Aeroelastic Similarity in Trees: Reassessing a 1983 Hypothesis in the Context of Modern Multiple-Resonance Damping

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Abstract

Trees are dynamically complex branched structures in which trunks, branches and higher-order crown elements possess characteristic motions and are mechanically coupled. In a doctoral thesis completed in 1983 and formally awarded in 1984, Scannell proposed a qualitative mechanical principle termed *aeroelastic similarity*. Measurements on Sitka spruce suggested approximate relationships between modal frequencies at successive structural levels, together with direct evidence of coupled branch motion. The original interpretation proposed that overlapping frequency ranges could permit wind-induced mechanical energy to be redistributed through the crown and dissipated, thereby restricting large-amplitude resonant motion. This paper reassesses that hypothesis against four decades of subsequent tree-biomechanics research. Later work explicitly tested the named aeroelastic-similarity theory and subsequently developed mass damping, multiple resonance damping and damping by branching. The evidence does not support a universal hierarchy of exact modal equivalence. It does, however, support a broader principle in which frequency-compatible, mechanically coupled tree motions can exchange energy and thereby provide access to distributed dissipative mechanisms. We formulate this surviving idea as *dynamically coupled modal compatibility, not modal identity*. A reduced coupled-oscillator model separates conservative energy redistribution from dissipation, introduces descriptive measures of spectral separation and mode hybridisation, and motivates a hierarchical modal-network interpretation. We then propose a falsifiable experimental programme based on controlled detuning in numerical models, laboratory branched structures and living trees. Aeroelastic similarity is therefore retained not as an exact frequency-scaling law, but as a testable hypothesis concerning the dynamical organisation of branched structures.

Keywords: tree biomechanics; wind loading; structural dynamics; aeroelastic similarity; multiple resonance damping; mass damping; modal coupling; damping; conifer; Sitka spruce

1 Introduction

Trees present an unusual problem in structural dynamics. They are tall, flexible, highly branched structures subjected throughout their lives to broadband and transient aerodynamic forcing. Their response to wind cannot in general be represented adequately by a rigid crown mounted on a single flexible cantilever. Trunk, primary branches and progressively higher branching orders possess characteristic dynamic responses, while mechanical coupling allows motion of one part of the structure to influence others (Kerzenmacher and Gardiner, 1998; Sellier and Fourcaud, 2005; Spatz et al., 2007).

The resulting dynamics are important because large coherent oscillations can concentrate mechanical loading in the stem and root–soil system. Understanding how trees dissipate wind-induced mechanical energy and restrict damaging oscillation is therefore a central problem in tree biomechanics (James et al., 2006; Spatz et al., 2007; Spatz and Theckes, 2013).

A substantial literature has developed around the natural frequencies and damping of trees. Moore and Maguire (2004) synthesised measurements from 602 conifers belonging to eight species and demonstrated systematic relationships between tree dimensions and natural sway frequency. Crown-removal experiments subsequently showed that branches affect both natural frequency and damping (Moore and Maguire, 2005). Sellier and Fourcaud (2005) demonstrated that motions of different axes in young *Pinus pinaster* were dynamically coupled and strongly influenced by crown architecture and foliage.

The importance of dynamically active branches later became more explicit. James et al. (2006) developed the concept of mass damping, in which branch masses moving relative to the trunk can reduce coherent trunk motion. Spatz et al. (2007) demonstrated multiple resonance damping in a Douglas-fir, finding that eigenfrequencies of its large branches lay close to the oscillation frequency of the complete tree. They interpreted the tree as a system of coupled damped oscillators in which mechanical energy could be distributed between stem, primary branches and higher-order branches and dissipated more effectively. Spatz and Theckes (2013) subsequently reviewed multiple mass damping, multiple resonance damping and the nonlinear mechanism of damping by branching, emphasising frequency tuning as a fundamental feature of branch-mediated damping.

An earlier proposal anticipated some of these physical ingredients. During experimental studies of Sitka spruce at Cranfield in the early 1980s, Scannell observed relationships among natural frequencies associated with the whole tree, branches, shoots and smaller crown elements. Together with observations of mechanically coupled branch motion, these findings led to a qualitative mechanical principle termed Aeroelastic Similarity (Scannell, 1984).

The thesis was completed in October 1983 and examined later that year; the doctoral degree was formally awarded in 1984. The thesis consequently appears in subsequent literature as Scannell (1984), although the hypothesis itself had been formulated in 1983. The term *aeroelastic similarity* is used here in this original tree-biomechanical sense and should not be confused with its conventional engineering use for aeroelastic scaling between models and prototypes.

The original hypothesis contained two propositions that can now be separated. The stronger proposition concerned an apparent hierarchical correspondence among modal frequencies. In the original notation, observations suggested relationships of the approximate form

$$S_1 \simeq B_2 \simeq N_3, \tag{1}$$

where modes associated with progressively smaller tree elements appeared to correspond to successively higher modes of larger elements. The broader proposition was dynamical: biological variation would broaden nominal frequencies into finite ranges; overlap between frequency ranges, combined with mechanical coupling, might permit wind-induced energy to be redistributed among tree elements and ultimately dissipated.

