The Aeroelastic Similarity Hypothesis for Tree Structure

A retrospective formulation of observations from a 1983 study of Sitka spruce

B. Scannell
Originally developed in PhD research at Cranfield Institute of Technology (1983)

2026

Abstract

A hypothesis termed *aeroelastic similarity* was proposed in a 1983 doctoral study of the interactive motions of atmospheric turbulence and a Sitka spruce canopy. The proposal arose from field and laboratory observations indicating an approximate organisation of the natural-frequency modes of different structural levels of the tree. In particular, branch modes were observed to lie close to the next higher whole-tree modes, while shoot modes extended the same pattern to higher frequencies. The tree also exhibited strongly damped post-gust motion and observable mechanical coupling between branches and smaller elements. These observations suggested that the tree may behave as a hierarchically coupled, broadband mechanical system in which incident wind energy is distributed among overlapping modal bands and dissipated by aerodynamic drag and elastic coupling. The present paper extracts that argument from the wider thesis and restates it as a testable hypothesis. Aeroelastic similarity is defined here as the proposition that the dimensions, masses, stiffnesses and hierarchical arrangement of tree elements are constrained such that modal bands of successive structural levels overlap in an organised manner, thereby promoting the sharing and dissipation of wind-induced mechanical energy and limiting the build-up of damaging resonant amplitudes. The hypothesis is presented as a retrospective formulation of the original work, not as a claim that the 1983 observations established a universal law of tree structure.

1 Introduction

A tree exposed to turbulent wind is not a single oscillator. It is a ramified mechanical system consisting of a bole, branches, shoots, twigs and foliage, with each structural level possessing its own masses, stiffnesses, aerodynamic loading and natural modes. The elements are mechanically connected and simultaneously immersed in a broadband atmospheric forcing field. The resulting dynamics therefore depend not only on the resonance of an individual element, but also on coupling between structural scales.

The present paper isolates one proposal made in the author's 1983 PhD thesis, *Quantification of the Interactive Motions of the Atmospheric Surface Layer and a Conifer Canopy* [Scannell, 1983]. That thesis treated atmospheric turbulence, instrumentation, canopy airflow, tree motion and air–canopy interaction. Its final mechanical proposal was that a simple relationship between resonances of the separate tree elements could provide the tree with an atmospheric "shock-absorbing" structure. The term *aeroelastic similarity* was introduced for a hypothetical qualitative mechanical design principle that might contribute to survivability in strong turbulent winds.

The purpose here is narrower than that of the thesis. The original observations relevant to this proposal are assembled, the logical distinction between observation and hypothesis is made explicit, and the proposal is reformulated in a way that admits modern experimental tests.

2 Origin of the hypothesis

The experimental programme was conducted on Sitka spruce (*Picea sitchensis*) and combined measurements of atmospheric motion with measurements of tree motion. Natural frequencies were estimated in several ways: field and laboratory sway tests, acceleration spectra obtained under wind excitation, and a discrete modal calculation based on measured flexibility influence coefficients and elemental masses [Scannell, 1983].

For a discretised elastic element, the thesis used the free-vibration eigenproblem

$$\left([K] - \omega^2[M]\right)\mathbf{q} = 0, \tag{1}$$

or, in the experimentally convenient flexibility form,

$$\left([I] - \omega^2[C][M]\right)\mathbf{q} = 0, \tag{2}$$

where $[K]$ and $[C] = [K]^{-1}$ are stiffness and flexibility matrices, $[M]$ is the mass matrix, ω is a natural angular frequency and $\mathbf{q}$ is the corresponding mode shape. The flexibility coefficients were measured directly by applying known loads at stations along sampled elements and recording their deflections.

The calculated modes were useful as a comparison, but did not reproduce all measured higher-mode frequencies. The thesis argued that the discrepancy itself was informative: simplified isolated-element calculations omitted the aerodynamic and mechanical interactions of the shoots, twigs and needles, whereas the real tree was an interacting aeroelastic system.

3 Observed organisation of the modal frequencies

The central empirical observation was made by comparing whole-tree and branch acceleration spectra with sway-test estimates. The similarity of each branch mode to the next higher whole-tree mode was described in the thesis as both remarkable and unexpected from the simplified theoretical calculations. The sway-test and spectral estimates listed in the thesis agreed, on average, to approximately 10%, giving additional confidence in identifying the modal peaks.

