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# *Damping by Branching: Bioinspired Strategies for Vibration Reduction*

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***Abstract.*** The paper will explore in depth the damping mechanism utilized in trees and tree - inspired buildings, focusing on how damping by branching can lower the range of vibration under the influence of wind or seismic loadings like earthquakes. With examinations on preexisting paper of this subject matter, we will reach conclusions by analyzing their models and methods, showing how damping by branching can reduce vibration by dissipating energy. Sources examined will show that the branching joints can significantly reduce the vibration and allow energy to pass through, which corresponds to our result that structures with branch damping can dissipate much more energy than structures that don't. The paper also examines bio-inspired structures, analyzing how branching methods like Y shape columns benefit structural stiffness, also discussing how this application can be applied in most places. The insights we gathered are targeted to provide a comprehensive understanding of damping via branching and its potential for enhancing the performance of slender structures.

***Keywords:*** Tree damping, branched structures, bioinspired design, vibration control, energy dissipation

## 1. Introduction

Slender structures such as towers, bridges, and aerospace components are vulnerable to wind and seismic excitation, leading to excessive vibrations that may compromise structural integrity and accelerate fatigue [1–3]. Conventional damping strategies—including tuned mass dampers (TMDs), viscous dampers, and base isolation—are widely used but often rely on external attachments, increasing system complexity, mass, and maintenance requirements [4–7].

Inspired by nature's efficiency, researchers have begun exploring biomimetic strategies for vibration control. Trees, which withstand dynamic loads with minimal structural damage, offer a compelling model. Studies have revealed that branching architecture plays a key role in redistributing and dissipating vibrational energy through internal resonance, viscoelastic damping, and aerodynamic drag [8–10]. This insight has led to the concept of Damping by Branching (DBB) —a passive, geometry-based damping mechanism wherein energy is transferred from the main structure to oscillating branches and dissipated via internal and aerodynamic effects [11–13].

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DBB is particularly effective under large vibrations due to internal resonances (e.g., 2:1 coupling between trunk and branches) that enhance energy transfer [14]. It enables passive, distributed damping over a range of frequencies and shows promise for architectural integration. Experimental models and simulations have confirmed its feasibility in various geometries, including Y-shaped and fractal-like structures [12, 15, 16].

However, DBB remains in early development. Challenges include scalability, integration into civil infrastructure, and performance under small-amplitude excitation. The lack of standardized design methods and limited experimental validation also hinders adoption in engineering practice [17].

This review summarizes recent advances in DBB research, comparing it with traditional damping techniques and discussing its engineering potential for future resilient and lightweight structures.

## 2. Physical mechanisms and models

Tree-like structures exhibit an inherent ability to mitigate vibrations through their geometry and modal dynamics. In such systems, energy from the primary sway motion of the trunk can be nonlinearly transferred to higher-frequency branch modes, especially under internal resonance conditions like 2:1 frequency ratios. These modal interactions—enabled by geometric coupling—facilitate energy dissipation through mechanisms such as material damping and aerodynamic drag in branches [13,17]. Notably, this energy transfer is amplified at large vibration amplitudes, making Damping by Branching (DBB) an effective passive strategy for vibration attenuation in slender structures.

Simplified Y-shaped models are widely used to understand DBB behavior. These 2DOF models capture the coupling between a primary trunk and angled branches, revealing that energy dissipation is maximized when the branch frequency is approximately twice that of the trunk. Analytical expressions such as effective damping ratio and energy loss over time have been derived to quantify this effect. Key influencing parameters include frequency ratio, branch damping, and branching angle, with peak performance near orthogonal branch orientations and under resonant conditions [14,18]. Experimental studies on real trees (e.g., Douglas-fir, Eucalyptus) confirm that branching increases natural frequencies and damping compared to debranched forms [6,7].

To model realistic dynamics, researchers have expanded beyond lumped-parameter approaches to use finite-element and fractal geometries, capturing complex branching topologies and hierarchical energy transfer. These models reproduce the cascade of energy through successive branch levels, mirroring the damping efficiency observed in natural trees. Such insights have not only advanced the theoretical understanding of DBB but also informed the development of bioinspired structural components with built-in damping capacities [9,10,19].

## 3. Damping methods: comparison with conventional strategies and limitations

### 3.1. Traditional damping methods

Traditional vibration control strategies include Tuned Mass Dampers (TMDs), Tuned Liquid Dampers (TLDs/TLCDs), base isolation systems, and a variety of passive, semi-active, and active dampers. Among these, TMDs are the most widely applied in civil and mechanical systems due to their simplicity and effectiveness. Their configurations include single TMDs, distributed TMDs (DTMD/MTMD), pendulum-type TMDs, and advanced designs incorporating inerters or impact elements [18].