Four decades of subsequent work allow these propositions to be distinguished. The evidence does not support Eq. (1), or an equivalent fixed hierarchy, as a universal rule. The more general idea that dynamically compatible and mechanically coupled tree motions can exchange energy, however, is closely related to later mass-damping and multiple-resonance descriptions. The historical connection is not solely retrospective: Moore's doctoral work explicitly described branch-frequency measurements as a test of the "aeroelastic similarity theory of Scannell (1984)", while Spatz et al. (2007) explicitly identified analogous concepts in Scannell and in James et al. (2006).

The purpose of this paper is therefore not to claim priority for multiple resonance damping. Rather, it makes three specific contributions. First, it reconstructs the original Aeroelastic Similarity hypothesis and traces its subsequent treatment in the tree-dynamics literature. Second, it separates the unsupported hypothesis of fixed hierarchical modal equivalence from the more general mechanism of dynamically coupled modal compatibility. Third, it formulates the latter

as a testable structural-dynamic hypothesis and proposes experiments capable of distinguishing frequency-mediated energy redistribution from branch-mass and aerodynamic effects. The central conclusion is

$$\boxed{\textbf{dynamically coupled modal compatibility, not modal identity.}} \tag{2}$$

2 The Original Aeroelastic Similarity Hypothesis

2.1 Experimental origin

The original investigation combined measurements of atmospheric motion within and above a Sitka spruce canopy with measurements of the motion of the trees themselves (Scannell, 1984). Tree response was examined using field acceleration spectra, manual sway tests and laboratory measurements on individual structural elements.

An unexpected observation was that natural frequencies attributed to different hierarchical levels appeared to possess a degree of organisation. The thesis noted that each observed branch mode was approximately similar to the next higher whole-tree mode and that independent estimates from sway tests and spectral measurements agreed, on average, to approximately 10%. The observations suggested relationships represented schematically by Eq. (1). Branches, shoots and twigs vary in length, diameter, mass, foliage and mechanical properties; each nominal modal family was therefore expected to occupy a finite frequency range.

2.2 Direct observations of coupling

The frequency observations were accompanied by evidence that tree elements were mechanically coupled. In a branch-release experiment, displacement and release of one branch caused another branch attached through the bole to begin moving. Their motions became approximately out of phase and relative amplitudes varied with time: motion of one branch could increase while that of the other diminished, after which the process could reverse (Scannell, 1984). In modern terminology this is consistent with coupled oscillators exchanging mechanical energy.

The original interpretation described such behaviour partly in terms of damping. A more precise distinction is now possible. Conservative elastic coupling permits mechanical energy to move between degrees of freedom; it does not by itself remove energy from the complete structure. Dissipation requires non-conservative processes such as aerodynamic drag, internal material damping, friction or root–soil losses. This distinction was made explicitly in later tree-dynamics work (Sellier and Fourcaud, 2005).

The field observations also suggested scale-dependent responses to transient forcing. Short disturbances preferentially excited higher-frequency crown elements, whereas longer gusts could produce more coherent whole-tree motion. These observations led to the description of the tree as a large, structured “shock absorber” (Scannell, 1984).

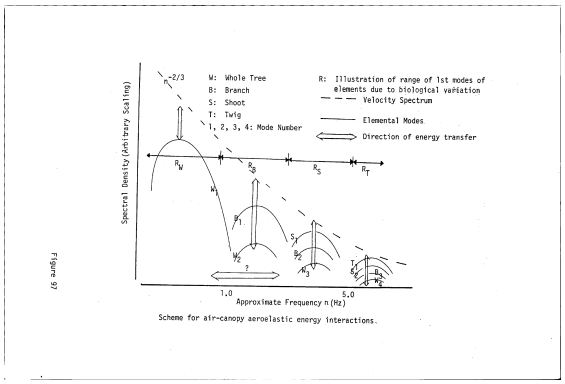
2.3 From observation to similarity principle

The interpretation was developed in comparison with elastic-similarity ideas for tree form. Aeroelastic Similarity was intended as a dynamical extension: a possible organisational principle in which structures at different hierarchical levels were related through their response to atmospheric forcing.

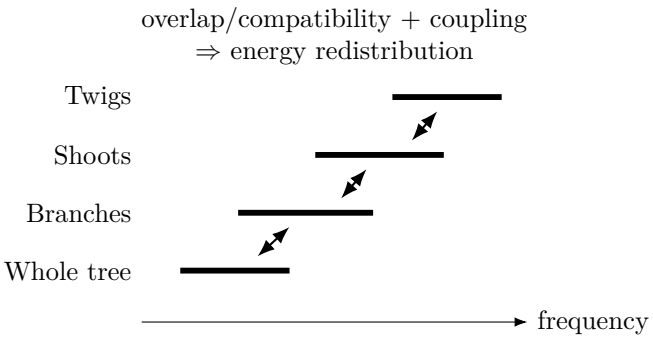
The proposed sequence was approximately

$$\text{hierarchical frequency relationships} \rightarrow \text{overlapping frequency ranges} \rightarrow \text{mechanical interaction} \rightarrow \text{redistributio} \tag{3}$$

The thesis's Figure 97 represented this qualitatively by superposing atmospheric wind spectra and resonance ranges associated with the whole tree, branches, shoots and twigs, with arrows indicating possible energy transfer. Figure 1 reproduces the original page and places it beside a modern reinterpretation.



