

Two Checks for Structures in a Moving Environment

Will the environment shake it apart, and will the environment outgrow it?

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Keywords: resonance avoidance, aeroelastic flutter, galloping, vortex-induced vibration, lock-in, damping, design event, design basis, climate projection, exposed structures

Scope statement. This document defines two checks for any engineered structure exposed to environmental loading — wind, waves, current, traffic, machinery, ice. It rests entirely on classical structural dynamics and ordinary practice in design-basis selection. **It contains no novel physics and claims none.** It is a checklist, written so that the two commonest omissions become visible: a designer treating resonance avoidance as though it covered self-excited instability, and a design inheriting numerical margins nobody ever traced to a source.

Who this is for. It is written to be cited by other work rather than read straight through. A design document should be able to reference it, complete the compliance statement of §4, and move on. The worked examples are drawn from marine and coastal engineering because that is where it was assembled, but nothing in the method is marine-specific — substitute your own driving frequencies into §2.4 and your own design events into §3.3 and it applies equally to a bridge, a mast, a conveyor gantry or a rooftop plant room.

1. Why these two checks, and why they are separate

Most structural failures under environmental load fall into two families that need different tests.

The first is **excitation**: the environment supplies energy at a rate the structure happens to accept, and motion accumulates until something breaks. The second is **exceedance**: the environment supplies a load larger than the one the structure was designed for, and the structure is simply not big enough.

Check One addresses excitation. Check Two addresses exceedance. They are separate because passing one tells you nothing about the other, and because the commonest error in practice is treating a single resonance calculation as though it covered both.

2. Check One — Will the environment shake it apart?

2.1 What this check governs, and what it must not

This check applies to structural members. It does not apply to power-take-off elements.

The distinction is not pedantic and it is the single most important line in this document. An energy absorber is frequently *designed* to resonate with its driving environment, because resonance is how a small force applied repeatedly at the right moment produces a large motion, and a large motion is what an absorber converts. A structural member that resonates with its driving environment accumulates motion it has no way to spend, and fails.

Resonance is therefore the objective for the absorber and the failure mode for the structure, and a rule written without that scope will either forbid the machine from working or permit the structure to destroy itself.

Where a resonant absorber is mounted to a structure that must not resonate, **the mount between them becomes a compliance item in its own right** and must be shown not to transmit the absorber's resonant response into the structure. See §2.7.

2.2 The forced-resonance criterion

For every natural frequency f_n of every structural member, and every environmental driving frequency f_d identified under §2.4, verify that

$$|f_n / f_d - p/q| > m, \text{ for all integers } p, q \leq 3$$

In words: no part of the structure may have a natural frequency that lands on the driving frequency, or on its double, its triple, its half or its third, within a margin m . The underlying theory of forced vibration and of the response near such a coincidence is standard and is set out in Den Hartog [3]. The small-integer ratios matter because a structure can be driven not only at its own frequency but at simple multiples of it — a member that likes to vibrate twice per wave will still be pumped by every wave.

The check must be run against **every** significant mode, not the fundamental alone. Torsional and local-plate modes are frequently lower than designers expect and are where this check most often finds something.

2.3 Margins

Member class	Margin m	Rationale
Primary structure — foundations, spine, main load path	0.30	Failure is not repairable and not survivable; modelling uncertainty in added mass and soil stiffness is large
Secondary structure — mounts, supports, brackets, walkways	0.10	Failure is local and inspectable; stiffness is better known
Power-take-off and absorber elements	not applicable	Deliberately resonant by design — see §2.1

These margins are engineering judgement calibrated to modelling uncertainty, and they are stated as such. **They are not derived from any published code and must not be represented as though they were.** Where a governing code applies to the structure in question, that code's margins take precedence and this table is superseded.

A note on why the primary margin is three times the secondary one: for a submerged or partly submerged structure the **added mass** of entrained water can be comparable to the structural mass itself, and it is not known precisely. An error of twenty percent in added mass moves the natural frequency by about ten percent, which consumes the entire secondary margin on its own.

2.4 Environmental driving frequencies

The designer must produce a site-specific version of the table below. The values here are typical bands for orientation only and **none is a substitute for a site record**.