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TMDs work by attaching an auxiliary mass-spring-damper system to the primary structure, tuned to its natural frequency, thereby absorbing energy and mitigating resonant vibrations. Their damping effectiveness is governed by closed-form expressions based on the mass ratio, damping coefficient, and frequency ratio [19]. TLDs utilize sloshing liquid motion to dissipate energy and are particularly ideal in structures with big roof tanks or towers. Base isolation systems integrate viscous, hydraulic, or friction dampers that offer high damping for seismic protection. Magnetorheological (MR) and electrorheological (ER) devices are capable of delivering tunable performance based on environmental conditions. Other passive damping systems, such as impact or ball dampers and pendulum absorbers, offer further choices for damping systems available to designers, with hybrids combining them to improve ruggedness and bandwidth.

### 3.2. Advantages of tree-like damping

Comparison between traditional damping and tree-like damping methods is listed in Table 1.

Table 1. Comparison between traditional damping and Tree-like damping methods

| feature | TMD formula | DBB formula |
|---|---|---|
| Number of aBsorbers | 1 or a few: $m_d$, $k_d$, $c_d$ | i = 1 to n (multiple) |
| Frequency tuning | All tuned to the same target | Naturally varies |
| Optimal parameter | $f_{opt}$, $\xi_d$ | None |
| Daming term | Explicit viscous damper $c_d$ in formulas | Internal branch damping + nonlinear aerodynamic |
| System size | 2 DOF or small MTMD | Large multi-DOF |
| Performance control | High, narrow-band control when tuned | Broadband, robust but lower peak suppression |

Damping-by-Branching (DBB) is a bio-inspired passive damping strategy where branched elements act as distributed resonators. Unlike traditional TMDs, which function as single tuned oscillators with precise parameter settings, DBB systems involve a network of coupled oscillators with varying parameters. This diversity enables broadband energy dissipation, rather than targeting a single frequency.

Key advantages of DBB include:

- Passive operation without the need for actuators or external power;
- Robustness to parameter uncertainties and mistuning;
- Enhanced bandwidth, owing to multiple coupled resonances;
- Cost efficiency, especially when branching structures are integrated during initial design.

However, DBB lacks active tunability and may be less effective for suppressing narrow-band resonances compared to optimally tuned TMDs. Its applicability may also be limited by structural geometry constraints and challenges in scaling for large infrastructure [18].

Research on hybrids that directly integrate natural branching with conventional dampers remains limited, though conceptual and small-scale laboratory studies suggest strong potential. In particular, DBB's broadband damping could be paired with tuned absorbers to target residual resonances, combining robustness with precise mode control [19]. Bio-inspired tuned mass dampers (BTMDs) and inerter-enhanced devices mimic the multi-resonant nature of branches, sometimes in semi-active configurations, offering expanded bandwidth and adaptability. While industry has implemented many hybrid combinations of traditional devices—such as TMD + TLCD or TMD + semi-active dampers—real-world applications that combine actual branching structures with conventional dampers are still rare, making this an emerging field for innovation.

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### 3.3. Parameter optimization