(a) Original Figure 97 from the thesis (Scannell, 1984).



(b) Modern interpretation: finite response bands can overlap, but energy exchange additionally requires mechanical coupling.

Figure 1: From hierarchical modal bands to dynamically coupled modal compatibility. The historical figure is reproduced for scholarly comparison from the author's thesis.

The suggested mechanical advantage was that wind-induced energy need not remain concentrated in a large-amplitude whole-tree response. Instead, motion could be distributed among structural elements and dissipated through aerodynamic and internal losses. The thesis did not establish that this mechanical principle uniquely determined tree morphology; the present paper likewise makes no claim that a particular architecture evolved specifically for this damping function.

2.4 Two separable hypotheses

With hindsight, the proposal contained a *modal-equivalence hypothesis*,

$$\boxed{\text{specified modal orders at successive levels possess approximately corresponding frequencies,}} \tag{4}$$

and a broader *modal-interaction hypothesis*,

$$\boxed{\text{frequency-compatible and mechanically coupled motions can redistribute wind-induced energy.}} \tag{5}$$

The first can produce conditions favourable to the second, but it is not necessary for it.

3 Development of the Concept, 1984–2026

3.1 Early transmission

The earliest clear post-1984 transmission identified in the present search occurs in the literature surrounding Gardiner's studies of wind and tree movement. Gardiner (1995) discussed interaction between wind and tree dynamics; Kerzenmacher and Gardiner (1998) subsequently developed a dynamic Sitka-spruce model in which the tree was represented by coupled differential equations. Comparison with measurements highlighted the inadequacy of treating branches only as lumped masses and pointed instead toward branches as cantilevers coupled to the stem.

The present search does not establish that Gardiner (1995) was the first publication after the thesis to transmit the idea; older literature is incompletely digitised. It is therefore described here only as the earliest clear post-thesis transmission identified in the present search.

3.2 Moore's explicit test

The clearest evidence that Aeroelastic Similarity survived as a named hypothesis is Moore's doctoral work (Moore, 2002), which explicitly stated that branch-frequency information would be used to test the aeroelastic-similarity theory of Scannell (1984). This is important historically because the later literature did not merely rediscover a superficially similar mechanism: at least one subsequent programme explicitly treated Aeroelastic Similarity as a testable theory.

The detailed mapping between Moore's measured branch frequencies and particular whole-tree modal orders should not be over-generalised here. The secure conclusion is narrower: later work retained the importance of branch–tree frequency relationships without establishing the particular universal hierarchy proposed from the original Sitka-spruce observations.

Moore and Maguire (2004) subsequently synthesised natural-frequency and damping measurements from 602 trees of eight conifer species. Crown-removal experiments further demonstrated that crown architecture affects whole-tree dynamic behaviour (Moore and Maguire, 2005).

3.3 Sellier and Fourcaud: transfer is not dissipation

Sellier and Fourcaud (2005) provide a particularly important conceptual bridge. Their analysis of *Pinus pinaster* saplings showed that motions of axes depended on topological position and that foliage influenced damping and coupling. They cited Scannell in the context of branch sway and damping, while explicitly distinguishing transfer of mechanical energy between axes from loss of energy from the complete structure. This yields the modern correction

$$\boxed{\text{conservative coupling redistributes energy; dissipative processes remove it.}} \tag{6}$$

3.4 Mass damping

James et al. (2006) approached the problem from a complementary direction. Branch masses moving relative to the trunk can act dynamically to reduce coherent harmonic trunk sway. The emphasis is on inertia and phase relationships rather than a prescribed modal hierarchy, but the mechanism likewise requires the crown to be dynamically active rather than merely a passive aerodynamic load.

3.5 Multiple resonance damping

Spatz et al. (2007) provide the strongest subsequent experimental connection with the surviving part of Aeroelastic Similarity. In a young Douglas-fir they found that eigenfrequencies of the large branches were close to the oscillation frequency of the complete tree. Branch removal substantially reduced damping. They interpreted the intact tree as a system of coupled damped oscillators in which resonance-energy transfer distributes mechanical energy between stem, primary branches and higher-order branches, and explicitly noted that analogous concepts had been developed by Scannell and by James and colleagues.

The conceptual transition is therefore

$$\boxed{\text{modal equivalence} \rightarrow \text{frequency compatibility} + \text{mechanical coupling.}} \tag{7}$$

3.6 Frequency tuning and other damping mechanisms

Spatz and Theckes (2013) reviewed primary and higher-order branches as multiple tuned mass dampers and emphasised overlapping frequency bands and resonance-energy transfer. Frequency tuning was identified as a fundamental requisite across several branch-mediated mechanisms. Frequency proximity alone, however, is insufficient: uncoupled oscillators do not exchange energy.

Branch-mediated resonance transfer is also not the only damping mechanism. Theckes et al. (2011) identified damping by branching, arising from geometric nonlinearities and particularly effective at large amplitudes. Aerodynamic damping, internal material damping and root–soil interaction may also contribute. These mechanisms are not mutually exclusive.

3.7 Later persistence in the literature

The connection did not end with the 2013 synthesis. Sellier and Suzuki (2020), in a finite-element study of tree sway across the life of a model *Cryptomeria japonica*, explicitly cited Scannell (1984) when stating that the efficiency of branch damping depends on fine tuning of branch natural frequencies. This is useful evidence that the frequency-tuning interpretation remained part of the tree-dynamics literature rather than being only a retrospective association made here.

