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ORIGINAL ARTICLE

Evaluation of instantaneous vibration parameters of a snowboard with a prototype granular dissipator

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Abstract

A container partially filled with loose plastic granules was attached to the shovel of the snowboard to suppress large-amplitude lateral vibrations by dissipating energy through non-conservative multi-granule interactions. A custom laboratory stand allowed to evaluate the performance using a full-scale snowboard deck. The response of the system with a prototype granular dissipator was measured for free lateral vibrations of the initially deflected board and under prescribed sinusoidal base motion. The damping characteristics for different fill ratios of the container were obtained using a direct method of nonparametric identification. The applied Hilbert–Huang transform-based vibration analysis method gave more insight into the board's damping performance than the logarithmic decrement analysis. The results show that using the granular dissipator with a predestined number of granules increases the damping capacity at large amplitudes but is less effective at small amplitudes. At best, the damping factor was 70% higher when the granular dissipator was used than when the board was damped only intrinsically.

Keywords Vibration · Damping · Granular material · Dissipation · Hilbert transform · Bending

1 Introduction

Since the first attempts in the mid-1960s, allowing for a surfing experience on a snow hill, manufacturers have made an effort to reduce unwanted vibrations of snowboards. Through the years, the characteristics of the snowboard decks have been improved with multi-material development, introducing composites, and shaping geometry of the board. Although manufacturers provide various snowboards of different shapes, sizes, and material compositions, the demand for damping solutions that establish a compromise between flexibility and vibration prevention is still great.

This paper explores the possibility of using a prototype multi-granule vibration dissipator attached to the shovel to effectively mitigate lateral vibrations of a snowboard deck. Granules could move freely inside the container, colliding and rubbing with each other to counteract the movement of the snowboard. Instead of modifying the board's geometry or introducing additional damping layers, attaching external damping devices to the board's surface is relatively rare.

Usually, damping is introduced to the snowboard through the material design of the layered core, while the modal frequencies are tuned by shaping the board's geometry [1, 2]. In Ref. [3], the authors combined laboratory, computational

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and field results, stating that damping ratios and relative values of bending and torsional frequencies are directly related to the controllability and handling of the snowboard. Comparative experiments on the vibration characteristics of snowboards were also presented in Ref. [4], where the authors conducted experiments in the laboratory and on-snow, using modal analysis for two different decks. In Ref. [5], frequencies and damping ratios under free-free boundary conditions were acquired, and damping ratios between 0.3 and 0.6% for bending and between 0.6 and 1.0% for torsion were reported. Some scholars proposed more advanced solutions to introduce additional damping without compromising the deck's flexibility. In Ref. [6], the authors used a piezoelectric device tuned to a selected frequency for a smoother snowboard ride. In Ref. [7], the snowboards were equipped with dedicated binding plates that modified their mechanical behaviour. Free vibration tests revealed a modest increase in lateral bending, a more substantial increase in torsional stiffness, and a substantial increase in damping for some of the binding plates.

Meanwhile, some researchers have proposed external dampers for alpine skis, but they could also be adapted for snowboard decks. In Ref. [8], a multilayer piezoelectric actuator was used to alter the dynamics of the ski in the first mode, leading to an attenuation up to 30 dB. Foss and Glenne [9] used a viscoelastic graphite damper attached to the top layer, demonstrating several percentages improvement in damping capacity. In Ref. [10], the authors improved the damping of alpine skis using passive piezoelectric patches, but only numerical results were discussed. In Ref. [11], the authors compared nontypical, commercially available solutions, including tuned mass dampers, liquid-filled particle dampers, constrained layer and rod-activated viscoelastic bushing. The authors reported a somewhat limited damping capacity for the observed accelerance maps. In Ref. [12], the single mass impactor comprising a disk-shaped counterweight in a flat container was examined and reported to reduce the half-life time for small deflections of 2.5 mm in laboratory tests.