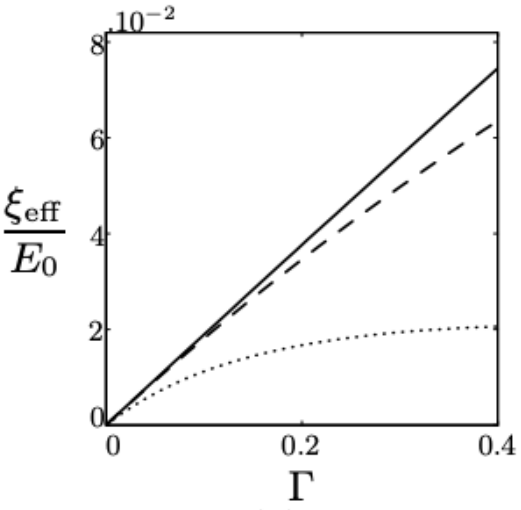


Figure 1. effect of mass ratioΓfor a spring mass model

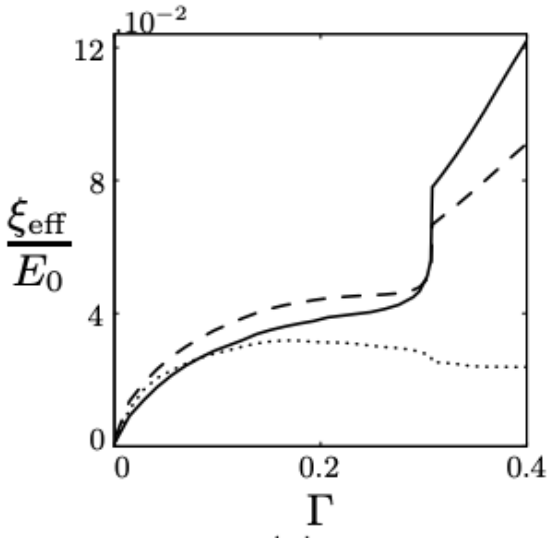


Figure 2. effect of mass ratioΓfor a spring mass model

Looking at research utilizing both a spring-mass model and continuous model of a Y shaped trunk with two branches, the branch to trunk mass ratio is directly proportional to the effective damping scaled by the initial energy and the highest value possible is considered optimal. Theckes et al [20] demonstrates this with the spring-mass models in FIG 1 and FIG 2, which in the graph they show that as the branch to trunk mass ratio increases, the effective damping scaled by the initial energy increases without reaching a maximum. In FIG 2, the graph shows a more complex pattern that also has the effective damping scaled by the initial energy increasing without an upper limit. The limiting factor of the branch-to-trunk mass ratio is the requirement of the trunk being able to support the branches and the other optimal conditions that would prevent an extremely high branch-to-trunk mass ratio. Therefore, the ideal branch-to-trunk mass ratio is the largest it can be with consideration for the optimal damping of other factors.

Looking at research utilizing both a spring-mass model and continuous model of a Y shaped trunk with two branches, the branch angle does in fact affect energy dissipation where an angle that produces branches that are further away from the tree is more effective. This means that 90 degrees would normally be optimal. However, Theckes et al [20] demonstrates that this is not always the case in the spring-mass model and the continuous model. In FIG 1, a low initial energy value closely matches the expected value of 90 degrees producing the highest effective damping to initial energy ratio. As the initial energy is set higher though, the optimal branch angle begins to increase leading to a value between 90 and 120. FIG 2 of the continuous model further highlights that 90 degrees is not always optimal, instead showing that the optimal angle is actually close to 120 instead of 90.

Upon studying the research on branched oscillators, the most effective damping natural frequency ratio between the branch and the trunk is roughly 2:1. This is because of an autoparametric internal resonance, a resonance where energy is distributed throughout the system from the modes of large branches down to the modes of smaller ones, dissipating in the process. Théckès et al. [11] explains this finding mathematically and, using a Y-shaped oscillator, shows that damping effects gets increased the most when the frequency on the branch is two times that of the trunk [12]. Studies of

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other fields, those that engages with nonlinear dynamics, explained that 1:2 is the most robust resonance condition for modal energy transfer, while other integer ratios, 3:1 or 3:2 for instance, are limited by the bandwidth and have a weaker performance [14]. The FEM study by Zhao J & Lu Z [15], fractal-inspired studies [13], and lab experiments [17] generally support the result that a coefficient of 2 acquires the best possible damping effect across geometries.

The near resonance condition with small detuning $\sigma$[20] would be

$$\omega_1 = 2\omega_2 + \sigma \tag{1}$$

$$x(t) = A(\epsilon t)\cos(\omega_1 t) \quad y(t) = B(\epsilon t)\cos\left(\frac{\omega_1 t}{2} + \phi\epsilon t\right) \tag{2}$$

When the trunk–branch PDE system is reduced to the two-mode ODE system, there will be a effective quadratic coupling constant $\kappa$[21]. In where the autoparametric branch occurs (B>0), steady state satisfies $\dot{A} = \dot{B} = \dot{\phi}$. Cancelling $\phi$ gets

$$B \approx \frac{\kappa A^2}{2\sqrt{(2\zeta_2\omega_2)^2 + \sigma^2}} \tag{3}$$

$$\dot{A} \approx -A\left(\zeta_1\omega_1 + \Delta\zeta_{eff}\omega_1\right) \tag{4}$$

$$\Delta\zeta_{eff} \propto \frac{\kappa^2 A^2}{(2\zeta_2\omega_2)^2 + \sigma^2} \tag{5}$$

The reason that 2:1 is best is that when the denominator is minimized ( $\sigma = 0$ ) [20], $\omega_1 = 2\omega_2$, and the frequency ratio would be 2:1, therefore $\Delta\zeta_{eff}$ is maximized at 2:1. If $\sigma$ is other than zero, the added damping falls off at $\frac{1}{\sigma^2}$.