Source	Typical band	Structures affected	Notes
Ocean swell	0.05–0.15 Hz	Sea walls, caissons, jetties, offshore platforms, wave devices	The dominant case for coastal work; take the band from a local wave scatter diagram, not from this table
Local wind sea	0.15–0.5 Hz	Slender members, railings, light superstructure	Broadband; check the whole range
Harbour seiche	0.001–0.01 Hz	Basins, moored bodies, long structures	Site-specific and easily missed
Tidal	$\sim 2 \times 10^{-5}$ Hz	Gates, moving barriers	Far below any structural mode; relevant to fatigue counting rather than resonance
Vortex shedding	Strouhal number $\times$ flow speed $\div$ member width	Piles, cables, blades, risers	Varies with current, so it sweeps across frequencies rather than sitting at one
Rotating machinery	Shaft speed and its multiples; blade-passing frequency	Foundations, housings, adjacent structure	Handled by isolation mounts and foundation decoupling
Ground motion	0.5–10 Hz	All structures in seismic regions	Governed by the applicable seismic code, not by this check
Ice interaction	Variable	Any structure in ice	Intermittent crushing can lock onto a structural frequency; see §2.5

2.5 Self-excited instability — a separate and mandatory check

Passing §2.2 does not protect against self-excited instability, and the two are routinely confused.

In forced resonance an external periodic driver matches a structural frequency. In a self-excited instability there is **no periodic driver at all**: the structure's own motion changes the fluid forces acting on it in a way that feeds energy back into that motion, and the amplitude grows under a steady flow. Detuning a structure away from every environmental frequency in §2.4 leaves such an instability entirely untouched.

The following must be checked independently for every slender member exposed to flow. The standard reference for all three, and for the section-shape data needed to assess them, is Blevins [2]:

- **Flutter** — coupling between two modes, typically bending and torsion, under steady flow.
- **Galloping** — single-degree-of-freedom instability of a member whose cross-section produces a negative aerodynamic or hydrodynamic damping slope. Ice accretion on a member can create the section that galloping requires, on a member that was stable when built.
- **Vortex-induced vibration with lock-in** — shedding frequency captured by a structural frequency and held there across a range of flow speeds, so the usual sweep-through argument fails.

The design defence in all three cases is **damping** and section shape, not frequency separation.

2.6 The famous example teaches the wrong lesson

The 1940 Tacoma Narrows collapse is the image almost every engineer carries of what §2.2 is for. **It is not an example of forced resonance, and treating it as one is the most-corrected error in structural engineering pedagogy** [1]. The collapse was aeroelastic flutter — the deck's own torsional motion altered the aerodynamic forces acting on it, feeding energy into the motion under a *steady* wind with no matching external frequency anywhere. Detuning that deck away from every driving frequency in its environment would not have saved it.

The 1850 Angers bridge collapse needs similar care. Marching troops were the trigger, but corroded cable anchorages were a substantial contributing cause, and citing it as a pure resonance failure overstates what the case demonstrates.

Why this matters is operational, not historical. A designer who holds Tacoma Narrows as the canonical warning, runs §2.2, and finds a clean margin will believe the structure is protected against the very thing that destroyed that bridge. It is not. **§2.5 is the check that would have caught it**, and the two are independent.

2.7 Damping and the absorber interface

Where §2.1 applies — a deliberately resonant absorber mounted to a structure required not to resonate — the interface must be demonstrated, not assumed.

- The isolator's own natural frequency shall be placed **well below** the absorber's operating frequency, so that the absorber's motion is not transmitted as force into the structure.
- The isolated assembly must be shown to satisfy §2.2 **as installed**, including the added mass of entrained water, and not merely as a dry component.
- Isolator degradation over service life shall be treated as a change in structural frequency and re-checked at the intervals set in the maintenance plan.

2.8 What must be recorded

A design is not compliant with this check until the following exist as documents: the modal analysis listing every mode checked with its frequency and its added-mass assumption; the site-specific version of the §2.4 table with sources; the margin table showing the computed ratio for every mode against every driving frequency; the §2.5 instability assessment; and, where applicable, the §2.7 interface demonstration.

3. Check Two — Will the environment outgrow it?

3.1 The most dangerous number in a design document

It is tempting to specify climate margins as a short table of multipliers — a factor on wave height, another on storm surge, another on wind — attributed to a published assessment. Almost every design basis that does this has copied the table from another design basis rather than from the assessment.

An inherited multiplier is the most dangerous kind of number in a design document. It is load-bearing. It looks authoritative. It propagates into every downstream calculation. And it is almost never checked, precisely because it arrived looking finished. **A multiplier quoted from memory is not a design margin; it is a guess wearing a citation's clothes.**

This check therefore specifies **a procedure that forces sourcing**, and deliberately specifies no numerical multipliers at all. If you want a number here you have to go and get it — from a record you can name, for the site you are actually building on.