Instead of using a single mass impactor, one can use multiple granules that collide with each other and with the container to attenuate the vibrations of the snowboard. When colliding inside an enclosure, non-conservative interactions combining friction and slip, momentum exchange, particle reorientation, local deformation, etc., result in dissipating energy [13, 14]. Such dissipation mechanisms mitigate the beams' vibrations by embedding small grains in structural voids [15, 16] or placing them in a container attached to the primary system [17, 18]. The dominant dissipation mechanism depends on the configuration of the system and the state of granular matter in which the particular damper operates [19]. Gagnon et al. [20] compiled a comprehensive overview of different approaches to particle damping. With the same added mass, granular dissipators usually show softer impacts but more substantial energy dissipation over a single counterweight impactor [17], which reveals the possibility of effectively using granular damping to mitigate vibrations of boards dedicated to sports activities, particularly snowboard decks.

In Ref. [21], a granular dissipator was used to attenuate vibrations of alpine skis. Only fundamental characteristics were discussed by analysing the damping ratio for consecutive peaks and the instantaneous characteristics. The current paper builds on those findings, extending the research to snowboards and discussing the nonlinear influence of the granular dissipator on the elastic and damping force characteristics, giving the complete signature of the performance of the equipment. Applying the granular damper to snowboards seems even more practical than to skis. Unlike skis, snowboard can be ridden nose-front and tail-front. Depending on the individual preferences and stance, a granular dissipator could be placed at either of the sections or at each end of the board. Those characteristics could be used as quantitative indicators for different decks replacing the marketing-focussed subjective descriptions of the board's performance. Furthermore, the dynamic excitation tests of the snowboard were performed using a custom experimental stand, providing frequency response under repeatable conditions that could be used for extended and updated normative tests of snowboard decks.

2 Methods

2.1 Experimental setup

The deck examined was a freeride snowboard (model Cruzer, Burton Snowboards, Burlington, USA) (Fig. 1). The considered model was almost 140 cm long with an effective edge of 110 cm. The nose, waist, and tail widths were 28, 25 and 28 cm, respectively, and the sidecut radius was 650 cm. The total mass of the snowboard was 2.32 kg. The deck had a layered sidewall construction, reverse camber profile and is marketed as an easy to manoeuvre, durable, and flexible learning board.

A cylindrical, 6.5 cm diameter × 2.5 cm high aluminium container weighing 22 g, was glued to the upper surface at the tip of the snowboard. The container was filled with different numbers (i.e. 50, 100, 200, 300, and 400) of acrylonitrile-butadiene-styrene (ABS) granules, and secured with a screw cap. The granules were calibrated, monodisperse spheres of 6 mm in diameter, weighing 0.2 g each. The container fitted a total of around 500 granules, so the fill ratio calculated as the number of used granules divided by the maximum number of granules was 10%, 20%, 40%, 60% and 80%. Attaching the dissipator resulted in a mass increase of

