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VIBRATION DAMPING CHARACTERISTICS OF THE CORK-BASED COMPOSITE MATERIAL IN LINE WITH FREQUENCY ANALYSIS

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The conducted research suggests possibility of replacing extruded polystyrene with a renewable cork-based material in laminated composite structures. Different fractions of the cork-based material of a composite laminate have been applied. The composites have been tested employing a hammer-focused vibration method. Conforming to obtained results, the cork-based material of smaller fraction has damping properties similar to those of the extruded polystyrene composite. Integrating cork into the structure of the composite has the opportunity to develop a more eco-friendlier and sustainable product and to improve the adaptive properties of passive control systems used for vibration damping applications operating in the middle and high frequency zones.

Keywords: composite material, cork, frequency, laminate structure, vibration testing

1. Introduction

Composite materials have been used in a wide range of applications in the field of transport engineering and cover components of land vehicles, aerospace and marine vehicles (Bogdevičius *et al.*, 2021). Composite materials have recently been used in hydraulic components and as energy absorbing elements of mechanical vibrations (Lubecki *et al.*, 2021). The scale of applying composite materials in the field of engineering is constantly increasing due to excellent performance characteristics like high stiffness and strength, resistance to corrosion, good dynamic and damping properties as well as fast manufacturing process and competitive priceses (Reis *et al.*, 2020). Composite materials to a large extent could be found in numerous solutions in the aerospace sector where the material properties of lightweight, high stiffness and strength, resistance to corrosion, etc. are highly important (George *et al.*, 2021). From the energy point of view, the increased use of composite material found in manufacturing vehicles may lead to reductions in fuel consumption due to their lower weight. Composite structures are also used for producing wings of fixed-wing Unmanned Aerial Vehicles (UAVs) (Sekar *et al.*, 2020), see Fig. 1a. This type of aircraft is operated remotely or automatically via a computer installed on board.

The fixed-wing UAV equipped with a simplified structure and aerodynamically efficient design is advantageous to long-range and autonomous flight at high speeds. De Breuker *et al.* (2016) suggest that these types of the aircraft face various flight conditions and require a detailed design of the shape and structure of the wing to obtain the highest aerodynamic efficiency. One of the most popular constructions of the fixed wing UAV (pure glider) UAV (Fig. 1b) is a composite structure based on a full-filled material (e.g. extruded polystyrene) and laminated with carbon

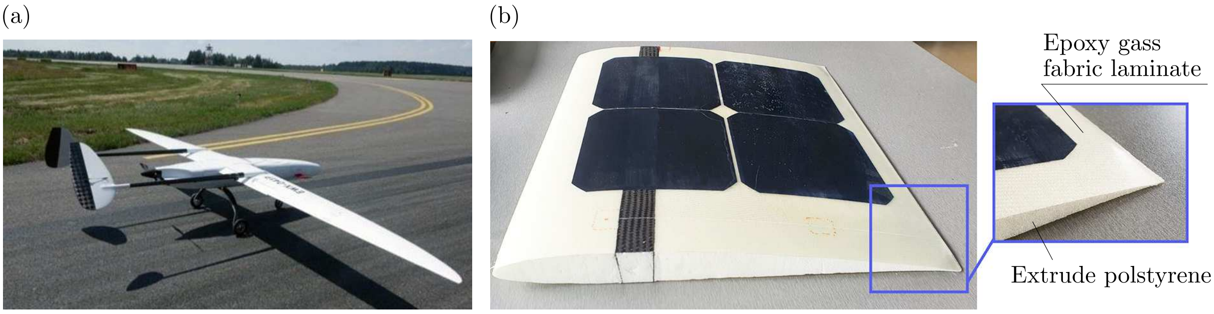

Fig. 1. The application of extruded polystyrene to unmanned aerial vehicles: (a) fixed-wing UAV (Sekar *et al.*, 2020), (b) composite structure of the wing

or glass fabric (Reis *et al.*, 2020). Bishay and Aguilar (2021) agree that the construction of this particular type of wings should simultaneously satisfy two main requirements: the high stiffness of the plane and great damping properties. This means that the skin of the wing must be stiff enough to withstand aerodynamic pressure loads of the wind and provide sufficient damping of vibration loads of the wind during a flight (George *et al.*, 2021).