The observed pattern was summarised symbolically as

$$B_1 \sim N_2, \qquad B_2 \sim N_3, \qquad B_3 \sim N_4, \tag{3}$$

where N_i denotes the ith whole-tree mode and B_i the ith branch mode. Inclusion of the shoot estimates suggested the continuation

$$S_1 \sim B_2 \sim N_3, \qquad S_2 \sim B_3 \sim N_4, \tag{4}$$

and the proposed hierarchy was extended qualitatively to the twig scale.

The original Table 55 represented the organisation as equivalent modal groups. Its content can be expressed compactly as Table 1.

This representation should not be read as asserting a set of sharply defined universal frequencies. Biological variation produces a range of element lengths, masses and stiffnesses. The physically relevant objects are therefore *bands* of modal frequencies. The hypothesis concerns overlap between such bands: for example, the band of first branch modes may overlap the broadened, damped second whole-tree resonance.

4 Observed coupling and damping

The frequency correspondence was accompanied by direct observations of coupled motion. Under stronger winds, a gust could displace the canopy substantially; after the gust the tree returned

Table 1: Schematic equivalent-mode hierarchy proposed in the 1983 thesis. Equality here means approximate coincidence or overlap of natural-frequency bands, not exact equality of eigenfrequencies.

Structural level	Group 1	Group 2	Group 3	Group 4
Whole tree	N_1	N_2	N_3	N_4
Branch		B_1	B_2	B_3
Shoot			S_1	S_2
Twig				T_1

with damped oscillations, usually lasting only a few cycles. Shaking of branches, shoots and twigs during this decay suggested that energy associated with the large-scale motion was not confined to the bole.

A simple manual experiment provided a particularly clear qualitative demonstration. A branch was displaced transversely so as to twist the bole and was then released. Motion appeared in adjacent branches through torsional coupling. The neighbouring branch could increase in amplitude while the initially displaced branch decreased, followed by a partial reversal of the exchange. The process continued while the total motion decayed. This was interpreted as transfer of elastic energy among coupled elements superposed on dissipation.

Short-duration disturbances preferentially excited the smaller, higher-frequency elements. Longer gusts displaced the canopy more nearly en masse and excited lower whole-tree modes. After an impulsive disturbance, motion propagated visibly through branches, shoots and twigs. The thesis therefore described the tree as acting as a large, well-structured shock absorber.

These observations motivate a distinction that is important for the present formulation. *Coupling* redistributes mechanical energy between degrees of freedom; it does not by itself destroy energy. Dissipation arises from mechanisms such as aerodynamic drag and internal/mechanical damping. A coupled hierarchy may nevertheless enhance effective damping of a dangerous large-scale mode by making more dissipative degrees of freedom available to receive its energy.

5 From elastic similarity to aeroelastic similarity

The proposal was developed in the context of the elastic-similarity ideas of McMahon [1976] and McMahon and Kronauer [1975]. Elastic similarity concerns geometrical and mechanical scaling of tree form. The 1983 thesis asked whether a description based primarily on static or isolated-element scaling was sufficient for a structure whose environment is intrinsically dynamic.

For elastic similarity, the thesis quoted a scaling of characteristic natural frequency f with element length l of the form

$$f \propto l^{-1/2}, \tag{5}$$

while noting that the experimental exponent reported by McMahon and Kronauer was approximately -0.59. The proposed extension was not merely a revised exponent. It was the suggestion that the *relationships among the modes of different structural levels* could themselves constitute a mechanical organising principle.

The distinction may be stated succinctly. Elastic similarity asks how the dimensions of a mechanically viable tree should scale. Aeroelastic similarity, as proposed here, asks whether those dimensions and mechanical properties are additionally organised so that the *dynamics of the coupled hierarchy* possess beneficial modal relationships.

6 The aeroelastic similarity hypothesis

The original proposal can be reformulated as follows.

> **Aeroelastic Similarity Hypothesis.** The dimensions, masses, stiffnesses and hierarchical arrangement of the structural elements of a tree are constrained such that modal frequency bands of successive structural levels overlap in an organised manner. Through mechanical coupling, this organisation allows wind-induced energy to be shared among multiple structural scales and dissipated through aerodynamic and mechanical damping, thereby restricting the build-up of damaging resonant amplitudes.

This formulation contains three logically separate propositions:

(i) **modal organisation:** successive structural levels possess systematically overlapping modal bands;

(ii) **dynamic coupling:** energy can be exchanged between modes belonging to different structural levels;

(iii) **functional consequence:** the coupled hierarchy increases the effective dissipation or redistribution of incident wind energy sufficiently to reduce damaging resonant response.