3.2 The procedure

1. **Name the design life and the decision year.** A structure designed in 2026 for a fifty-year life is being designed for conditions in 2076, not for conditions now.
2. **Enumerate the design events** the structure must survive and the ones it must operate through. These are different lists and must be kept apart — see §3.3.
3. **Select the emissions or forcing scenario explicitly and record why.** The choice of scenario is a policy decision embedded in an engineering document and must be visible as such.
4. **Source each projected quantity from a citable published record for the specific region**, at that scenario and that horizon. Global-mean figures are not admissible as site design values.
5. **Record the uncertainty range**, not only the central estimate, and state which end of it the design uses.
6. **State the consequence of being wrong** in each direction: what happens if the projection is exceeded, and what the over-design costs if it is not.
7. **Re-check at a stated interval.** Projections are revised; a fifty-year structure should have its design basis re-examined against current science at least once per decade, with the result recorded whether or not anything changes.

3.3 The design event register

Every project shall maintain a register distinguishing these categories, because conflating them is how structures end up over-built for the wrong load and under-built for the right one.

Category	Question it answers	Typical governing quantity
Operating envelope	What does it work in, every day?	Modal sea state, mean wind, normal tidal range
Curtailment threshold	Above what does it stop producing and protect itself?	Sea state at which the machine goes to survival mode
Survival event	What must it live through without loss of primary function?	1-in- <i>N</i> -year wave, surge and wind, at the design horizon
Non-survival event	What is explicitly accepted as beyond design, and what is the consequence?	Stated and accepted, not omitted

The fourth row is mandatory. **A design that does not state what it is not designed for has not finished its analysis**, and the absence is usually discovered by the event itself.

3.4 Interaction effects

Design quantities must not be escalated independently and then combined as though they were unrelated. Wave height, storm surge and wind are physically correlated in the same storm; sea-level rise raises the baseline on which surge and wave run-up both act; and the joint probability of a correlated set is not the product of the marginals. Where a project lacks the data for a joint analysis, that limitation shall be recorded in the design basis rather than concealed by conservative single-variable factors.

3.5 What must be recorded

The design basis document shall contain: the design life and horizon year; the selected scenario with the reason for its selection; every projected quantity with its source, region, horizon and uncertainty range; the completed design event register of §3.3; the interaction treatment of §3.4; and the date of the next scheduled re-check.

4. Compliance statement format

A project claiming compliance shall publish a statement of the following form, so that a reviewer can locate every input without reading the whole document.

Check One. Modes checked: *n*. Lowest margin found: *m* on mode *k* against *source*. Instability assessment: *reference*. Absorber interface: *applicable / not applicable*, demonstration at *reference*.

Check Two. Design life *L* years, horizon *year*. Scenario *S*, selected because *reason*. Projected quantities and sources: *table reference*. Design event register: *reference*. Next re-check: *date*.

An incomplete statement is a finding, not a formatting problem. **The purpose of publishing the statement is to make an omission visible without an audit.**

5. What this document does not do

- It sets no numerical climate multipliers, deliberately. See §3.1.
 - Its dynamic margins in §2.3 are engineering judgement, not code-derived, and are superseded wherever a governing code applies.
 - It does not address fatigue, which is a separate check governed by the applicable materials standard — though the driving frequencies of §2.4 are the correct input to a cycle count.
 - It does not address seismic design, which is governed by the applicable seismic code.
 - It contains no novel physics and no novel method. It is a checklist written so that the two commonest omissions — treating resonance avoidance as covering instability, and inheriting unsourced design factors — become visible.
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References

[1] Billah KY & Scanlan RH. Resonance, Tacoma Narrows bridge failure, and undergraduate physics textbooks. *American Journal of Physics* **59**, 118–124 (1991).

[2] Blevins RD. *Flow-Induced Vibration*. Van Nostrand Reinhold (1990).

[3] Den Hartog JP. *Mechanical Vibrations*. McGraw-Hill (1956).

References [1]–[3] carry substantive claims and should be verified against the publisher record before deposit.

6. Tool and computational resource disclosure

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Tools used. Claude (Anthropic) was used for literature search, for drafting and restructuring prose, for checking arithmetic, and for producing the typeset artifact. Typesetting used python-markdown and wkhtmltopdf, driven by a build script that performs a font-coverage preflight before rendering. No numerical result in this document was produced by an automated system without being reproduced independently from stated inputs.

Responsibility. Responsibility for the correctness and adequacy of the arguments and results presented here, and for the completeness and accuracy of the citations, rests entirely with the named human author. No automated system is an author of this work.

Verification performed. The two design margins in §2.3 are stated as engineering judgement rather than as code-derived values, and are labelled as such in the text. The historical correction in §2.6 was checked against the cited paper. The built artifact was checked for orphaned headings, for split heading-formula pairs, and for internal cross-reference consistency — every §-pointer in this document was verified against the section it names by an automated pass over the source.

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Computational resources. None material.

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