Considering the information mentioned above, in order to increase the flight time of the UAV, structural optimization is vital for wing construction (Alsahlani and Rahulan, 2017). Furthermore, the selection of suitable air foil configuration and composite materials of the wing (Alsahlani and Rahulan, 2017) play an important and critical role in the UAV design process. The development of a new type of composites provides an effective way to reduce weight, increase structural efficiency and create the possibility of reducing the cost of manufacturing and maintaining the UAV. With reference to the strength layer of the composite wing structure, plenty of researchers (Reis *et al.*, 2020) investigated an increase in the efficiency of using different layers. The carried out investigations focused on the impact of laminates stacked with different orientation angles of fiber (Naresh *et al.*, 2017), on how the orientation of the composite ply applied in the wing could increase its efficiency, the issues of optimization and implementation under different environmental conditions, the implementation of different types of laminate layers of the epoxy matrix, e.g. carbon fiber, Kevlar fiber, etc.

A literature review has indicated that the main attention is currently paid to the optimization, application and investigation of issues related to laminate layers of the epoxy matrix. However, there is lack of investigation on properties of filling materials used for the construction of composite wings. Chanzy and Keane (2018) reported that extruded polystyrene was one of the materials commonly used for the full-filling base of fixed wings of small UAVs. Vibration analysis of an aircraft wing (Yoshihara and Maruta, 2019) and the analysed behaviour of the extruded polystyrene material under loading show good damping properties of a low weight parameter. Simultaneously, it is necessary to find a new structure and application of composites to reduce weight, increase the structural efficiency and, if possible, decrease the cost of UAV manufacturing and maintenance. The most recent publications have mainly concentrated on hybrid filling materials of composite laminates. Gürgen and Sofuoğlu (2021) state that a smart polymer containing integrated cork composites and hybrid cork and carbon-epoxy laminate (Fernandes *et al.*, 2019) have good stiffness and fracture characterization. At the same time, the cost of the cork-based composite material is much lower.

The paper is aimed at finding a possibility of integrating the cork-based material into the field of aerospace engineering in order to increase the structural efficiency of composites and to reduce the cost of UAV manufacturing or maintenance. The findings of this paper could support the European Green Deal strategy using environmentally friendly materials to reduce environmental degradation.

2. The application of cork composites in the field of engineering

A WWF Report (2006) acknowledges that cork is considered an environmentally friendly and sustainable material highly evaluated for its application in different areas (from building construction to machine engineering). Cork oak is highly useful for ecological conservation; it is indispensable for fauna and earth biodiversity. Furthermore, Mestre and Vogtlander (2013) document that the cork-based material is more eco-friendly than polymers, metal and even wood, because the tree is not cut down and is easy to recycle for cork production. The research on the mechanical behaviour of composites filled with agro-waste materials (Reis *et al.*, 2020) demonstrates that the main characteristics of structures are similar to those filled with synthetic materials. These composites are less expensive, abundant and renewable as well as there is no abrasiveness during manufacturing. Also, the above mentioned features make these composites usable for entanglement.

Silva *et al.* (2005) and Gürgen and Sofuoğlu (2021) indicate that around 22% of all cork-based materials is used for other technological applications, for example cork-based composites. The composites containing cork are often used for sealing applications on vibration and acoustic insulation in the automotive sector (vehicles, rail, etc.), particularly in electrical transformers and heater meters (Gil, 2014). The product made of cork composites also provides promising results under different loads. Fernandes *et al.* (2019) investigated cork composites under different dynamic loads and concluded that the products were alternative solutions to synthetic foams of protective structures. For example, Fernandes *et al.* (2019) agree that cork composites are suggested for helmet liners to enhance the protective performance of conventional liners made from polystyrene foams. Different papers, for example Kaczynski *et al.* (2019), explored how cork properties were tailored optimizing various parameters such as density, grain size and binder of composites. The study by Sarasini *et al.* (2020) concluded that cork-based material sheets had strong energy absorption compared to synthetic counterparts of the composite structure. Besides, the research done by Prabhakaran *et al.* (2019) discloses that cork-based composites provide excellent properties of resistance and sound vibration isolation. Kaczynski *et al.* (2019) mentioned that cork composites were also studied for energy absorbing properties at various temperatures. The features and cork applications mentioned above are also employed in aerospace engineering. The applications of cork-based composite materials are found to be anti-vibration and thermal shields of a spacecraft in both the European Space Agency (ESA) and the National Aeronautics and Space Administration (Drescher *et al.*, 2017). A spacecraft is subjected to extremely high temperatures while released to the orbit. Even upon returning to the Earth, spaceship structures are at risk of fire, and cork is often applied to the essential parts for safety of the spacecraft, including the nose cone and some extra parts. The application of cork in space industry and rockets started with the mission of Apollo 11 in 1969 – the construction of the Launch Escape System (NASA, 1969). Cork-based materials are still widely used.