The 1983 observations provided evidence suggestive of all three, but did not establish any of them as a universal property of trees. In particular, the functional or evolutionary interpretation remains a hypothesis requiring comparative tests.

7 A hierarchical shock-absorber model

Figure 1 is a modernised schematic of the physical interpretation represented in Fig. 97 of the thesis. Atmospheric turbulence supplies a broad spectrum of forcing. Different structural levels have overlapping resonant bands. Coupling permits energy exchange between these bands, while aerodynamic and material/mechanical damping remove energy from the system.

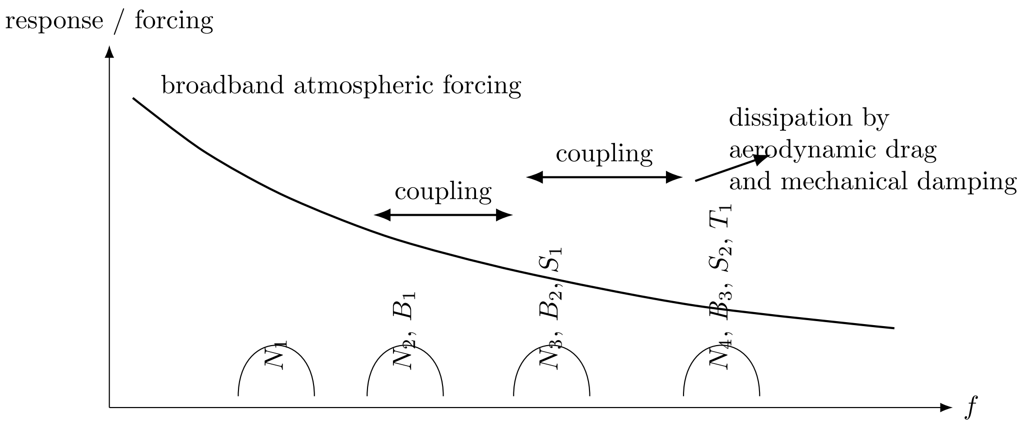

Figure 1: Conceptual representation of aeroelastic similarity. The atmospheric spectrum can excite several structural scales. Approximate modal overlap and coupling distribute energy among the hierarchy; damping then removes energy. The drawing is schematic and is not a fit to measured spectral amplitudes.

The proposed protective effect is therefore not that resonance is eliminated. On the contrary, many resonances are available. The conjecture is that the organisation and coupling of these resonances prevent incident energy from remaining concentrated in one structural mode long enough to generate a dangerously large amplitude. In modern mechanical language, the tree would behave qualitatively like a distributed, multi-degree-of-freedom vibration absorber rather than a single cantilever oscillator.

8 What was established and what was inferred

It is useful to separate the evidential levels of the original study.

Directly observed or measured. The study measured tree accelerations under wind excitation, estimated natural frequencies by sway tests, observed strongly damped post-gust motion, and observed flexural/torsional coupling between tree elements. It also found approximate correspondence between certain branch modes and the next higher whole-tree modes, with shoot estimates consistent with a continuation of the pattern.

Inferred from the observations. The thesis inferred that ranges of element size would create modal bandwidths in which modes of different structural levels merge or overlap, and that this could provide an efficient natural damping system for atmospherically induced motion.

Hypothesised. The further step was to suggest that the organisation itself may represent a mechanical design criterion of tree structure, beneficial to survival in strong winds. That proposition was explicitly presented as qualitative and hypothetical. No evolutionary mechanism was established, and the thesis noted that the structural mechanism might involve genetic specification and/or mechanically active biological feedback such as reaction wood.

This separation is retained deliberately. The significance of the 1983 work lies in the testable mechanical idea; it does not require the original evidence to be stronger than it was.

9 Testable predictions

The hypothesis can now be stated in experimentally discriminating terms. If aeroelastic similarity is more than an accidental coincidence in one set of spruce measurements, at least some of the following should be observed.

1. **Modal-band overlap.** Across a sufficiently large sample of trees, the distribution of B_1 should overlap N_2 more strongly than expected from an appropriate null model; similarly for B_2 with N_3, and for the corresponding shoot and twig modes.
2. **Cross-scale energy transfer.** Time-resolved measurements following a gust or controlled impulse should show energy leaving an initially excited mode while appearing in coupled modes at other structural levels before dissipation.
3. **Architecture dependence.** Selective removal or alteration of branches should change whole-tree damping and the modal structure in a way predictable from the loss or displacement of overlapping modes.
4. **Broadband robustness.** A hierarchically coupled tree should exhibit lower peak response over a broad forcing-frequency range than a mechanically comparable structure in which the modal hierarchy has been detuned, even if total mass and gross stiffness are held approximately fixed.