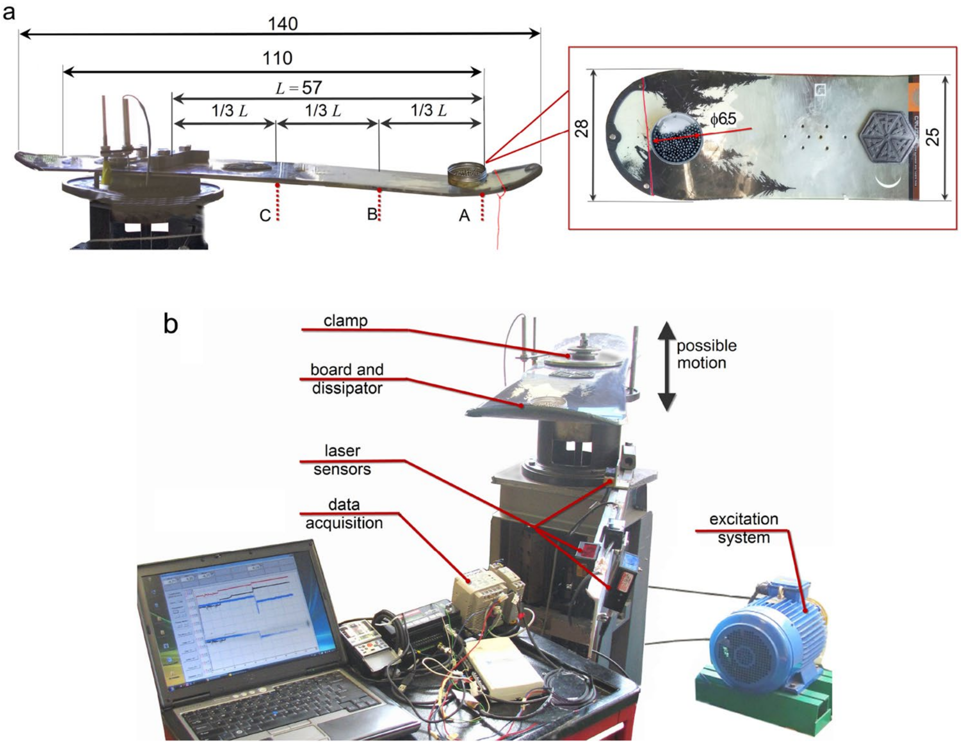

Fig. 1 Dimension of the examined board with attached dissipator and the measurement points A, B, and C (dimensions in centimetres) (**a**) and photo of the laboratory stand for kinematic excitation (**b**)

less than 4% compared to the snowboard without the dissipator. The high-amplitude and low-frequency vibrations of the frontal part of the deck were focussed.

In the first stage of the experimental work, the transient response of a snowboard deck subjected to bending was evaluated. A custom laboratory stand was used to benchmark the free lateral vibrations of an initially deflected board, which was fixed in a horizontal cantilever orientation (Fig. 1a). The snowboard heel was fixed to massive support along the straight line that traversed the snowboard through the midpoint of the two centre points of the shoe and secured with a flat plate clamp at the backfoot binding mounting spot to isolate the front section of the board. The shovel remained free, and three independent laser sensors ZS-HL and ZX-LD (OMRON Corporation, Kyoto, Japan), and Microtrak II (MTI Instruments, Albany, USA) measured the deflection over time at points A, B, and C, at a resolution of 40 µm. These lasers were positioned along the longitudinal axis of the board, perpendicular to the snowboard base at the tip and 1/3, 2/3 of the free length $L = 57$ cm.

In the free vibration test, a wire looped around the shovel was pulled using the pull and release mechanism to introduce the initial deflection. After release, the vibration decayed until all potential and kinetic energy received and stored was dissipated. Data were collected at a sample rate of 200 Hz using an acquisition card NI-USB6211 (National Instruments, Austin, TX).

In forced vibration tests, the snowboard deck was harmonically excited with a prescribed sinusoidal base motion whose frequency increased at a linear rate over time, to demonstrate the efficiency of the dissipator under repeatable conditions imitating real-ride. The dynamic load system was placed underneath the board support, which was connected with a linear guide to a rotary motor (Fig. 1b). The linear guide restricted the movement only to a translational up and down motion with 5 mm amplitude.

On-snow field measurements of ski and snowboard performance benefit from closeness to reality but often are hard to conduct, and results are difficult to reproduce due to variation between test runs influencing the final performance. In Refs. [22–24], the authors used advanced experimental stands to replicate on-snow loading conditions to the maximum extent possible. While not so advanced as the referenced experiments, the proposed test stand was robust and allowed for a repeatable excitation and forcing large amplitudes of displacement of the snowboard deck. Nevertheless, the most objective method would be to confront the obtained laboratory results with the experts' opinions on the hill, which might be considered the next step in testing the prototype dissipator.

2.2 Instantaneous parameters' analysis

Although there is no regulation for examining the damping of snowboards, the standardised procedure for alpine skis described in ISO6267:1980 *Alpine skis—Measurement of bending vibrations* [25], can be referenced. However, the ISO standard, which uses the logarithmic decrement slope or half-life time as a damping measure, deals only with the integrated damping estimation, omitting the nonlinear effects present in modern multilayered decks [26–29]. Moreover, granular damping was expected to introduce even more nonlinearities, so obtaining the instantaneous damping parameters was crucial for describing the system's complete performance.

In this study, the combination of empirical mode decomposition (EMD) followed by the Hilbert transform (HT), referred to in the literature as the Hilbert–Huang transform [30, 31] (HHT), was used to track the instantaneous time evolution of the envelope, stiffness, damping and frequency, including their nonlinearities demonstrated by the damping characteristics. Only the principals of the HHT will be recalled below.

