Failure of the Tacoma Narrows Bridge: Flutter not Resonance

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http://www.ccs.fau.edu/~liebovitch/larry.html
What can a mechanical system do?

What really happened to the Tacoma Narrows Bridge?

What dynamic properties could be present in ion channel proteins?
What Didn’t Happen

NOT Resonance

Resonance
• excite at a given frequency $f_o$.
• resonance frequency of the bridge $f_b \approx f_o$.

There was NO driving at fixed frequency $f_o$.

NOT Alternatively shed vortices

• Strouhal frequency $\approx 1$ Hz.
• Bridge frequency $\approx 1/5$ Hz.

Wind tunnel tests show that:
the bridge controlled the vortices,
NOT that the vortices drove the bridge.
The Area
The Site
The Bridge at the Site
<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bids received</td>
<td>Sept. 27, 1938</td>
</tr>
<tr>
<td>Contract awarded</td>
<td>Nov. 23, 1938</td>
</tr>
<tr>
<td>Construction commenced</td>
<td>Nov. 23, 1938</td>
</tr>
<tr>
<td>Main piers completed</td>
<td>Sept. 11, 1939</td>
</tr>
<tr>
<td>Towers completed</td>
<td>Jan. 6, 1940</td>
</tr>
<tr>
<td>Cables completed</td>
<td>Mar. 9, 1940</td>
</tr>
<tr>
<td>Suspended steel completed</td>
<td>May 31, 1940</td>
</tr>
<tr>
<td>Concrete roadways completed</td>
<td>June 28, 1940</td>
</tr>
<tr>
<td>Bridge opened to traffic</td>
<td>July 1, 1940</td>
</tr>
</tbody>
</table>

The bridge failed on November 7, 1940.
Suspension Bridge

towers

cables

main span

water
Cable Stay Bridge

Why?
- For medium spans, less steel, less money.
- Pretty.
Tacoma Narrows Bridge

335 m  853 m  335 m
1100 ft  2800 ft  1100 ft
425 ft
130 m

water
Tacoma Narrows

Main span: Plate Girder.

Why? Because it was beautiful.

By far, this was the longest, narrowest, bridge with a man span built using a plate girder.

Normally, a Truss, would be used.
A frame houses:

Tinker Toy:

Each piece is $\sqrt{2}$ larger than the next smaller piece.
## Bridges Damaged or Destroyed by Wind

<table>
<thead>
<tr>
<th>Location</th>
<th>Country</th>
<th>Length</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryburgh Abbey</td>
<td>Scotland</td>
<td>260 ft.</td>
<td>1818</td>
</tr>
<tr>
<td>Union</td>
<td>England</td>
<td>449 ft.</td>
<td>1821</td>
</tr>
<tr>
<td>Nassau</td>
<td>Germany</td>
<td>245 ft.</td>
<td>1834</td>
</tr>
<tr>
<td>Brighton Chain Pier</td>
<td>England</td>
<td>255 ft.</td>
<td>1836</td>
</tr>
<tr>
<td>Montrose</td>
<td>Scotland</td>
<td>432 ft.</td>
<td>1838</td>
</tr>
<tr>
<td>Menai Straights</td>
<td>Wales</td>
<td>580 ft.</td>
<td>1839</td>
</tr>
<tr>
<td>Roche-Bernard</td>
<td>France</td>
<td>641 ft.</td>
<td>1852</td>
</tr>
<tr>
<td>Wheeling</td>
<td>U.S.A.</td>
<td>1010 ft.</td>
<td>1854</td>
</tr>
<tr>
<td>Niagara-Lewiston</td>
<td>U.S.A.</td>
<td>1041 ft.</td>
<td>1864</td>
</tr>
<tr>
<td>Niagara-Clifton</td>
<td>U.S.A.</td>
<td>1260 ft.</td>
<td>1889</td>
</tr>
<tr>
<td>Tacoma Narrows</td>
<td>U.S.A.</td>
<td>2800 ft.</td>
<td>1940</td>
</tr>
</tbody>
</table>
Chair Pier at Brighton
# Modern Bridges Active in the Wind