5. **Environmental or interspecific variation.** If the organisation is adaptive, populations or species exposed to systematically different wind regimes may differ in modal organisation in ways associated with their mechanical environment.

Modern three-dimensional motion capture, scanning laser vibrometry, distributed inertial sensors and finite-element modelling would allow these predictions to be tested far more directly than was possible in 1983.

10 Limitations

Several limitations of the original evidence must be emphasised. The key modal relationships were obtained from a restricted number of Sitka spruce trees and sampled elements. Some higher modes were inferred from spectral peaks rather than measured independently. The calculated isolated-element model did not include the complete aeroelastic coupling whose importance the hypothesis subsequently emphasised. Biological variability broadens all frequency relationships. Finally, similarity of frequencies alone does not demonstrate energy transfer; the latter requires phase-resolved or otherwise causal measurements of coupled dynamics.

There is also a terminology issue. "Similarity" in the present hypothesis is not intended to imply exact geometric self-similarity or exact equality of eigenfrequencies. It denotes an approximate dynamical organisation across hierarchical structural levels. The most robust version of the hypothesis is consequently statistical: modal *bands*, not individual frequencies, should exhibit non-random overlap and coupling.

11 Discussion

The original insight can be reduced to a simple mechanical question: might the ramified architecture of a tree do more than provide static strength and aerodynamic streamlining? Might it also organise the spectrum of structural motion so that the tree possesses an intrinsic, distributed vibration-control system?

The observations in the 1983 study made this plausible for the Sitka spruce system examined. Whole-tree, branch and shoot modes appeared in an ordered hierarchy; post-gust motion was strongly damped; and mechanical coupling between elements could be observed directly. These facts motivated the proposed aeroelastic-similarity principle.

The strongest contemporary formulation is not that trees must satisfy the exact equivalences in Eqs. (3)–(4). Rather, those equalities should be treated as the first empirical indication of a broader proposition: a ramified biological structure may achieve dynamic robustness through an organised overlap of modal bands and cross-scale coupling. The original frequency correspondences are therefore a candidate signature of the mechanism, not its definition.

This distinction also makes the hypothesis falsifiable. A sufficiently broad survey might show that the reported correspondences were accidental, species-specific, or consequences of ordinary scaling without any additional organisation. Alternatively, direct measurements of energy flow may show little transfer between the nominally corresponding modes. Either result would weaken the hypothesis. Conversely, reproducible non-random modal overlap accompanied by measured cross-scale energy transfer and enhanced damping would provide much stronger evidence than was available in the original study.

12 Conclusion

The aeroelastic similarity hypothesis originated from measurements of Sitka spruce dynamics made in the early 1980s. The key observation was an approximate correspondence between natural modes of successive structural levels, notably between branch modes and the next higher whole-tree modes, together with evidence of strong damping and mechanical coupling throughout the tree. This led to the proposal that the tree behaves as a hierarchically organised shock absorber.

Restated in testable form, aeroelastic similarity proposes that tree architecture constrains modal frequency bands so that successive structural levels overlap and interact, allowing incident wind energy to be distributed among many coupled degrees of freedom and dissipated before damaging resonant amplitudes develop. The original study supplied suggestive evidence rather than a general proof. The hypothesis is therefore best regarded as a specific mechanical conjecture, historically proposed in 1983, that can now be tested quantitatively using modern experimental and computational methods.

Historical note

The term *aeroelastic similarity* and the underlying qualitative mechanical design principle were introduced in the author's PhD thesis submitted to the Cranfield Institute of Technology in December 1983. The present article is a retrospective extraction and reformulation of that proposal. It intentionally distinguishes the observations reported in the thesis from the broader hypothesis inferred from them.

References

T. A. McMahon. The mechanical design of trees. *Scientific American*, 233:92–102, 1976.

T. A. McMahon and R. E. Kronauer. Tree structures: Deducing the principle of mechanical design. *Journal of Theoretical Biology*, 59:443–446, 1975.

B. Scannell. *Quantification of the Interactive Motions of the Atmospheric Surface Layer and a Conifer Canopy*. PhD thesis, Cranfield Institute of Technology, Ecological Physics Research Group, December 1983.

R. G. White et al. Measurement of the motion of trees in two dimensions. Technical Report No. 86, Institute of Sound and Vibration Research, University of Southampton, 1976.