The original vibration source signal $s(t)$ can be represented as the sum of j monocomponent intrinsic mode functions (IMFs) identified using EMD and the residual part r_n:

$$s(t) = \sum_{j=1}^{n} y_j(t) + r_n(t). \tag{1}$$

All local extrema of the source signal $s(t)$ are identified initially, and the mean function between the maxima and minima of the envelopes $m_1(t)$ is subtracted from the source:

$$e_1(t) = s(t) - m_1(t). \tag{2}$$

The first estimate e_1 becomes the new source, and after i siftings, the final estimate becomes the first IMF denoted $e_{1i} = y_1$. The remaining residue

$$r_1(t) = s(t) - y_1(t) \tag{3}$$

becomes a new source for extracting subsequent IMFs in the same way. Each of the IMFs contains an elementary oscillatory component. The IMF of the highest amplitude corresponds to the dominant vibration mode, while isolating higher IMFs denoises the signal. The HT of the particular IMFs can be derived as

$$\tilde{y}(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{y(\tau)}{t-\tau} \mathrm{d}\tau, \tag{4}$$

where P denotes the Cauchy principal value.

Combining the original and transformed signal derives a complex analytic signal:

$$Y(t) = y(t) + i\tilde{y}(t) = A(t)\mathrm{e}^{i\theta(t)}, \tag{5}$$

where $A(t) = \sqrt{y(t)^2 + \tilde{y}(t)^2}$ is the envelope and $\theta(t) = \arctan(\tilde{y}(t)/y(t))$ is the phase.

Then, the instantaneous frequency (IF) $\omega(t)$ is calculated as:

$$\omega(t) = \dot{\theta}(t) = \frac{y(t)\dot{\tilde{y}}(t) - \dot{y}(t)\tilde{y}(t)}{A^2(t)}. \tag{6}$$

In virtue of Eq. (5), the HT of the motion equation of free vibration for the selected IMF becomes

$$\ddot{Y} + 2h_0(A)\dot{Y} + \omega_0^2(A)Y = 0, \tag{7}$$

where $h_0(t)$ is the viscous damping and $\omega_0(t)$ is the instantaneous undamped natural frequency, derived from Eqs. (5) and (6) as

$$h_0(t) = -\dot{A}/A - \dot{\omega}/(2\omega) \tag{8}$$

and

$$\omega_0^2(t) = \omega^2 - \ddot{A}/A + 2\left(\dot{A}/A\right)^2 + \dot{A}\dot{\omega}/(A\omega). \tag{9}$$

Since there are no assumptions about the forms of amplitude and damping, the identification method is considered nonparametric. Moreover, since the equivalent equation of motion can be written as

$$\ddot{y} + 2h_0(\dot{y})\dot{y} + k(y) = 0 \tag{10}$$

the elastic and damping force characteristics can be reconstructed as

$$k(y) \approx \omega_0^2(t)A(t)\mathrm{sgn}y \tag{11}$$

and

$$h(\dot{y})\dot{y} \approx h_0(t)A_{\dot{y}}(t)\mathrm{sgn}\dot{y}, \tag{12}$$

where $k(y)$ is the restoring force as a function of displacement, $h(\dot{y})\dot{y}$ is the damping force as a function of velocity, and $A_{\dot{y}}(t)$ is the envelope of velocity. The force characteristics are considered static symmetric and deal only with a unit mass of a system.

3 Results

3.1 Free vibrations

After selecting the dominant IMF which filters out the noise, the displacement at the tip point A (Fig. 1) for an intrinsically damped snowboard (no granules) was compared with the results for a different number of granules inside the container. The data history was cropped to the initial 2 s to remove the excess data (Fig. 2).

The dissipation surged after the board was released due to the rapid colliding of the granules. When 50 or 100 granules were used, corresponding to a 10 or 20% fill ratio, the recorded amplitude peaks were markedly reduced compared to the board without the dissipator. This is well