Burcham and Au (2022) also cited the original work when discussing the relationship between natural frequencies measured during free and wind-induced vibration. Their operational-modal-analysis study emphasised that modal properties observed under ambient wind depend on the loading environment. This supports an important qualification of the present reformulation: dynamically coupled modal compatibility need not imply sustained resonant atmospheric forcing, and the modes activated in natural wind may depend on the forcing distribution and amplitude.

The concept has also persisted outside the immediate tree-dynamics literature. Toader et al. (2024), in a biomimetic study of coniferous trees as models for structural columns, cited Scannell in their review of the influence of branches on trunk-sway dynamics. This later citation does not itself constitute new evidence for multiple-resonance damping, but it documents continued recognition of the original work in a structural-bioinspiration context.

3.8 Historical interpretation

The defensible genealogy is summarised in Table 1. It does not establish that Scannell discovered multiple resonance damping or that the thesis was the first discussion of branch-mediated damping in every sense. The narrower conclusion is that, in the literature examined here, Aeroelastic Similarity can be identified as an early documented conceptual antecedent of later branch-mediated resonance-damping descriptions: it explicitly formulated organised frequency relationships and mechanically coupled energy redistribution among hierarchical tree elements, and later authors explicitly recognised the conceptual relationship.

4 What Survived—and What Did Not?

Table 2 separates the original propositions.

The central revision is therefore not merely "overlap rather than identity". Spectral overlap without coupling produces no exchange. The surviving principle is Eq. (2), and the physical sequence becomes

$$\boxed{\text{wind input} \rightarrow \text{modal excitation} \rightarrow \text{coupled redistribution} \rightarrow \text{dissipative loss.}} \tag{8}$$

Table 1: Citation and conceptual genealogy relevant to Aeroelastic Similarity.

Date	Source	Documentary relationship to Scannell and what it establishes
1983/84	Scannell	Hierarchical modal relationships; branch coupling; overlapping ranges; proposed "Aeroelastic Similarity".
1995	Gardiner	Early post-thesis transmission identified in the present search; wind–tree interaction and branch-mediated interpretation.
1998	Kerzenmacher & Gardiner	Dynamic Sitka-spruce model; branches need treatment as cantilevers coupled to the stem rather than lumped masses.
2002	Moore	Explicitly describes branch-frequency measurements as a test of the "aeroelastic similarity theory of Scannell (1984)"; establishes that the named hypothesis entered later research as a testable proposition.
2004–05	Moore & Maguire	Large synthesis of natural sway data; crown-removal experiments demonstrate crown effects on frequency and damping.
2005	Sellier & Fourcaud	Coupled crown dynamics; crucial distinction between transfer among axes and dissipation from the whole structure.
2006	James et al.	Multiple mass damping: dynamically moving branch masses reduce coherent trunk sway.
2007	Spatz et al.	Demonstrates multiple resonance damping and explicitly identifies analogous concepts in Scannell (1984) and James et al. (2006); documents a later conceptual link to MRD.
2008	Moore & Maguire	Finite-element treatment of branches as individual cantilevers; branch oscillations contribute to damping and may approach antiphase with the stem.
2011	Theckes et al.	Damping by branching: distinct nonlinear geometric mechanism.
2013	Spatz & Theckes	Synthesis of mass damping, multiple resonance damping and damping by branching; frequency tuning emphasised.
2020	Sellier & Suzuki	Explicitly cites Scannell (1984) in stating that branch damping efficiency depends on fine tuning of branch natural frequencies; documents persistence of the frequency-tuning interpretation.
2022	Burcham & Au	Cites Scannell's comparison of free and wind-induced natural frequencies; operational modal analysis shows that identified modal properties under ambient wind depend on the loading environment.
2024	Toader et al.	Cites Scannell in a biomimetic review of conifer dynamics and branch effects on trunk sway; documents continued recognition in structural bioinspiration.

Table 2: Original propositions and their status after four decades of subsequent work.

Proposition	Present status	Interpretation
Natural modes occur at multiple structural levels	Supported	Trees are multi-degree-of-freedom branched structures.
Tree elements are mechanically coupled	Supported	Demonstrated experimentally and in coupled structural models.
Mechanical energy can be redistributed among structural motions	Supported	Coupled systems exchange energy; later mass/MRD work supplies stronger evidence.
Transfer itself constitutes dissipation	Requires correction	Conservative transfer redistributes; non-conservative processes dissipate.
Dynamically active branches can enhance whole-tree damping	Supported, context dependent	Demonstrated in pruning, full-tree and modelling studies.
Frequency compatibility is dynamically important	Supported	Later MRD literature emphasises overlapping bands and frequency tuning.
Fixed hierarchy such as $S_1 \simeq B_2 \simeq N_3$ is universal	Not established	Too restrictive to retain as a general principle.
Biological variability broadens useful modal coverage	Plausible hypothesis	Requires direct testing; excessive detuning may weaken interaction.
Tree acts as a distributed dynamic absorber	Consistent with later models and experiments	Useful modern interpretation where dynamically active branches contribute materially to whole-tree response.
Architecture evolved specifically for this mechanism	Not established	Mechanical consequence does not demonstrate evolutionary causation.