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Built</th>
<th>Span (ft.)</th>
<th>Stiffened</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fyksesund (Norway)</td>
<td>1937</td>
<td>750</td>
<td>Rolled I-beam</td>
</tr>
<tr>
<td>Golden Gate</td>
<td>1937</td>
<td>4200</td>
<td>Truss</td>
</tr>
<tr>
<td>Thousand Islands</td>
<td>1938</td>
<td>800</td>
<td>Plate Girder</td>
</tr>
<tr>
<td>Deer Isle</td>
<td>1939</td>
<td>1080</td>
<td>Plate Girder</td>
</tr>
<tr>
<td>Bronx-Whitestone</td>
<td>1939</td>
<td>2300</td>
<td>Plate Grider</td>
</tr>
</tbody>
</table>
Tacoma Narrows
Tacoma Narrows

Tie down cables.
Events: Before Bridge Was Finished

Static Model
To check the erection sequence.

Dynamic Model
“Unprecedented motion” of the Bronx-Whitestone bridge.

Wind Tunnel Tests
Events

June 1, 1940
Center ties installed.
Diagonal cables from the span to the main suspending cables.

June 28, 1940
Hydraulic damping.
Shock absorbers - destroyed by sandblasting the steel.

July 1, 1940
Bridge opened.

October 4, 1940
Side span hold-down cables.

November 7, 1940
Maximum wind = 42 mph (68 Km/hr).
Several hours of typical vertical motion.
Suddenly, violent TORSION.
• 10 minutes - damage
• 50 minutes - collapse.
Symmetric Modes
Asymmetric Modes
Eyewitness’ Account

"A series of observations and photographs taken just before 10:00 AM showed the bridge to be moving with the usual vertical motion...

Observations of the wind at this time showed 42 mph...

a few minutes later a violent change in motion was noted. This change appeared to take place without any intermediate stages and with such extreme violence that the span appeared to roll completely over.

not more than 8 or 10 minutes after the start of this violent motion, a considerable amount of damage had been done to the concrete sidewalks and curbs and several of the lamp posts in the vicinity of the Tacoma towers were already off their bases.

A car was stalled some little distance beyond the quarter point toward the center of the bridge. An effort was made during a momentary decrease in the violence of the motion to drive this car to safety; but shortly after reaching the car, the violence increased to a point where the acceleration must have reached that of gravity, since the car began to shift around in a most alarming manner. While out on this position of the span, opportunity was taken to examine the state of the bridge...the double amplitude of approximately 28 feet was causing no distress in the girder.

It now became necessary to return to the toll house for a fresh supply of film and there ensued a gap of some ten or twelve minutes in the observations.

the frequency had changed to 12 [cpm = 0.2 Hz]...

failure occurred so rapidly that observation become difficult and impression and fact are somewhat mixed.”
“Somewhat irregular torsion in main span after about 30 minutes of catastrophic motion.”
Static Model
Dynamic Model

\[ \frac{\text{Length(bridge)}}{\text{Length(model)}} = 100 \]

Model > 50 feet (15 m) long!

The motion was driven by electromagnets.

Used to measure:
- the damping of different models
- effects of cables, shock absorbers
<table>
<thead>
<tr>
<th>Property</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>( \frac{L \text{ (bridge)}}{L \text{ (model)}} = n )</td>
</tr>
<tr>
<td>Area</td>
<td>( \frac{A \text{ (bridge)}}{A \text{ (model)}} = n^2 )</td>
</tr>
<tr>
<td>Volume</td>
<td>( \frac{V \text{ (bridge)}}{V \text{ (model)}} = n^3 )</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>( \frac{I \text{ (bridge)}}{I \text{ (model)}} = n^4 )</td>
</tr>
<tr>
<td>Acceleration</td>
<td>( \frac{a \text{ (bridge)}}{a \text{ (model)}} = 1 )</td>
</tr>
<tr>
<td>Time</td>
<td>( \frac{t \text{ (bridge)}}{t \text{ (model)}} = n^{1/2} )</td>
</tr>
<tr>
<td>Velocity</td>
<td>( \frac{v \text{ (bridge)}}{v \text{ (model)}} = n^{1/2} )</td>
</tr>
<tr>
<td>Frequency</td>
<td>( \frac{f \text{ (bridge)}}{f \text{ (model)}} = n^{-1/2} )</td>
</tr>
<tr>
<td>Density</td>
<td>( \frac{\rho \text{ (bridge)}}{\rho \text{ (model)}} = 1 )</td>
</tr>
<tr>
<td>Mass</td>
<td>( \frac{m \text{ (bridge)}}{m \text{ (model)}} = n^3 )</td>
</tr>
<tr>
<td>Weight</td>
<td>( \frac{W \text{ (bridge)}}{W \text{ (model)}} = n^3 )</td>
</tr>
<tr>
<td>Force</td>
<td>( \frac{F \text{ (bridge)}}{F \text{ (model)}} = n^3 )</td>
</tr>
</tbody>
</table>
Wind Tunnel: Cross Sections