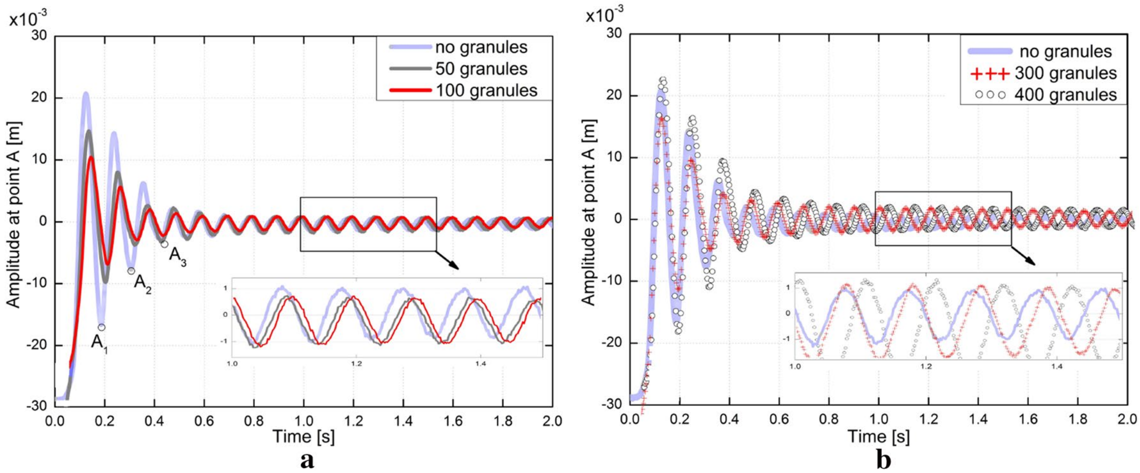

Fig. 2 Displacement after initial deflection of 30 mm for a snowboard with: **a** no granules, 50 granules (10% fill ratio) and 100 granules (20% fill ratio), and **b** no granules, 300 granules (60% fill ratio) and 400 granules (80% fill ratio)

manifested for the first few peaks of large amplitudes, whereas the discrepancies in damping performance diminish as the amplitudes reduce over a longer time interval. After an initial deflection of 30 mm the second extremum of amplitude (A_2 in Fig. 2a) reached 8.4 mm without dissipator, but only 3.8 and 2.6 mm (which is 70% less) for 50 and 100 granules, respectively. The performance for 200 granules (40% fill ratio) was close to that for 100 granules, so it was omitted from the figures for better readability (see Online Resource 1).

On the other hand, increasing the number of granules to 300 and 400 (60 and 80% fill ratio) did not improve the damping capacity further, negatively affecting vibration abatement. The increased fill ratio limits the free space inside the container, which restricts the dissipating interactions among granules. For 300 granules, the amplitude at peak A_2 reached 5.4 mm, showing worse damping performance than in the case of 50 and 100 granules. In addition, increasing the number of granules adds more mass to the board and decreases the frequency, further limiting movement within the container. In the initial phase, the results for 400 granules were worse than those without the dissipator.

Since different stiffness and damping values act within their amplitude zones, causing the nonlinearity of the vibration system, tracking the instantaneous parameters gives more insight into the response.

The elastic force characteristics (Fig. 3a) consists of a polynomial segment representing the softening spring behaviour for higher amplitudes in the 5–30 mm range and a segment representing the linear restoring force for amplitudes below 1 mm. By analysing of the topography of the curves, the elastic force may be described in zones as

$$k(y) = \begin{cases} \omega_{01}^2 y & \text{if} \quad |y| \le y_{01} \\ \omega_{02}^2 y - \omega_{03}^2 y^3 & \text{if} \quad |y| > y_{01} \end{cases}, \tag{13}$$

where y_{01} is the displacement limit, in our case below 5 mm. When granules were used, the estimated amplitude vs. frequency curves, offset towards lower frequencies, demonstrated a softening type of nonlinear stiffness.

As the restoring force is not proportional to deformation, the resulting amplitude vs. frequency curves present a piecewise characteristic (Fig. 3b). For better readability, the results for 200 and 300 granules were omitted from the figures (see Online Resource 1).

As there is more than one dissipation mechanism in the multilayered snowboard structure, the damping forces distort the characteristics (Fig. 4a), making the instantaneous damping coefficient dependent on the amplitude.