5 A Quantitative Reformulation of Aeroelastic Similarity

5.1 Coupled damped dynamics

Consider a passive linear baseline

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{F}(t), \tag{9}$$

where $\boldsymbol{M}$ and $\boldsymbol{K}$ are constant symmetric matrices, $\boldsymbol{K}$ represents conservative elastic restoring forces, and $\boldsymbol{C}$ is taken here as symmetric positive semidefinite. Define

$$E = \frac{1}{2}\dot{\boldsymbol{q}}^T\boldsymbol{M}\dot{\boldsymbol{q}} + \frac{1}{2}\boldsymbol{q}^T\boldsymbol{K}\boldsymbol{q}. \tag{10}$$

Then

$$\frac{dE}{dt} = \dot{\boldsymbol{q}}^T\boldsymbol{F} - \dot{\boldsymbol{q}}^T\boldsymbol{C}\dot{\boldsymbol{q}}. \tag{11}$$

Without forcing,

$$\frac{dE}{dt} = -\dot{\boldsymbol{q}}^T\boldsymbol{C}\dot{\boldsymbol{q}} \leq 0. \tag{12}$$

Thus Eq. (6) follows within the passive structural model. Aerodynamic coupling can contain non-conservative terms, so this is a structural baseline rather than a claim about every possible fluid–structure interaction.

5.2 Minimal two-degree-of-freedom system

A simple trunk–branch analogue is

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 + k_c(x_1 - x_2) = F_1(t), \tag{13}$$

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 + k_c(x_2 - x_1) = F_2(t). \tag{14}$$

When $k_c = 0$, the undamped uncoupled frequencies and damping ratios are

$$\omega_i = \sqrt{\frac{k_i}{m_i}}, \qquad \zeta_i = \frac{c_i}{2m_i\omega_i}. \tag{15}$$

With coupling present, the true normal modes belong to the combined system. "Tree frequency" and "branch frequency" therefore refer here to uncoupled subsystem frequencies or to experimentally identifiable trunk- and branch-dominated responses.

Define

$$\Delta\omega_{ij} = |\omega_i - \omega_j|, \qquad \delta_{ij} = \frac{|\omega_i - \omega_j|}{(\omega_i + \omega_j)/2}. \tag{16}$$

Exact identity is $\delta_{ij} = 0$, but the reformulated hypothesis does not require it.

5.3 Spectral separation

For a lightly damped SDOF oscillator the approximate half-power bandwidth is

$$\Delta\omega_i \simeq 2\zeta_i\omega_i. \tag{17}$$

We introduce the following dimensionless descriptive spectral-separation parameter:

$$D_{ij} = \frac{|\omega_i - \omega_j|}{\zeta_i\omega_i + \zeta_j\omega_j}. \tag{18}$$

Small D_{ij} denotes proximity relative to nominal damping bandwidths; large D_{ij} denotes separated responses. At $D_{ij} = 1$, the nominal frequency separation equals the sum of the two approximate half-power half-widths used in the denominator. This geometrical interpretation does not make $D_{ij} = 1$ a physical threshold for energy transfer.

5.4 Coupling and hybridisation

Frequency proximity alone is insufficient. In a specified mass-normalised *subsystem* basis, rather than the final eigenbasis of the complete coupled structure, write a generic reduced local conservative interaction matrix as

$$\begin{pmatrix} \omega_1^2 & g_{12} \\ g_{12} & \omega_2^2 \end{pmatrix}, \qquad [g_{12}] = T^{-2}. \tag{19}$$

Equation (19) is a generic reduced mass-normalised representation and is not obtained by simply inserting the uncoupled frequencies of Eq. (15) into Eqs. (13)–(14). Its diagonal entries represent the assigned self terms in the chosen reduced basis; coupling-induced diagonal contributions may therefore be absorbed into those terms, while g_{12} denotes the corresponding off-diagonal interaction. The coupled squared frequencies are

$$\Omega_{\pm}^2 = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\left(\frac{\omega_1^2 - \omega_2^2}{2}\right)^2 + g_{12}^2}. \tag{20}$$

A useful hybridisation diagnostic is

$$\chi_{ij} = \frac{2|g_{ij}|}{|\omega_i^2 - \omega_j^2|}. \tag{21}$$

Thus χ_{ij} is the ratio of the coupling term to the uncoupled half-separation appearing under the square root in Eq. (20). For $\chi \ll 1$, detuning dominates; for $\chi \gtrsim 1$, coupling is comparable to the uncoupled spectral separation. At exact degeneracy Eq. (21) diverges because the uncoupled-mode distinction ceases to be a useful perturbative description; no physical divergence is implied.

Frequency separation and coupling do not alone determine the forced response. Modal phase relationships, forcing distribution and damping also affect instantaneous energy exchange. The diagnostics D_{ij} and χ_{ij} are therefore not combined into a universal scalar index.

5.5 Operational definition

A modern definition is

> A hierarchically branched structure exhibits aeroelastic similarity when dynamically compatible structural motions are sufficiently coupled for externally injected mechanical energy to be redistributed among degrees of freedom through which dissipative processes can act effectively. (22)

Here *dynamic compatibility* is a graded property rather than a binary resonance condition. Motions become increasingly compatible as their frequency separation, relative to damping, coupling and the relevant forcing bandwidth, permits appreciable interaction; exact frequency identity is neither required nor, by itself, sufficient.

