Nonlinear granular damping of structures with cavities from additive manufacturing

Sebastian Tatzko*, Tobias Ehlers†, Gleb Kleyman* and Roland Lachmayer†
**Institute of Dynamics and Vibration Research, Leibniz University Hannover, Hannover, Germany*
†*Institute of Product Development, Leibniz University Hannover, Hannover, Germany*

Summary. Additively manufactured parts are often created with cavities for weight reduction or other mechanical purposes. These cavities offer the optimal base for granular damping. Unfused raw material particles can be left inside the structure or another granular material can be filled in to increase structural damping. In this paper, a simple mechanical model is developed based on measurements of a basic experiment for granular damping with only a small amount of particles.

Additive manufacturing for lightweight structures

Today, the term additive manufacturing characterizes a multitude of different processes with which almost all materials from metals to plastics to ceramics, glass and concrete can be processed. The potential of additive manufacturing offers new possibilities to realize optimized solutions in the development process. This includes in particular the manufacture of components with a high degree of complexity and shape variance.
The possibility of integrating cavities into components is particularly attractive for lightweight construction. The overall weight is reduced while lattice structures can be added easily to provide the necessary stability. A major drawback of these lightweight integral structures is their susceptibility to vibrations and noise emissions. A common additive manufacturing process for metals is laser powder bed fusion (LPBF). Smallest particles of the raw material are melted with a laser and formed into a structure in layers. A CT-scan of a LPBF-printed beam with unfused material in the cavity is shown in Fig.1a). The raw granular material is removed from the cavities at the end of the manufacturing process. The obvious idea is to leave the unfused granules inside the structure to make use of the granular damping effect [1], [2]. In order to keep the weight low, the raw material can be replaced by another granule with a lower density [3]. The simpler way is to leave only a small part of the granules in the cavity.

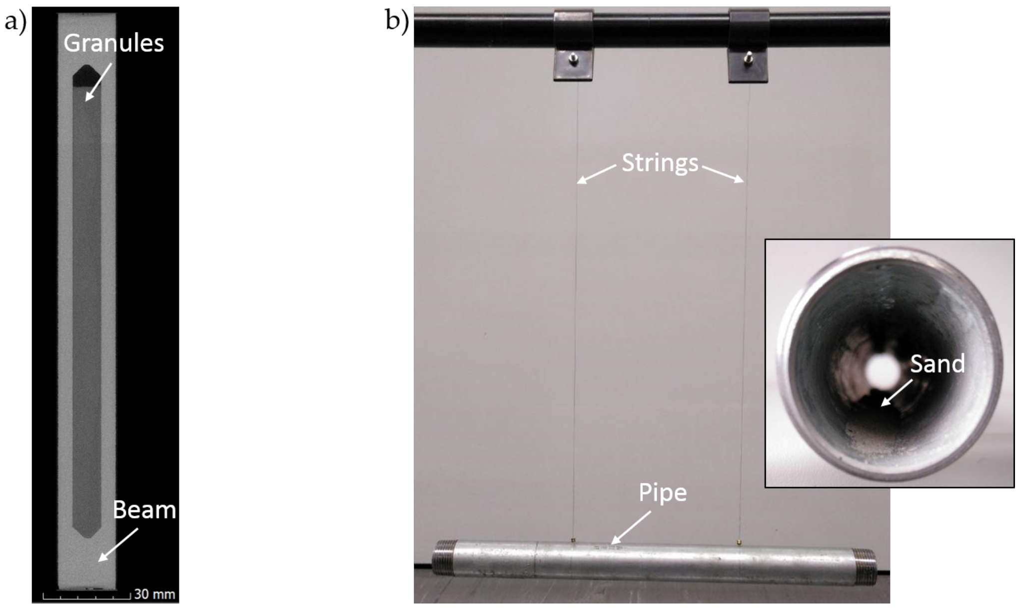


Figure 1: a) Additively manufactured beam with unfused granules in cavity; b) Experimental set up of steel pipe hanging on strings

Fundamental investigations on granular damping

For first investigations on increased damping through a small amount of particles a standard steel pipe is tested with sand as granular medium. Sand can have a strong damping effect on mechanical structures [4]. The pipe hangs freely on strings as shown in Fig.1b). Free decay from impact excitation is recorded with a microphone and then analyzed by applying a short-time Fourier transform (STFT). Fig.2a) shows the results for the unfilled pipe in the frequency range around the first bending mode. Due to a slight asymmetry two close frequencies are recognized. Repeating the measurement with a small amount of sand inside the pipe, see Fig.1b), a strongly increased damping is noticable. After a certain time, the damping effect disappears with a distinct frequency shift., cp. Fig.2b). The structure then vibrates at significantly lower amplitudes with low damping.

