune and optimise the vibration-damping ability of novel materials.

**POLYURETHANE GRANULAR MATERIALS**

**Materials**

Oman and his collaborators applied these ideas to engineer a vibration-damping element based on thermoplastic polyurethane in granular form. This material combines the flexibility and elasticity of rubber with the ability to retain its chemical structure even after being repeatedly melted and solidified. They have developed a method for preparing and characterising tubular elements containing thermoplastic polyurethane granules and have shown that this material exhibits vibration damping performance up to four times larger than that of the bulk material. The approach they have been using is currently covered by two patents in the United States and in the European Union. This elegant work has shown that GDEs offer the unique ability to achieve extreme damping performances, which are many times higher than those of the best damping materials/systems currently available on the market.

One important finding described in the patent ‘Sound Insulating Element’ is that, in suitable conditions, granular materials can flow like liquids, but they retain the physical and chemical properties of the bulk material. This phenomenon is known as ‘flowability’ and occurs when the forces between granules and their packing make it possible for them to move and rearrange freely, resembling the behaviour of a fluid. According to the researchers’ analysis, this liquid-like behaviour is observed when a stress larger than a given threshold is applied to a granular material. Flowability in turn enhances vibration damping by redistributing vibrational energy within the material and promoting its dissipation.

Emri has also shown that optimal flowability can be achieved when the granule sizes display a multimodal distribution, characterised by the coexistence of multiple size ranges. Other granule parameters, including their shape and size, and the initial stress applied to the material, or preload, can also influence flowability, and provide additional means to tune and optimise the vibration-damping ability of novel materials.

**References**


**Personal Response**

Granular damping elements that use force-network technology for vibration mitigation can be used in various areas of technology, e.g. in the marine and automotive industries, in the seismic isolation of buildings, in rail transportation and in other areas. One of the key areas we are currently focusing on is reducing the propagation of vibrations from high-speed rail lines to the surrounding area. Vibration problems occur especially with freight trains, as the different wagons can have very different masses, which means that it is practically impossible to avoid the phenomenon of resonance when the excitation frequency is equal to the natural frequency of the system. This is also one of the main reasons why the maximum speed of freight trains is limited to 120 km/h. If we want to increase the speed of freight trains in the future, we need to adapt the tracks by increasing their ability to absorb much more energy than the current tracks can. To this end, GDE elements have proven to be a potentially ideal damping element that could replace the current materials (mostly rubber compounds) in the future and thus enable an increase in the speed of freight trains.