The damping force (Fig. 4a) is a multiline, showing higher damping forces for 50 and 100 granules than for no granules and for 400 granules as well. At high velocities, the response can be described with a linear dependence, whereas the viscous damping model may be better suited for describing amplitudes below the limit y_{02}:

$$h(\dot{y})\dot{y} = \begin{cases} 2h_1\dot{y}|\dot{y}| & \text{if} \quad |\dot{y}| \le \dot{y}_{02} \\ 2h_2\dot{y} & \text{if} \quad |\dot{y}| > \dot{y}_{02} \end{cases}. \tag{14}$$

After releasing the board without the dissipator, when the displacement was much higher than 5 mm, the vibrating snowboard exhibited a maximum damping coefficient of 4.7 s^{-1} (Fig. 4b). Then it slowly diminished with the decreasing amplitude, dropping to 0.8 s^{-1} for amplitudes below 2 mm.

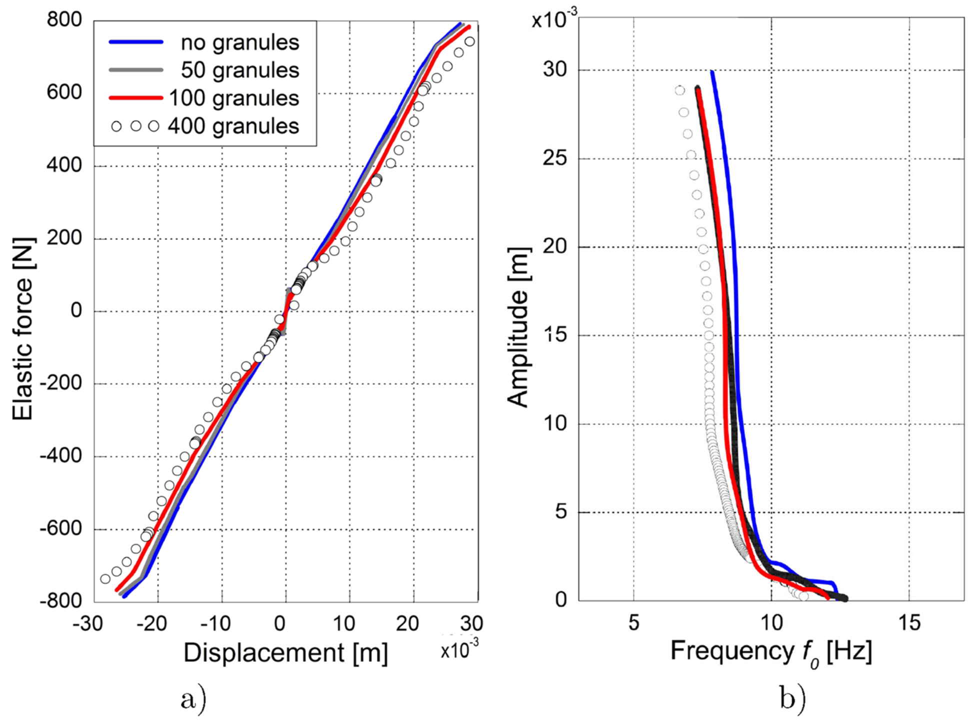

Fig. 3 Experimentally obtained **a** estimated elastic force and **b** amplitude vs. frequency curve for a vibrating snowboard with different number of granules