The number of branching levels directly affects how broadly the system can dissipate energy across frequency ranges. A single branch stage typically produces narrow band damping focused on a trunk–branch internal resonance (coefficient ≈ 2). However, introducing multiple branching levels creates a hierarchy of coupled oscillators, each tuned to different frequency ratios, which generates a distribution of resonant interactions that widens the overall damping bandwidth. Numerical and fractal beam models confirm that higher order branches act as distributed dampers, capturing vibrational energy at successively higher frequencies [13]. Experiments made on bioinspired fractal shaped oscillators further demonstrates that two to three branching levels are often sufficient to achieve significant broadband mitigation without too much structural complexity [22]. Beyond three levels, marginal benefits diminish due to energy being divided among too many modes and

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increasing fabrication constraints. Therefore, multi-stage branching offers a usable balance where medium levels (two to three) [22] provide effective broadband damping while remaining appliable for engineering projects. The number of branching levels directly determines how broadly the system can dissipate energy across frequencies. A single branch stage typically produces narrow-band damping centered around an internal resonance (coefficient ≈ 2, where $\frac{\omega_b}{\omega_t}$ is the branch-to-trunk frequency ratio) [22]. By adding a second or third stage, additional branch natural frequencies ($\Omega_2$, $\Omega_3$, …) are introduced which distribute resonant energy transfer across multiple frequency bands. In fractal-like models, the effective damping ratio scales approximately as

$$\xi_{eff} \approx \sum_{i=1}^{n} \Gamma_i \xi_i \tag{6}$$

[22] where $\Gamma_i$ and $\xi_i$ are the mass ratio and damping ratio of the $i^{th}$ branch stage. Expressions confirm that higher-order stages yield diminishing returns because the modal energy is split among too many oscillators [13, 22].

Several papers taken into our account provided design guidelines and parameter that inform engineers on how to integrate branches into architecture. Théckès et al. [12] presented the ratio, branch mass and angle to achieve maximum damping effectiveness in their research. The work by Yamaguchi and Tanaka [16] validated the existing parameters and identified key angles and weight distribution that maximizes vibration mitigation, and Zhao and Lu [15] acquired knowledge on branch material properties in their method of FEM. Kareem and Kline [5] and Soong and Dargush [7] provided with more broader strategies in their detailed research on multi-tuned mass dampers (MTMD), where they gave tuning charts for frequency spacing, mass ratio, and damping effects under multiple loads, making their works useful for branched systems too. State-of-the-art reviews of TMD technology [18] and practical design guides [19] also provide instructions on branched layouts in systems within smaller amplitudes. All of these studies confirm that engineers ought to first use classical TMDs to set branch mass and damping levels, then tune branch frequencies near a 2:1 ratio with the trunk to exploit nonlinear internal resonance for maximum effectiveness ( [11,12,16,17]).

## 4. Engineering applications and design implications

Certain biomechanical principles that help trees withstand wind and earthquakes include active dynamic balancing, in which the trees are able to physically change their structure in response. Kenneth R. et al demonstrates this with data from 12 months of monitoring the loading forces of wind and the sway motion of trees from a variety of types that differed in branch structure. As the tree experiences loads, it usually grows branches in response which allow the tree to adapt, but can also shed and lose branches during strong environmental occurrences like wind and earthquakes [23]. The ability of trees to gain and remove its branches is something that separates it from traditional mass dampers which are set and do not change, allowing it to withstand wind and earthquakes more effectively.

The fractal geometry, branching angle, and mass tampering of trees play a large role in its stability, as they are what allow trees to differentiate themselves from what would otherwise be a straight pole. The fractal geometry of trees allows it to contain multiple tuned mass dampers with a hierarchy of order. Trees have 1st order branches which then themselves contain their own 2nd order

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branches and so on, allowing the branches which dampen the tree to be dampened themselves replicating having a mass damper containing its own mass damper [23]. Branching angle also plays a critical role in a tree's stability. Having too extreme of a branching angle such as 0 or 180 minimizes the effect of a tree's branches to act as mass dampers and simulates a tree with virtually no branches. The observation study by Kenneth R et al. [23] found statistically significant differences in damping capability across branch structures in a comparison of differently branched trees. Theckes et al. also found that branching angle played a critical role with certain optimal values for the most effective damping [20]. Mass tapering seemed to have the least prominent role for a tree's stability, as Moore. Et al. found that tapering a tree to reduce its mass near the top had little effect with over 80% of the crown of the tree needing to be removed for noticeable changes [21].