University of Washington, Seattle.

F. B. Farquharson et al.
Wind Tunnel: Cross Sections

California Institute of Technology.

T. von Karman and L. G. Dunn.
Wind Tunnel
University of Washington, Seattle.
Wind Tunnel
University of Washington, Seattle.
Full Model Wind Tunnel

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

\[
\frac{\text{Length(bridge)}}{\text{Length(model)}} = 50 \quad \text{Model > 100 feet (30 m) long!}
\]
Full Model Wind Tunnel
Full Model Wind Tunnel

Wind = 2.6 mph (4 km/hr): 2nd asymmetric vertical mode.
"when the section is rotated, the vortex pattern is distorted, as also indicated in Figure 7, and the vortex remaining nearest to the deck creates a high suction tending to further twist the deck"
Positive Feedback

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

Static Wind Tunnel Tests

unstable

unstable
Positive Feedback

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

Static Wind Tunnel Tests

unstable

unstable
Positive Feedback

California Institute of Technology.

T. Von Karman and L. G. Dunn. 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part ?.

Dynamic Wind Tunnel Tests
Positive Feedback

R. H. Scanlan and J. J. Tomko.


Wind Tunnel Tests 1970’s

Old Tacoma Narrows Bridge
Positive Feedback

R. H. Scanlan and J. J. Tomko.


Wind Tunnel Tests 1970’s

Airfoil, OTN = Old Tacoma Narrows Bridge
Calculated vs. Measured Symmetric Modes
Calculated vs. Measured
Asymmetric Modes
Full Model Wind Tunnel

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.
Full Model Wind Tunnel

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950  Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

\[
\frac{\text{Length (bridge)}}{\text{Length (model)}} = 50 \quad \frac{\text{Velocity (bridge)}}{\text{Velocity (model)}} = 50^{1/2} \quad \frac{\text{Frequency (bridge)}}{\text{Frequency (model)}} = 50^{-1/2}
\]

The torsional mode (1-NT) first appears at 7 mph and becomes catastrophic at 14 - 24 mph (<< 42 mph).

The frequency of this mode:

Model: 1.44 Hz

Corresponds to Computed Bridge: 12.2 cycles/minute.

Actual Bridge Measured: 12.0 cycles/minute
Vortices
Shed Vortices
Vortex Street
NOT Driven by Vortices

\[ f = \frac{SV}{D} \]

Tacoma Narrow Bridge: \( S = 0.11, V = 42 \text{ mph}, D = 8 \text{ ft.} \)

**Strouhal Frequency** \( f = 1.0 \text{ Hz.} \)

**Bridge Motion Frequency** = 0.2 Hz

The alternative shed vortices did NOT drive the motion of the bridge.

The motion of the bridge controlled the release of the vortices.
Model at Rest

California Institute of Technology.

T. Von Karman and L. G. Dunn 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.
Model in Motion

California Institute of Technology.