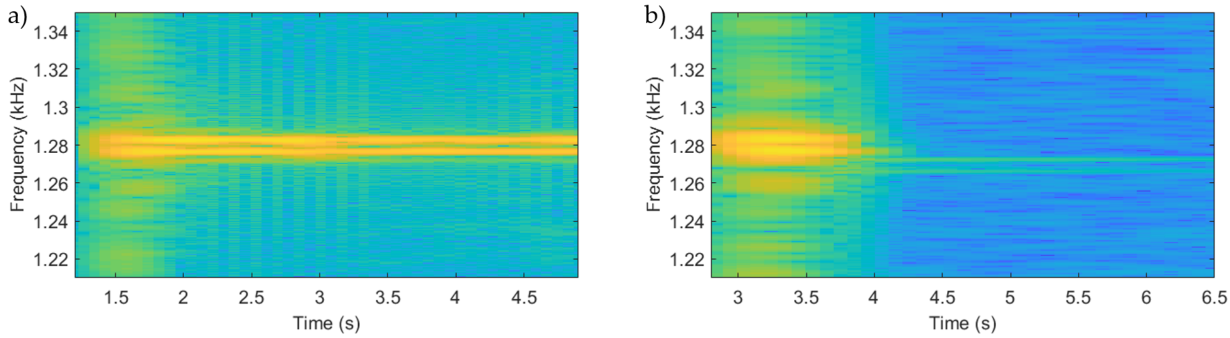
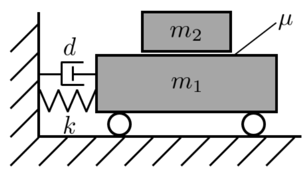


Figure 2: STFT results after impact excitation: a) unfilled pipe ; b) pipe filled with a small amount of sand

Minimal model showing observed phenomena

Motivated by the measurement results, a minimal model is developed to reproduce the observed vibration phenomena. A strongly increased damping with a shift to a lower vibration frequency are approached by the dual mass model shown in Fig.3a). An unbound mass m_2 is connected via Coulomb friction to a single degree of freedom (SDOF) oscillator with mass m_1. The frictional force depends on the relative velocity of the two masses and the factor μF_n. In the case of an impact excitation of the lower mass, it will initially move independently. The upper mass stays at rest due to its inertia and resulting friction forces provide increased vibration damping. After a certain amount of time, the upper mass will move synchronously with the lower mass and practically increase the mass of the SDOF-system. This leads to a sudden reduction of the vibration frequency clearly visible in the spectral analysis result in Fig.3b). Numerical results are obtained by time step integration for which a Matlab/Simulink model of the system is set up. The natural frequency of the system is tuned to match the first bending mode of the pipe. All remaining parameters are manually set in order to obtain a qualitative characteristic close to the measurements. The acoustic measurement results for a single vibration mode could be very well reproduced with the presented minimal model. If it is possible to find a physical interpretation of the model parameters and to identify these parameters from measurements, the minimal model could be used for a simple first approach in granular damping design.

a)



$$m_1\ddot{x}_1 + d\dot{x}_1 + kx_1 + \mu F_\mathrm{n}\mathrm{sign}(\dot{x}_1 - \dot{x}_2) = F(t)$$
$$m_2\ddot{x}_2 - \mu F_\mathrm{n}\mathrm{sign}(\dot{x}_1 - \dot{x}_2) = 0$$

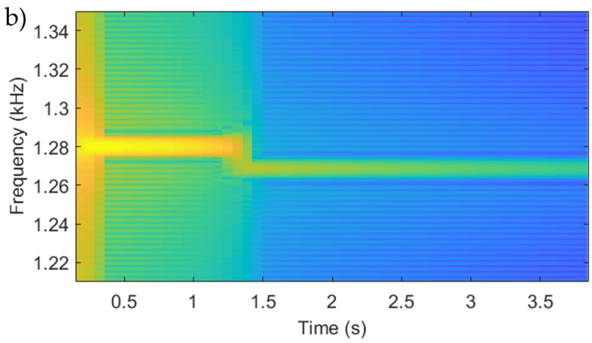


Figure 3: a) Dual mass model and equations of motion; b) STFT result after impact excitation from numerical time integration

Conclusion

Granular damping of structures is a promising and cost-effective method for vibration reduction. Additively manufactured components with cavities of various types open up new possibilities for placing granules. For weight reasons, partially filled cavities are of particular interest. In this work experimental studies are carried out and observed phenomena are modelled using a mechanical oscillator. The model shows the same characteristic as found in measurments and maybe helpful for granular damping design with only a small amount of particles.

References

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