As trees have evolved over time, natural selection created trees that either prioritized using flexibility or damping through strength to avoid breaking. In a study by O Ojo et al analyzing the branching patterns of flexible trees, it was discovered that some trees evolved to be highly inflexible and others more flexible. The inflexible trees instead utilized stronger trunks and had hotspots of stress where branches would often first break in specific areas keeping the rest of the tree safe. Trees that were flexible evolved to utilize flexibility to avoid stress hotspots to prevent the chances of breaking overall, but risked breaking in more vulnerable and dangerous areas if the environmental pressures (like wind and earthquakes) were too strong [24].

Some key structural features that are most valuable include the bilayer arrangement of movement actuators in plants, the tendency for plants to take a slender-bodied structure, and their self similar structures. Rahel Ohlendorf et al. highlights these key features and their relation to human engineering themes and why we should focus our observations and studies on them [25]. In our case, the three listed structural features are especially important in trees which we are taking inspiration from. The bilayer actuators relate to the tree's movement and how it changes and adapts its structure overtime, the slender-bodied structure concerns how the tree tends to grow upwards and tall yet still handle vibrational forces, and the self-similar structure pertains to the repeated generation and growth of branches in trees overtime. Considering how all three of those components play a key role in a tree's ability to dampen/withstand the vibrational forces, they are the most valuable for engineering inspiration in our case.

It is possible to simulate plant growth rules for generating optimized damping structures, though there are limitations. A study by Lei Yi et al. introduced a method for modeling the growth of trees constrained by growth equations. In their study, the realism of the tree model and close similarity to its real-life counterpart was prioritized. One of the key components of their study that demonstrate the possibility of using such simulations for optimized damping structures is the ability for such models to account for and simulate within environmental impacts [26]. Considering how trees grow and gain their damping structures from its environmental impacts, such simulations could be a worthy candidate for generating the desired damping structures. However, the limitations that most simulations are not designed for engineering use must be considered as the viability of the structure in its damping capabilities would have to be separately analyzed after generation.

### 4.1. Real-world structures

Tree-mimetic branching structures have transitioned from being merely ornamental design themes to functional components in modern architectural and engineering application. Bioinspired shapes such as dendriform supports and canopy-like branchlike forms are applied widely in exhibition centers, airports, and other big-span buildings to duplicate the visual and structural characteristics of trees.

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These branching systems not only mimic the visual morphology of tree development but also enhance the structural efficiency by loading in various directions [27].

One of the first architects of this type of integration was Antoni Gaudí, whose Sagrada Família used column configurations taken from the natural growth and stress patterns of trees [28]. The architectural aspects enhanced the stability of the building and gave it a biomorphic shape. Engineers have only recently begun to explore branching geometries as seismic metamaterials. Bai et al. demonstrated that bioinspired branched structures can suppress low-frequency Rayleigh surface waves and hence are potential materials for earthquake regions' vibration isolation [29].

### 4.2. Benefits of branched designs in buildings and bridges

Branched structural forms offer both architectural and mechanical benefits. Mechanically, the division of load paths across multiple branches reduces stress concentration, enhancing seismic resilience and structural redundancy. This mimics how trees dissipate external forces through hierarchical branching networks [28]. Architecturally, branching supports open and uninterrupted interior spaces with improved spatial quality and visual impact—beneficial in atriums and public facilities [29].

From a vibration control perspective, tree-like geometries act as a network of distributed resonators, much like multiple tuned mass dampers (TMDs) embedded into the structure. These designs can effectively spread damping over a broader frequency range, improving robustness against multi-modal excitations [27]. Unlike single-mode TMDs, which target narrow frequency bands, DBB configurations inherently provide broadband damping capacity by design.

### 4.3. Vibration performance tests on bioinspired structures

While many architectural applications emphasize aesthetic and static performance, recent research has begun addressing the dynamic behavior of tree-like systems. Bai et al. conducted laboratory-scale experiments using branching metamaterials and confirmed their ability to reduce Rayleigh surface wave propagation in low-frequency ranges [27]. These findings validate DBB's potential as a practical damping strategy, especially where traditional devices may be limited.

Though large-scale vibration tests on actual buildings are rare, the convergence of modeling and lab-scale experimentation shows strong potential. Such work supports the premise that DBB is not only a naturalistic motif but also a performance-oriented engineering concept.