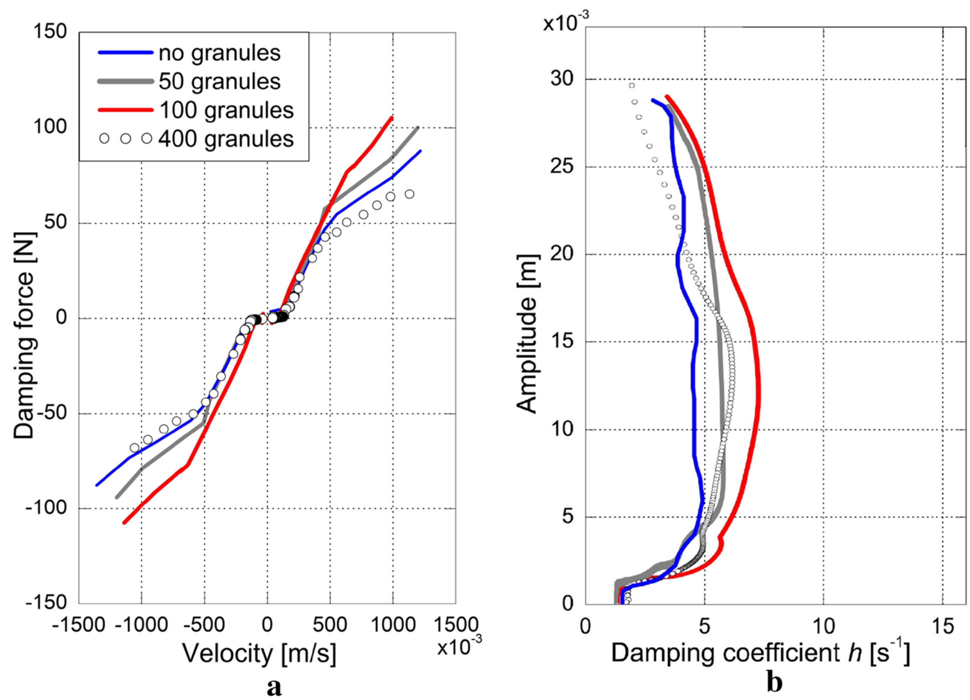

Fig. 4 Experimentally obtained **a** damping force characteristics and **b** damping curve for a different number of granules

When using granules, just after releasing the board, the damping coefficient increased to 7.9 s^{-1} for 100 granules, which was damping 60% higher compared to the board without the dissipator. When the fill ratio exceeded 40% and more than 200 granules were used, the damping capacity became limited. At the initial phase, the damping curve for 400 granules (80% fill ratio) showed even less dissipation than the board with no granules. For 400 granules, after the initial phase, the damping coefficient increased to 6.2 s^{-1}, which was less than the values observed for 100 granules (20% fill ratio).

3.2 Forced vibrations

In forced vibration tests, snowboard oscillations were forced by the sine wave with a constant amplitude of 5.0 mm and a frequency that increased linearly up to 15 Hz. The displacement of the tip of the snowboard for a different number of granules is shown in Fig. 5a. For clarity, for no granules and 50 granules only the envelopes were plotted.

One-hundred plastic granules (20% fill ratio) gave the best damping performance. The maximum displacement was reduced from 35 mm for intrinsic damping to 20 mm for 100 granules. Similarly to the free vibration results, using more than 100 granules did not result in a further increase in damping. The results for 200 granules (40% fill ratio, not plotted) were similar to results recorded for 100 granules, while using higher fill ratios resulted in worse performance.

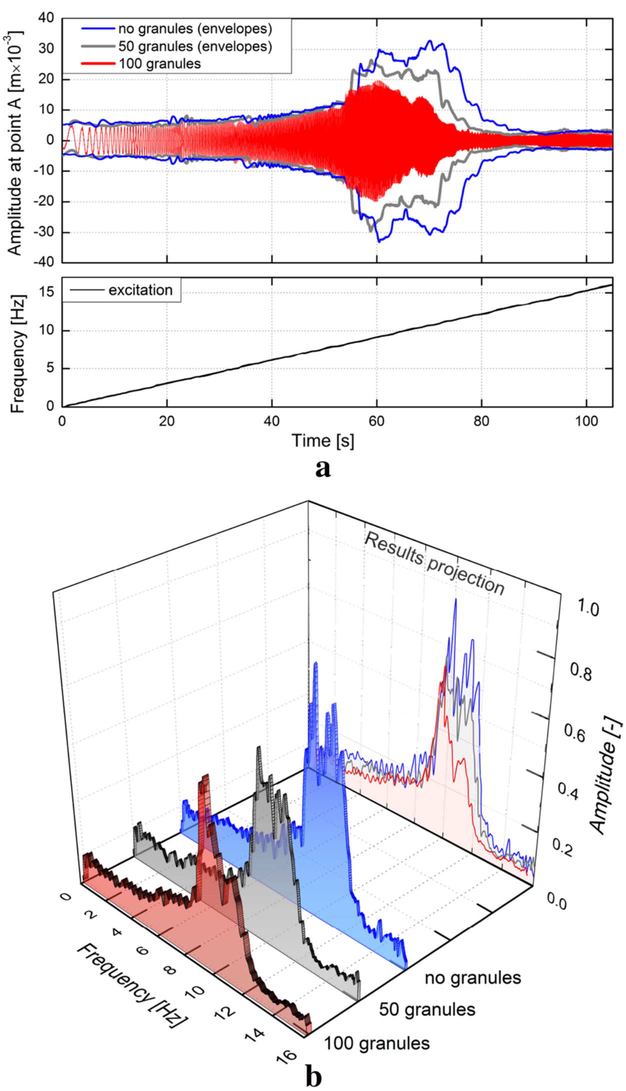

Fig. 5 Comparison of **a** amplitudes and **b** frequency responses for a dynamically excited snowboard with different numbers of granules

The frequency vs. normalised unitless amplitude results presented in Fig. 5b show that when 50 or 100 granules are used, the amplitude peaks were reduced. Moreover, from the projection of the results, one can see that the resonant peak is biased towards lower frequencies from 8.1 to 7.8 Hz when the dissipator was used.