A review of literature on cork composite studies, dee for example Silva *et al.* (2005) identifies the advantages of the cork powder-filled composite to the impact on strength and glass transition temperature. A more detailed study of the impact resistance was carried out by Reis *et al.* (2020) and proved the ability to obtain elastic recuperation, residual tensile strength and a damage area when cork was added to epoxy resin. Similar research done by Petit *et al.* (2007) resulted in a longitudinal crack involving delamination of monolithic laminates instead of the longitudinal crack without evidence of extensive delamination when the cork-based material layer was included in the composite structure (Silva *et al.*, 2017). Furthermore, Reis *et al.* (2020) confirm that, independently of the lower static bending strength observed, the fatigue strength is insensitive to the presence of cork in resin.

The literature review has identified different applications of cork composites thus covering a variety of use cases when cork-based material properties have added a value or created alternative renewable solutions. The main problem of all above mentioned investigations is that although strength and thermal analysis are extensively performed, still, the knowledge gap of damping properties, particularly those in the form of the damping ratio using frequency analysis, is observed. The extruded polystyrene and cork-based materials of different fractures, including those laminated by epoxy glass fabric, have been investigated and their damping properties based on frequency analysis have been compared.

3. Methodology for the experiment and data processing

Composite materials embracing extruded polystyrene (LP) and three types of cork-based materials laminated by the epoxy glass fabric of different fractures (from the largest to a smaller fraction: LC1; LC2; LC3) were chosen (see Fig. 2). The dimensions of the objects were approximately $\sim 30 \times 25 \times 3\,\mathrm{mm}$. The main properties, in line with the information given by the manufacturer and considering the performed research on the above introduced types of materials (Cascell® RS Machine Department), are found in the reference.

LC1 LC2 LC3 LP

Fig. 2. The investigated composite materials

The laminate layer consists of a single layer of 110 g/m2 glass fabric (R&G Faserverbundwekstoffe manufactory) containing Epoxy Resin L. The main properties of the materials of the laminate layer are given on the official website provided in the reference list. The materials have the International Certificate, they are used in most of the fields of engineering and are publicly available for purchase.

The present experimental tests have been conducted to expand the possibilities of using the cork-based composite materials laminated by epoxy glass fabric with reference to damping properties assessed during vibration and frequency analysis. Composite materials have been investigated using hammer-based vibration tests and modal analyses of structural constants, which assists in finding the natural frequency and damping ratio. The hammer-based vibration technique includes modal analysis that helps determination of the vibration characteristics (natural frequencies and mode shapes) of a mechanical structure or a component thus showing the movement of different parts of the structure under dynamic loading conditions. Natural frequencies and mode shapes are important parameters for designing the structure in dynamic loading conditions.

The current modal analysis has been performed transforming the registered vibration by conducting Fast Fourier Transform (FFT) spectrum analysis. The key focus of the research is to find the resonance and to compare damping properties of the investigated objects. As for the guidelines, there are several steps to follow in order to conduct successful current analysis.

The research steps include:

1) taking tests and collecting data on measuring velocity of the object vibration under the impact of an impulse (excluding low vibration of the environment),

2) performing additional testing in the case further data are required and conducting FFT spectrum analysis on comparison of three composite materials (automatically performed employing test bench equipment),
3) analysing the obtained data to evaluate overall values and specific frequencies,
4) comparing damping properties of three composite materials and having a discussion.

