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Computational and experimental studies of microvascular void features for passive-adaptation of structural panel dynamic properties

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The performance, integrity, and safety of built-up structural systems are critical to their effective employment in diverse engineering applications. In conflict with these goals, harmonic or random excitations of structural panels may promote large amplitude oscillations that are particularly harmful when excitation energies are concentrated around natural frequencies. This contributes to fatigue concerns, performance degradation, and failure. While studies have considered active or passive damping treatments that adapt material characteristics and configurations for structural control, it remains to be understood how vibration properties of structural panels may be tailored via internal material transitions. Motivated to fill this knowledge gap, this research explores an idea of adapting the static and dynamic material distribution of panels through embedded microvascular channels and strategically placed voids that permit the internal movement of fluids within the panels for structural dynamic control. Finite element model and experimental investigations probe how redistributing material in the form of microscale voids influences the global vibration modes and natural frequencies of structural panels. Through parameter studies, the relationships among void shape, number, size, and location are quantified towards their contribution to the changing structural dynamics. For the panel composition and boundary conditions considered in this report, the findings reveal that transferring material between strategically placed voids may result in eigenfrequency changes as great as 10.0, 5.0, and 7.4% for the first, second, and third modes, respectively.

1. Background and motivation

Harmonic or random excitations of structures can lead to large amplitude oscillations at the modes of vibration, which are significantly magnified when structures are driven around the natural frequencies. For aerospace structures, vibrations at resonance are particularly concerning. In turbine engines for instance, vibration response has been found to be magnified by 1000 times normal levels when driven at resonance [1]. For compressor blades of such turbines, it was found that oscillations at the lowest order modes are the primary reasons for fatigue fractures [2]. In fact, over half of aircraft structural failures are caused by fatigue which includes the oscillatory stress cycles that are magnified at the natural frequencies of the system [3]. Vibrations excited by diverse energy sources, such as external flows or internal motors, also play large roles in the progressive

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weakening of aircraft panels and have been intently studied to understand the magnitude of their impact [4–6]. The need to avoid such resonant operating conditions for aircraft structural panels pertains to multiple concerns, including structure safety, aerodynamic performance, and integrity.

Research on structural vibration control methods has flourished, especially considering archetypal structures such as cantilever beams and structural panels. For instance, piezoelectric materials have been embedded within or directly mounted on structures such as those used in aerospace applications for low profile, active vibration control purposes [7–9]. In addition, the reduction of vibration or acoustic energy transmission through panels has been achieved using piezoceramic actuator transducers [10], variable stiffness panels with piezoelectric control actuators [11,12], sensoriactuators that are used in contrast to control units composed of separate sensors and actuators [13], control systems that are aided with the use of rib-stiffened panels [14], and shunted piezoelectric patch absorbers [15]. Such active vibration control strategies may apply to a wide range of working conditions [16] and enable fast response time [17] at the expense of complexity, electrical power demand, and potential stability concerns.

Yet, the added complexity of the active electronic implementations, energy required to put the methods to practice, and the potential for loss-of-control are reasons to instead prioritize development of *passive adaptive* methods that address vibration concerns often without such drawbacks. For example, recent studies have explored the viability of embedding temperature-sensitive silicone fluids within a cantilever beam having an internal channel [18]. In this case, the natural frequencies and damping ratio are seen to change due to the added fluid mass and operating temperature [18]. Similarly, others have focused on the incorporation of nanoscale channels and fluids to tailor the damping properties and frequency sensitivities of nanomechanical resonators [19]. Alternative concepts of material redistribution for structural vibration control have been achieved by using free-sliding masses along cantilever beams [20,21], while continued development of this idea has shown that a passive restoring force to return the free-sliding mass to a starting position enhances vibration reduction capability [22]. Other studies have shown that straight, fluidic passage networks attached to the top of a cantilever beam can change the natural frequencies of vibration due to characteristics similar to vibration absorbers [23] while fluidic flexible matrix composite tubes containing air-pressurized fluid may act as tunable vibration isolators [24]. The change in fundamental vibration characteristics of the systems accomplished by such passive adaptive strategies diminishes the possibility for unrestrained resonant response when subjected to excitation energies.

Researchers have also explored changes to interior material distribution of structures to favorably tune the forced response. For instance, internal honeycomb cores and viscoelastic cores augment stiffness and damping of structural panels to advance system resilience when compared to panels composed of bulk materials [25–27]. Multi-layer and laminate panels are also shown to balance structural integrity and light-weighting demands with desirable acoustic performance [28]. Furthermore, embedded poroelastic materials [29–31] reduce transmitted elastic energy through sandwich panels, while porosity realized by perforated geometries reduces sound radiation compared to their solid counterparts [32]. All together, by leveraging internal material, geometric, and structural features, the dynamic response of cantilever or panel architectures may be favorably tuned to promote performance needs and system robustness when subjected to adverse excitation energies.

Despite the advancements surveyed above, it remains to be determined how concepts of material redistribution applied to mostly one-dimensional cantilever beams [18–21] affect the structural dynamics of systems like panels whose three-dimensional (3D) geometry is pivotal towards the dynamic behavior. One idea under investigation similar to this spirit is the concept of microvascular channels within panels that are used to pass liquid metal and polymers for sake of realizing tunable antenna [33,34], self-healing [35–37], and adaptive thermal properties [38]. Inspired by this idea, this research explores the ability to tune low order vibration characteristics of structural panels by the transfer of material among internal voids via microvascular channel passages that connect them. For panels, the multi-dimensional modal vibrations signify that internal void placement obtains an increased importance when compared to the lower dimensionality of cantilever beams [7,16,18]. Indeed, the attention to 3D structural panels opens up design flexibility for void shape, number, size, and location that may tailor the vibration properties of structural systems commonly found in diverse engineering applications. Motivated to fill this knowledge gap, this research uses computational and experimental methods to create and assess strategies of design and implementation for microvascular voids in structural panels to tune panel dynamic properties.

This paper is organized as follows. Sec. 2 describes the development of finite element models to probe the adaptation of dynamic response via microvascular channels and voids and presents results from comprehensive parameter studies. Then, Sec. 3 presents the experimental undertakings for validating the model and exploring opportunities that may not yet be probed by the finite element method due to computational feasibility. Finally, Sec. 4 summarizes the knowledge derived from these investigations.

2. Finite element model investigations

This section presents the finite element (FE) model investigations that are used to evaluate the ability of voids to tailor the vibration characteristics of structural panels. In all cases considered, the voids are positioned at the mid-plane of the panels. Void shape, number, size, and location are the parameters considered to be available for manipulation. Then, guidelines that enable changes in eigenfrequency via a material transition between voids are presented to direct experimental validation efforts.

The FE method via COMSOL Multiphysics software is leveraged to model the panel dynamics. A solid model is used to capture the through-thickness variation of material realized experimentally. Two cases of boundary conditions are