4 Discussion

Using the HHT method gave superior insight into the snowboard performance than the ISO 6267 procedure would. The recreated instantaneous parameters vividly showed the system's specific type and level of existing nonlinearities dominating the board's response, especially when damping curves and force characteristics were considered.

It takes some time to reach maximum damping because granules initially rest on the floor and need a swing to start colliding in the first phase of motion. When the displacement amplitude declines and granules starts settling, the impacting diminishes and so does the damping ratio. The prototype granular damper effectively mitigated large-amplitude vibrations and exhibited lower efficiency for deflections below 5 mm, since the granules settled as the amplitude decreased. While snowboarding, the granules would be constantly excited, which would intensify the dissipation, as demonstrated in the forced vibration experiment. However, the dissipator behaves like a solid mass attached to the board's tip when the granules are settled and locked with gravity.

The experimental stand used in the research allowed for repeatable dynamic excitation and eliminated the inaccuracies and complexity accompanying on-snow experiments performed in Ref. [21] simultaneously for one ski with a damper and another one without it. Such an experimental configuration would be impossible for a snowboard, while repeating runs for differently damped decks would introduce inconsistency and uncertainty into the results. Instead of providing descriptive and marketing-focussed information on the snowboard characteristics, the manufacturers could provide the discussed force characteristics, which could benefit the more conscious users.

The snowboard equipped with the damper should be more forgiving because it dissipates the energy introduced by the terrain irregularities and technique mistakes. Moreover, it could help enhance the on-snow performance and manoeuvrability of the board, which is demanded by novice users seeking stability and better board handling. The dissipator could be easily attached or detached without alternating the original layers of the board and integrated into existing equipment despite the shape, size, or material composition of the snowboard deck. It could be introduced to the board at the design stage by embedding it in the laminated board's top shell, sticking out just to the minimum. The weight penalty would be marginal. In the considered case, the board with the dissipator was less than 4% heavier than without it. Using two dissipators, one on each end of the board seems like a rational development of the idea. However, the rattling noise surrounding the operation of the dissipator may be a drawback.

Changes in the container size, location or excitation amplitude may positively or negatively affect the performance. While the experiments were limited to testing only one board, the granular dissipator should be effective for various board designs, however, different fill ratios might be required. In our experiment, the fill ratio between 10 and 40% resulted in a better damping behaviour than for intrinsic damping, while the 80% fill ratio resulted in a performance worse than that for the snowboard without dissipator. The required fill ratio could be identified in further optimisation after deriving a system model, which is beyond the scope of this article. A challenge with this type of work is that the damping gains found in the laboratory do not always transfer to actual use on the slopes. Conducting additional on-snow tests seems inevitable to provide statistically sufficient information on the performance of the dissipator, which is required to make further advances in this area.

5 Conclusions

The container filled with granules adds substantial dissipation compared to intrinsic damping, making the snowboard less prone to vibrations. While mimicking the snow conditions is challenging, the presented laboratory test stand for dynamic excitation could guide the design of personalised decks with dissipators that correspond to the experience that a customer is looking for. Among the desirable features of the multiparticle dissipator are the appreciable attenuation of the peak-level vibration, ruggedness, reliability, design simplicity, and cost-effectiveness.

Although more damping leads to a lower dynamic response with better handling and stability, one must be aware that a board that is completely devoid of vibrations would provide a disappointing sensation for the athlete. Due to the robustness of the prototype solution, it could be adapted to other boardsports taking place on a wide variety of terrain, including ground, water, and snow.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest. The manuscript does not include work that involved humans and/or animals.

Consent for publication Not applicable.

Consent to participate Not applicable.

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