Experimental tests are done using a double-sample measurement and are based on a single--sample statistical method for the estimation of uncertainty in the repeated measurements of data processing (Bogdevičius *et al.*, 2021). The test bench and measurement setups for research cover a metal base with a rubber layer that provides protection from an impact of low frequency on the environment, research objects, a laser scanning system for measuring vibration of the object surface under an Integrated Electronics Piezo-Electric (IEPE) impulse hammer with an impact sensor and FFT analysis (Fig. 3). Measurement tests include three vibration tests on

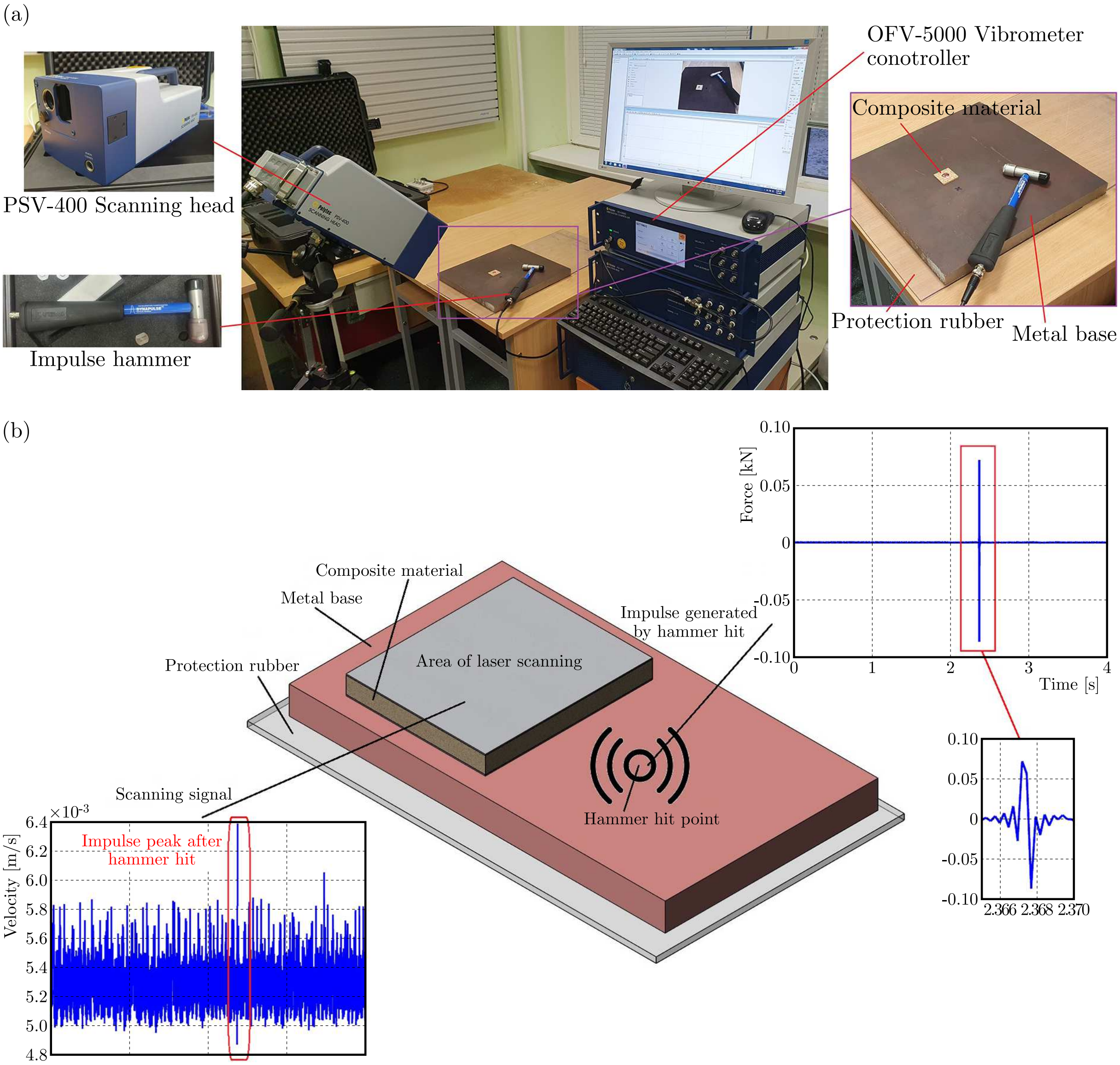

Fig. 3. Experimental details: (a) test bench for experimental measurements, (b) scheme for measurement setup

the outer surface deformation (velocity/displacement) of the composite material considering the impact exerted by the impulse hammer. When testing, the time for a single measurement using the PSV Sensor Head is 4 seconds. This is the time the IEPE impulse hammer generates an impulse on the metal base. The measurement of vibration velocity done by applying the PSV Sensor Head on the composite material is shown in Fig. 3b.