For a chosen modal normalisation, the generalised forcing of mode r is

$$Q_r(t) = \boldsymbol{\phi}_r^T \boldsymbol{F}(t). \tag{23}$$

Sustained resonant atmospheric forcing is not required by the present coupled-system formulation: broadband or transient wind can inject energy into several responses, after which coupling influences redistribution.

Figure 2 summarises the conceptual change.

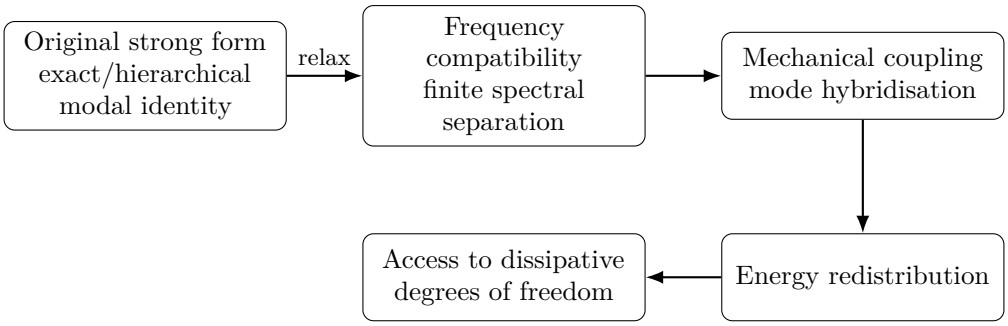


Figure 2: Conceptual reformulation from modal identity to dynamically coupled modal compatibility. Frequency proximity or overlap alone is insufficient: appreciable energy exchange also requires mechanical coupling, while increased whole-tree damping additionally requires access to effective dissipative pathways.

6 A Proposed Hierarchical Modal-Network Interpretation

Let

$$G = (V, E) \tag{24}$$

represent a network in which vertices correspond to experimentally or numerically identified structural modes or dynamically meaningful subsystem responses. A vertex may be characterised by

$$v_i : (\omega_i, \zeta_i, m_i^*, \boldsymbol{\phi}_i). \tag{25}$$

An edge e_{ij} denotes dynamically significant interaction. Interaction strength should preferably be inferred from transfer functions, cross-spectra, identified coupling terms or a validated finite-element model rather than assigned by an arbitrary formula.

For a fixed decomposition in which subsystem energies remain physically meaningful, define a signed pairwise energy flux J_{ij} with

$$J_{ij} = -J_{ji}, \tag{26}$$

and $J_{ij} > 0$ denoting transfer from j to i. Then a coarse-grained balance is

$$\frac{dE_i}{dt} = P_i^{\text{ext}} - P_i^{\text{diss}} + \sum_{j \neq i} J_{ij}. \tag{27}$$

Because internal conservative transfers cancel pairwise,

$$\frac{dE_{\text{tot}}}{dt} = \sum_i P_i^{\text{ext}} - \sum_i P_i^{\text{diss}}. \tag{28}$$

In strongly coupled or non-proportionally damped systems, energy cannot in general be assigned uniquely to arbitrary "branch" and "trunk" modes. Equations (27)–(28) therefore use a specified modal or subsystem decomposition only where it remains physically meaningful; the total energy balance is the more robust statement.

The original hierarchy

$$W \leftrightarrow B \leftrightarrow S \leftrightarrow T \tag{29}$$

is thus a coarse representation of a richer network. Wind acts directly on branches and foliage as well as on the complete crown, and internal transfer can reverse direction. Figure 3 illustrates the modern interpretation.

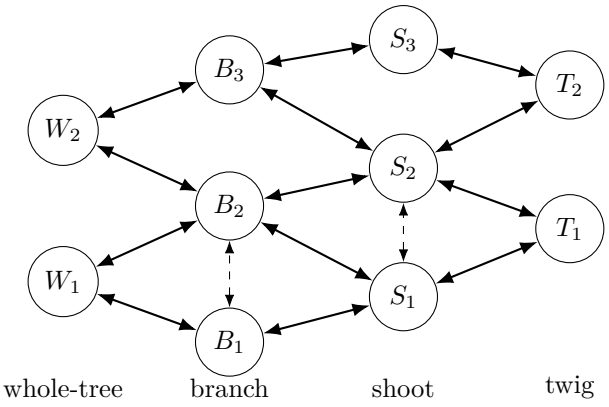


Figure 3: Hierarchical modal-network interpretation. Nodes are dynamically meaningful responses, not botanical elements one-to-one; edges denote measured or modelled interactions. Energy transfer is not assumed to be unidirectional.

6.1 Distributed dynamic absorption

If energy is initially concentrated in a trunk-dominated response and the response is dynamically isolated, dissipation is limited to pathways directly associated with that motion. Coupling to compatible crown responses can redistribute the energy and expose it to additional dissipative mechanisms. Redistribution does not by itself imply increased damping: an enhancement of effective whole-tree damping requires that the recipient degrees of freedom provide effective dissipative loss, or that redistribution otherwise changes the forcing–response relation advantageously. This is consistent with the later description of primary and higher-order branches as multiple tuned mass dampers (Spatz and Theckes, 2013).