T. Von Karman and L. G. Dunn  1950  Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

The Bridge controlled the vortices!
"The experimental results described in a previous report indicated rather definitely that the motions were the result of vortex shedding. Resonance between the frequency of vortex shedding and one of the natural frequencies of the bridge were often suggested as the reason for the vertical oscillations. However, this hypothesis does not explain the fact that the self-excited oscillations exist over rather wide ranges of velocities. It has been found that in general the vortex frequency produced by a blunt obstacle in the wind stream is proportional to the wind velocity...While the structure is at rest the vortex frequency is controlled by the wind...Beyond the critical wind velocities the oscillating structure and not the wind velocity controls the vortex frequency."
"Did the vortices cause the motion or the motion cause the vortices? In this case (flutter) it was the latter...The final destructive oscillation of the old Tacoma Narrows bridge produced a flutter wake, not a Karman vortex sheet...The action which brought the bridge down, occurred in a fundamentally antisymmetric torsion mode...basically a single-degree-driven unstable oscillation with effective negative damping representing an inflow of wind energy cause by the synchrony of motion-induced pressures with the motion itself."
"Could this be called a resonance phenomena? [It could] if we now identify the source of the periodic impulses as self-induced, the wind supplying the power, and the motion supplying the power-trapping mechanism. If one wishes to argue, however, that it was a case of externally forced linear resonance, the mathematical distinction between Eqs. (1) and (3) is quite clear, self-excited systems differing strongly enough from ordinary linear resonant ones. The [elementary physics] texts we have consulted have not gone this far in explanation."

\textbf{Externally forced resonance:}
\[
\ddot{x} + A \dot{x} + Bx = f(t) \quad \text{non-autonomous} \quad \text{Eq. (1)}
\]

\textbf{Self-excitation (Tacoma Narrow bridge):}
\[
\ddot{x} + A \dot{x} + Bx = f(x, \dot{x}) \quad \text{autonomous} \quad \text{Eq. (3)}
\]
The New Tacoma Narrows Bridge

Look at that Truss!
Fixing the Problem

**Restrict the motion of the bridge.**

- **Stiffen the span with a truss.**
  Bronx-Whitestone bridge in New York City

- **Damp the oscillations with shock absorbers.**
  Commodore Barry bridge, Chester, Pennsylvania.

  Not good: Basically, letting the energy from the wind into the bridge, then trying to contain it.

**Prevent the wind from giving its energy to the bridge.**

- **Streamlining to reduce vortex formation.**
  Long's Creek bridge, Severn bridge, U.K.

- **Open span, wind flows through, to reduce vortex.**
  Forth Road bridge, U.K.

For Physicists

Cell

$10^{14}$ ≈ human

Ion Channel

$10^{-21}$ kg

$10^{-8}$ m

$10^{-5}$ m

$10^{-12}$ kg

Cell membrane lipids (fats)

Proteins
Patch Clamp

- micropipette
- ion channel
- cell membrane
- cell
- electrode
- ammeter
- current
- open
- closed
- time
- current
  - 5 pA
  - 0 pA
- 0 ms
- 100 ms
Ion channels are like small molecules, relentlessly kicked by the surrounding heat from one state to another.

The change of states is driven by chance $kT$ thermal fluctuations.

Usual Picture

Ion channels are little mechanical machines with sticks and springs.

The change of states is driven by coherent motions that result from the structure and the atomic, electrostatic, and hydrophobic forces in the channel protein.

Alternative Picture
Ion Channels

If a simple mechanical structure, such as a bridge, can have such surprising dynamical behavior and such a strong interaction with its environment, what can we expect of the dynamics of a much more complex ion channel protein, with intertwined structural and functional elements developed through a billion years of evolution?
Failure or Success?

"...the Tacoma Narrows bridge failure has given us invaluable information...It has shown [that] every new structure which projects into new fields of magnitude involves new problems for the solution of which neither theory nor practical experience furnish an adequate guide. It is then that we must rely largely on judgment and if, as a result, errors or failures occur, we must accept them as a price of human progress"

- Othmar Ammann

"No one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art. Contrary to their popular characterization as intellectual conservatives, engineers are really among the avant-garde. They are constantly seeking to employ new concepts to reduce the weight and thus the cost of their structures...The engineer always believes that he is trying something without error, but the truth of the matter is that each new structure can be a new trial...Such is the nature not only of science and engineering, but of all human endeavors."

- Henry Petroski

H. Petroski, To Engineer Is Human, Vintage Books, 1992
Aerodynamic Stability of Suspension Bridges
with special reference to
The Tacoma Narrows Bridge
A Report of an Investigation conducted by The Structural Research Laboratory, University of Washington under the direction of The Washington Toll Bridge Authority in cooperation with The Public Roads Administration, Federal Works Agency, University of Washington Engineering Experiment Station Bulletin No. 116, Parts I, II, and III.