To decrease the impact of errors in different measurements, the average results were used. The main result obtained from testing was the frequency response of composite materials, which was based on spectrum analyses using the Doppler effect. The created grid counted 25 points on each of the established objects that produced a close surface for measurements.

The laser scans each point during a hammer-hit impulse and measurement time. The scanning status was in optimal conditions, which means that the grid of the points and the focus of the laser were optimal for this type of reflection materials. Additionally, the frequency domain included a bandwidth of 1.6 kHz with the step resolution of 0.25 Hz. Frequency response graphs are presented in the velocity domain because power spectrum analysis makes the resonance points more visible.

4. The analysis and discussion of the obtained results

The analysis in Fig. 4a shows a comparison of the composite cork-based materials (LC1, LC2, and LC3) applying the frequency response. The chart indicates three regions for the analysis and characterization of the damping properties of materials: low frequency (up to 200 Hz), mid-range frequency (from 200 Hz to 1 kHz) and high frequency (from 1 kHz). Furthermore, the main interest of the conducted analysis is a frequency range of up to 600 Hz (shown in Fig. 4b) as this frequency range presents the main resonant modes with a reverse exponential curve displaying the tendency.

Frequency analysis reveals that the main resonance frequency of the laminated cork-based materials is in the low frequency range and acts as the beginning of the middle frequency range. Thus, the main resonant modes are observed in this particular frequency range. Also, frequency analysis shows that the main and the first resonance frequency of the investigated composite materials is equal to 20 Hz and has a harmonic at each 20 Hz $(20, 40, 60, \ldots$ Hz). Frequencies in the low frequency range (62.5 Hz) with a harmonic step should be pointed out, as they remain in the midrange frequency $(62.5, 125.0, 187.5, \ldots$ Hz). The existing frequencies of the second resonance type are explained by the nature of the composite material.

A comparison of the damping properties of the objects is provided at the first resonance point of 20 Hz. At the current point, the velocity amplitude at LC1 makes $0.9 \cdot 10^{-4}$ m/s, that at LC2 – $0.72 \cdot 10^{-5}$ m/s and that at LC3 – $0.68 \cdot 10^{-5}$ m/s. Moreover, LC1 and LC2 show almost similar results of damping properties (difference $< 2\%$) where the frequency is 60 Hz and higher up to middle and high frequencies. This may lead to the conclusion that LC3 material has better damping properties compared to the other two types of laminated ones with cork. Hence, a smaller fraction of the cork-based material provides a higher damping ratio on the same frequency compared with the cork filler of a larger fraction.

The following analysis includes a comparison of laminated cork (LC3) and extruded polystyrene (LP) composite materials the frequency response of which is shown in Fig. 5.

The frequency analysis of LC3 and LP materials demonstrates that the main resonance frequency of the laminated cork and extruded polystyrene materials is almost the same in the low frequency range as well as at the beginning of the middle frequency range. The match of the resonance points at the same frequency can be explained considering the factors in cork lamination and extruded polystyrene containing the same epoxy glass fibre material.

A comparison of the damping properties of the objects is provided with reference to the example at the first resonance point of 20 Hz. At the current point, laminated cork vibrated with a velocity amplitude of $0.68 \cdot 10^{-5}$ m/s and the laminated extruded polystyrene of