We use *dissipative connectivity* descriptively for the existence of dynamically accessible pathways from strongly excited responses toward degrees of freedom with effective damping. No graph invariant is assigned to the term.

The network reformulation further suggests, but does not establish, the testable hypothesis that several partially redundant compatible pathways may make the response less sensitive to local detuning than a system dependent on one precisely tuned absorber. Similarly, we propose that biological variability *could* broaden dynamical coverage; excessive detuning could instead weaken interaction.

7 Testable Predictions and Experimental Tests

The reformulated hypothesis makes a stronger claim than the observation that branches contribute to damping. It predicts that controlled alteration of dynamically relevant frequency relationships should alter energy redistribution in a manner that cannot be explained solely by aerodynamic area or added mass.

7.1 Stage 1: validated numerical model

A finite-element or reduced-order branched model should first be calibrated against measured natural frequencies, mode shapes and damping. Mass, stiffness, damping and coupling can then be varied independently. For a selected branch-dominated response,

$$\omega_B \to \omega_B' \tag{30}$$

can be produced by controlled parameter changes. The measurable outputs include D_{BT}, χ_{BT}, transfer functions, trunk response and decay rate. As an optional exploratory diagnostic, where a fixed modal basis with non-negative assigned modal energies remains meaningful, define

$$p_i(t) = \frac{E_i(t)}{\sum_j E_j(t)}, \qquad N_{\text{eff}}(t) = \frac{1}{\sum_i p_i^2(t)}. \tag{31}$$

Here $N_{\text{eff}} \simeq 1$ denotes concentration predominantly in one represented mode, while larger values denote participation by more represented modes. This quantity is basis dependent and should be compared only across repeated measurements using the same identification procedure.

The prediction is not that maximum damping must occur at $\omega_B = \omega_T$. The optimum depends on mass ratio, damping, coupling, phase and forcing. The more defensible prediction is

$$\boxed{\text{controlled detuning produces a reproducible, model-consistent dependence of energy redistribution on frequer}} \tag{32}$$

7.2 Stage 2: laboratory branched structure

A physical branched structure permits branch mass, stiffness and damping to be manipulated more independently than in a living tree. A trunk-dominated motion can be excited repeatedly while one branch is tuned across a range of frequencies.

The crucial comparison is between configurations with similar target frequencies but different mass distributions and configurations with similar mass but different frequencies. For example,

$$(m_1, r_1) \to \omega_B', \tag{33}$$

$$(m_2, r_2) \to \omega_B', \qquad m_1 \neq m_2. \tag{34}$$

These should be compared with stiffness-based tuning that approaches the same ω_B'. Convergence of results from independently varied mass- and stiffness-based interventions, interpreted using remeasured mode shapes and coupling, would provide stronger evidence that frequency compatibility contributes independently of simple mass loading.

7.3 Stage 3: controlled living-tree detuning

Only after the mechanism has been isolated in numerical and laboratory systems should it be tested in a living tree or sapling. Adding a mass to a branch is not by itself a clean detuning experiment because it changes modal mass, inertia, mode shape, coupling, damping and gravitational preload as well as frequency. Several reversible interventions should therefore be used, with modal properties remeasured after each.

The essential sequence is

$$\text{baseline identification} \to \text{controlled intervention} \to \text{remeasurement} \to \text{controlled excitation} \to \text{baseline restorat} \tag{35}$$

7.4 Direct observation of redistribution

For causal transfer measurements, controlled forcing should initialise motion predominantly in a chosen trunk-dominated response. Simultaneous trunk and crown measurements can then test for a temporal sequence

$$\boxed{\text{initially concentrated response} \to \text{measurable redistribution} \to \text{dissipative decay.}} \tag{36}$$

Under natural wind, by contrast, branch responses can be directly forced. The appearance of branch energy under turbulent loading is therefore not by itself evidence of trunk-to-branch transfer; wind experiments test whether the coupled dynamics identified under controlled conditions remain active under realistic forcing.

7.5 Selective branch intervention and falsification

The network interpretation predicts that dynamic importance need not scale with branch mass alone. Intervening on a branch with strong measured coupling to a trunk-dominated response should have a greater effect on redistribution than an equivalent intervention on a dynamically peripheral branch, all else being comparable.

Falsification criterion. If controlled alteration of modal compatibility, after controlling for branch mass, aerodynamic area and coupling, produces no reproducible alteration in energy redistribution or whole-tree response, the proposed Aeroelastic Similarity mechanism is not supported. The hypothesis would likewise be weakened if controlled trunk excitation decayed without measurable interaction with compatible crown motions, or if validated models reproduced the observations without dynamically active branch degrees of freedom or an equivalent interaction mechanism.

Figure 4 summarises the proposed causal test.

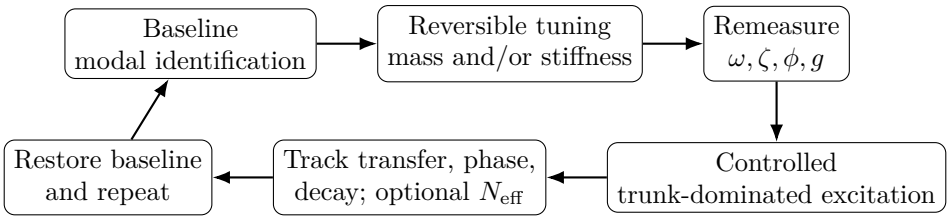


Figure 4: Proposed controlled-detuning experiment. Independent or convergent mass- and stiffness-based interventions are used to separate frequency effects from simple mass loading.