### 4.4. Analytical and experimental methods

The structural analysis of branching systems has evolved from physical prototyping to sophisticated computational modeling. Gaudí's early hanging chain models exemplify physical exploration of load redistribution through branching [28]. Today, finite element modeling (FEM) is the standard tool used to simulate modal interactions, stress wave propagation, and dynamic responses in tree-like systems. Bai et al. integrated FEM and physical experimentation to validate their seismic metamaterial performance [27].

This dual-pronged approach—computational simulations for prediction and physical models for validation—has become essential in understanding and designing complex DBB systems.

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### 4.5. Shared design principles between trees and engineered systems

Both natural and synthesized branching structures are restricted by principles such as hierarchical organization, modularity, and material efficiency. The fractal-like arrangement within trees allow for force distribution and peak stress reduction, resulting in an efficient multi-scale energy distribution. Engineering systems mimic this with branching trusses and metamaterials that enable distributed stiffness and damping properties [28, 27].

Moreover, modularity in branches allows parts of the structure to resonate differently, ensuring distributed damping across a wide range of frequencies. This concept parallels multi-mode control strategies in structural engineering. Architectural implementations that emphasize sustainability and adaptability also reflect the ecological efficiency of trees [29], reinforcing DBB as a principle grounded in both form and function.

## 5. Conclusions and discussion

This review has consolidated the current understanding of damping by branching (DBB), a bioinspired vibration control mechanism derived from the dynamic behavior of trees. By analyzing current research on this subject, including models, simulations and experimental studies, the review has illustrated how geometric coupling between a primary structure and its secondary components—in other words, a trunk and its branches—facilitate effective energy dissipation through modal energy transfer and the system's internal resonance. Both through finite element analysis and model examinations, the review established the core elements of damping by branching, including the 2:1 internal resonance ratio, the role of distributed mass, and energy loss in exchanges.

The review provides insights on damping by branching's strengths and weaknesses when compared to conventional damping methods like tuned mass dampers and other variations of it, where DBB does present a distinct set of advantages in certain scenarios. Being a passive damping itself, DBB's strength lies in its robustness and extensive nature. The branch like oscillators can provide a natural resilience to variation in the parameter and instances of mistuning, a huge advantage compared to the narrow-band, highly sensitive operation of a single TMD. This feature of DBB makes it highly desirable for circumstances where loading is unpredicted, or when large space-consuming dampers are impractical, particularly for slender buildings that have to withstand seismic and wind loading. When integrated to a building's initial design, branched dampers require less maintenance, a cost-effective solution that meets both material efficiency and architectural aesthetics.

However, as current DBB research has stated, DBB generally faces significant challenges that are parts of the reasons why it is not widely adopted. DBB's effectiveness often depends on the amplitude, performing best when there are large vibrations, which doesn't take into consideration other operational scenarios. The scalability of DBB to be applied in large engineering projects remains a primary setback to this particular damping mechanism, as achieving necessary scales and desirable geometry can conflict with functional, financial, and architectural constrains. The most pressing limitation of DBB among all remains in its lack of large-scale experimental validations, much needed for gaining acceptance within the conservative structural engineering community.

DBB's full potential is achieved when it is integrated into a hybrid system instead of serving as a direct replacement for conventional damping mechanism. The concept of combining the passive, broadband damping generated through the use of branches with correctly tuned TMD would offer a direction that provides highly robust and adaptable vibration mitigation system. Future research

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must focus on bridging the gap between theoretical models and real-world application, in the directions including:

1. Validate the methods using large scale experiments to derive prototypes and algebraic models, displaying DBB's functions under ideal circumstances.

2. In order to reach the optimal conditions for damping by branching, certain guidelines should be established to specify the branch-trunk mass ratio, geometry and material selections, while also considering specific engineering projects.

3. Testing systems that combine branched damping with conventional active dampers, exploring potentials in these integrated hybrid systems by examining their applications and performances.

4. By using more advanced fabric techniques, studies should focus on achieving optimized branching geometries with these more complex materials to reach feat otherwise impossible with more traditional materials.

In conclusion, damping by branching is a completely new approach that is aimed at replacing the added-on damping devices by introducing damping to biomimetic structural designs. By drawing inspiration from the branches on trees, this method of damping is very promising for creating the next generation of aesthetically pleasing, robust, and efficient structures. Realizing this potential will require a concerted, interdisciplinary effort to transition DBB from a compelling biological concept to a standardized engineering solution.

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