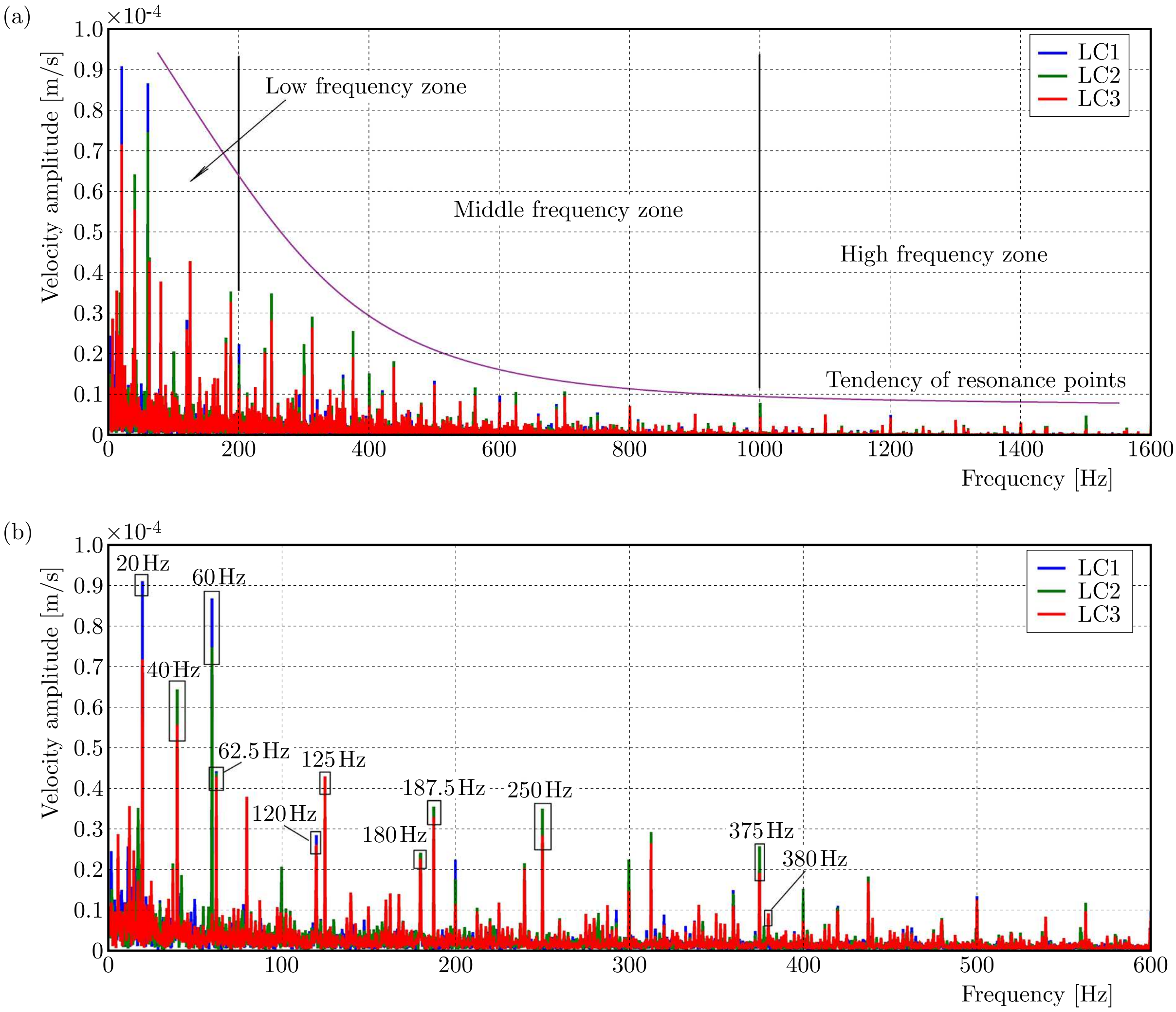

Fig. 4. The analysed spectrum of composite cork: (a) frequency response of up to 1.6 kHz, (b) frequency response of up to 600 Hz