8 Discussion and Conclusions

The Aeroelastic Similarity hypothesis originated from an unexpected observation: natural frequencies associated with different hierarchical elements of Sitka spruce appeared to possess organised relationships. Together with direct observations of mechanically coupled branch motion, these relationships suggested that a tree might behave as an integrated dynamic structure in which wind-induced mechanical energy could be transferred among whole-tree, branch, shoot and twig motions (Scannell, 1984).

Four decades of subsequent research permit the original proposal to be divided into what survived and what did not. The precise hierarchy $S_1 \simeq B_2 \simeq N_3$ has not been established as a universal rule. Later work instead points toward a broader principle: dynamically active branches can possess frequency relationships with whole-tree motion that permit substantial interaction without conforming to one prescribed hierarchy (Spatz et al., 2007; Spatz and Theckes, 2013).

The useful content of the original concept therefore lies in three physical ingredients:

$$\boxed{\text{dynamic compatibility} + \text{mechanical coupling} + \text{dissipative pathways.}} \tag{37}$$

Dynamic compatibility concerns whether responses occupy ranges in which appreciable interaction is possible; coupling determines whether mechanical energy can be exchanged; non-conservative mechanisms determine whether redistributed energy is removed.

8.1 Historical relationship to modern damping concepts

The historical relationship to multiple resonance damping should be stated carefully. Scannell proposed organised frequency relationships and suggested that coupling among tree elements

could transfer wind-induced mechanical energy and contribute to damping. Later work supplied substantially stronger experimental and theoretical foundations. Sellier and Fourcaud clarified transfer versus loss; James and colleagues developed mass damping; Spatz and colleagues demonstrated multiple resonance damping experimentally; and Spatz and Theckes integrated these mechanisms with nonlinear damping by branching.

It would therefore be inappropriate to describe the 1983 work retrospectively as the discovery of multiple resonance damping. The defensible conclusion is narrower:

$$\boxed{\text{Aeroelastic Similarity is an early documented conceptual antecedent in the literature examined here.}} \tag{38}$$

This interpretation is strengthened because later authors themselves made the connection: Moore explicitly tested the named Aeroelastic Similarity theory and Spatz et al. (2007) explicitly identified an analogous concept in Scannell.

8.2 Limitations

The literature combines species, ages, architectures and experimental conditions. Branch-mediated damping cannot be assumed to operate identically in every tree. The mathematical formulation here is intentionally reduced: real trees exhibit geometric nonlinearities, non-proportional damping, aerodynamic nonlinearities, reconfiguration, anisotropic materials and root–soil interaction. The modal structure can itself change with wind loading and configuration, so the network may be state dependent.

The proposed D_{ij} and χ_{ij} quantities are diagnostics rather than universal criteria. The optional N_{eff} diagnostic is basis dependent. "Dissipative connectivity" is qualitative. The variability/robustness proposal is a new hypothesis rather than an established result. Most importantly, the present paper is a retrospective theoretical synthesis; it does not provide new experimental evidence that the network reformulation is correct.

8.3 Conclusion

The original Aeroelastic Similarity hypothesis contained one proposition that proved too restrictive and another that proved more durable. The restrictive proposition was a prescribed hierarchical equivalence among modal frequencies. The durable proposition was that the branched structure contains dynamically interacting elements whose frequency relationships can influence how wind-induced mechanical energy is distributed and, when redistributed energy reaches effective dissipative pathways, how rapidly it is removed.

The development may be summarised as

$$\boxed{\begin{array}{c}\text{hierarchical modal identity}\\ \downarrow\\ \text{frequency compatibility} + \text{mechanical coupling}\\ \downarrow\\ \text{energy redistribution}\\ \downarrow\\ \text{distributed dissipation.}\end{array}} \tag{39}$$

A modern definition is therefore:

Aeroelastic Similarity in Trees. A tree exhibits aeroelastic similarity to the extent that its branched architecture provides dynamically compatible and mechanically coupled structural motions through which wind-induced mechanical energy can be redistributed among structural responses, potentially reducing its concentration in strongly excited load-bearing motions and making it accessible to distributed dissipative processes. (40)

This definition abandons exact modal identity, separates energy transfer from energy dissipation, and replaces a prescribed hierarchical sequence with a dynamically connected branched structure. The historical development is consequently neither simple confirmation nor rejection of the 1983 proposal. Its particular modal hierarchy has not survived intact, but its broader proposition became closely aligned with later experimental and theoretical descriptions of branch-mediated damping.

The remaining question is experimental:

Does controlled alteration of dynamically coupled modal compatibility predictably alter energy (41)

That question provides a direct test of whether Aeroelastic Similarity, reformulated four decades after its original proposal, constitutes a useful general dynamical principle of branched structures.

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Conflict of interest

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Data availability

No new experimental data are reported in this article. The historical observations discussed here were reported in the author's doctoral thesis. The equations, figures and proposed experimental framework in the present article are contained within the manuscript.

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