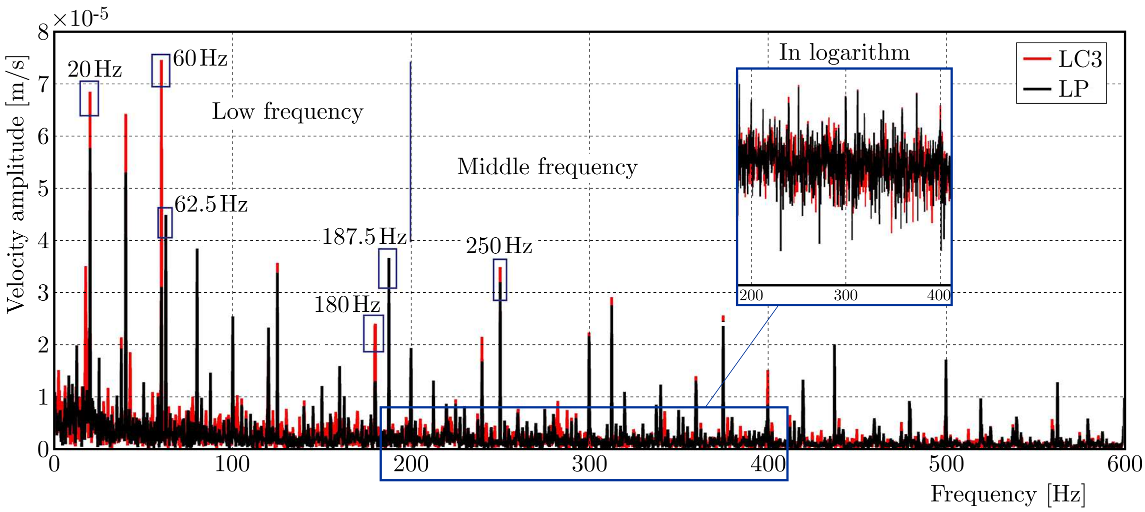

Fig. 5. A comparative analysis of the frequency response of LC3 and LP composite materials

$0.57 \cdot 10^{-5}$ m/s (difference in damping $\sim 16\%$). Additionally, at a frequency of 60 Hz, the velocity amplitude of the laminated cork was $0.74 \cdot 10^{-5}$ m/s and that of laminated extruded-polystyrene – $0.32 \cdot 10^{-5}$ m/s (difference in damping $\sim 57\%$). Deformation velocity amplitude at frequencies of 62.5 Hz, 125 Hz, etc. indicates lower damping of the extruded polystyrene. Likewise, starting from the middle frequency zone, the difference in damping properties among the materials is $< 3, \ldots, 6\%$. The established difference in the amplitude of the materials confirmed that the use of extruded polystyrene was a better option in terms of damping properties. At the same time, the small fraction cork-based material shows similar characteristics of damping properties in the middle frequency zone, which results in the laminated cork that can be used in some applications instead of the laminated material of extruded polystyrene.

The obtained results give a reason for further research on expanding cork applications in transport engineering, because the integration of cork in composite material structures has a promising future to develop eco-friendly and sustainable products and to improve the adaptive properties of passive control systems for vibration damping applications operating in the middle and high frequency zones.

5. Conclusions

The carried out research has compared extruded polystyrene and renewable cork as elements of damping reducing vibration. Different fractions of cork-based materials from the filling layer to composite laminates have been applied. The employed composite materials have been tested applying the IEPE hammer-based vibration method and comparing vibration damping characteristics of the materials in order to determine natural frequency following modal analysis (FFT transformation). The frequency response of the composite material has been found to display a reverse exponential curve tendency from the low to high frequency zone. The main analysis has been performed at a frequency range of up to 600 Hz thus observing the main resonant modes. The research findings demonstrate that a smaller fraction of the cork-based material leads to a higher vibration damping ratio at the same frequency compared to a larger fraction of the cork filler.

The results obtained in the current research have showed that the integration of cork in composite material structures would have promising future for developing eco-friendly and sustainable products and would improve the adaptive properties of passive control systems for vibration damping applications operating in the middle and high frequency zones. The frequency analysis of the small fraction cork and the extruded polystyrene e-fibre composite material concludes that the main resonance frequency of the laminated cork and extruded polystyrene materials is almost the same in the low frequency zone and at the beginning of the middle frequency range. The match of resonance points at the same frequency is explained by the laminating cork and extruded polystyrene having the same epoxy glass fibre material. Starting from the middle frequency zone, difference in damping properties between the materials is $< 3, \ldots, 6\%$. The established difference in the amplitude of the materials has confirmed that the extruded polystyrene should be better used for damping impact impulses than the cork-based material. At the same time, a small fraction of the cork-based material shows similar characteristics of damping properties in the middle frequency zone thus indicating that in some applications the laminated cork is replaced with the laminated extruded polystyrene material.

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