13.42 Lecture: Vortex Induced Vibrations

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Offshore Platforms
Fixed Rigs

Tension Leg Platforms

Spar Platforms
If neglected in design, vortex induced vibrations can prove catastrophic to structures, as they did in the case of the Tacoma Narrows Bridge in 1940.
In another city, the John Hancock tower wouldn't be anything special – just another reflective glass box in the crowd. But because of the way Boston and the rest of New England has grown up architecturally, this “70’s modern” building stands out from the rest. Instead of being colonial, it breaks new ground. Instead of being quaint, it soars and imposes itself on the skyline. And instead of being white like so many buildings in the region, this one defies the local conventional wisdom and goes for black. For these reasons and more the people of Boston have fallen in love with the 790-foot monster looming as the tallest building in New England at the time of its completion. In the mid-1990's, The Boston Globe polled local architects who rated it the city's third best architectural structure. Much like Boston's well-loved baseball team, the building has had a rough past, but still perseveres, coming back stronger to win the hearts of its fans. The trouble began early on. During construction of the foundation the sides of the pit collapsed, nearly sucking Trinity Church into the hole. Then in late January, 1973 construction was still underway when a winter storm rolled into town and a 500-pound window leapt from the tower and smashed itself to bits on the ground below. Another followed. Then another. Within a few weeks, more than 65 of the building's 10,344 panes of glass committed suicide, their crystalline essence piling up in a roped-off area surrounding the building. The people of Bean Town have always been willing to kick a brother when he's down, and started calling the tower the Plywood Palace because of the black-painted pieces of wood covering more than an acre of its facade. Some people thought the building was swaying too much in the wind, and causing the windows to pop out. Some thought the foundation had shifted and it was putting stress of the structural geometry. It turns out the culprit was nothing more than the lead solder running along the window frame. It was too stiff to deal with the kind of vibrations that happen every day in thousands of office buildings around the world. So when John Hancock Tower swayed with the wind, or sighed with the temperature, the windows didn't and eventually cracked and plummeted to Earth. It cost $7,000,000.00 to replace all of those panes of glass. The good news is, you can own a genuine piece of the skyscraper. According to the Globe, the undamaged sheets were sold off for use as tabletops, so start combing those garage sales. For any other skyscraper, the hardship would end there. But the Hancock building continued to suffer indignities. The last, and most ominous, was revealed by Bruno Thurlimann, a Swiss engineer who determined that the building's natural sway period was dangerously close to the period of its torsion. The result was that instead of swaying back-and-forth like a metronome, it bent in the middle, like a cobra. The solution was putting a pair of 300-ton tuned mass dampeners on the 58-th floor. The same engineer also determined that while the $3,000,000.00 mass dampeners would keep the building from twisting itself apart, the force of the wind could still knock it over. So 1,500 tons of steel braces were used to stiffen the tower and the Hancock building's final architectural indignity was surmounted.


Classical Vortex Shedding

Alternately shed opposite signed vortices
Potential Flow

\[ U(\theta) = 2U_\infty \sin \theta \]

\[ P(\theta) = \frac{1}{2} \rho U(\theta)^2 = P_\infty + \frac{1}{2} \rho U_\infty^2 \]

\[ C_p = \frac{P(\theta) - P_\infty}{\frac{1}{2} \rho U_\infty^2} = 1 - 4 \sin^2 \theta \]

Axial Pressure Force

i) Potential flow:
\[-\pi/w < \theta < \pi/2\]

ii) \( P \sim P_B \)
\[ \pi/2 \leq \theta \leq 3\pi/2 \]
(for LAMINAR flow)

\[ F_{axial} = \int P(\theta) R \, d\theta \cos \theta \]
Wake Instability

Shear layer instability causes vortex roll-up

- Flow speed outside wake is much higher than inside
- Vorticity gathers at downcrossing points in upper layer
- Vorticity gathers at upcrossings in lower layer
- Induced velocities (due to vortices) causes this perturbation to amplify
Reynolds Number Dependency

\[ R_d < 5 \]
\[ 5 - 15 < R_d < 40 \]
\[ 40 < R_d < 150 \]
\[ 150 < R_d < 300 \]
\[ 300 < R_d < 3 \times 10^5 \]
\[ 3 \times 10^5 < R_d < 3.5 \times 10^6 \]
\[ 3.5 \times 10^6 < R_d \]

Transition to turbulence

Vortex shedding dictated by the Strouhal number

\[ S_t = f_s d/U \]

\( f_s \) is the shedding frequency, \( d \) is diameter and \( U \) inflow speed
Additional VIV Parameters

- **Reynolds Number**
  \[
  \text{Re} = \frac{UD}{v} \approx \frac{\text{inertial effects}}{\text{viscous effects}}
  \]
  - subcritical (Re<10^5) (laminar boundary)

- **Reduced Velocity**
  \[
  V_{rn} = \frac{U}{f_n D}
  \]

- **Vortex Shedding Frequency**
  \[
  f_s = \frac{SU}{D}
  \]
  - S=0.2 for subcritical flow

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**Strouhal Number vs. Reynolds Number**

Fig. 3-3 Stouhal number–Reynolds number relationship for circular cylinders
(Lienhard, 1966; Achenbach and Heinecke, 1981). S = 0.21 (1-21/Re) for 40 < Re < 200
(Roshko, 1955).
Vortex Shedding Generates forces on Cylinder

Both Lift and Drag forces persist on a cylinder in cross flow. Lift is perpendicular to the inflow velocity and drag is parallel.

Due to the alternating vortex wake ("Karman street") the oscillations in lift force occur at the vortex shedding frequency and oscillations in drag force occur at twice the vortex shedding frequency.

Vortex Induced Forces

Due to unsteady flow, forces, X(t) and Y(t), vary with time.

Force coefficients:

\[ C_x = \frac{D(t)}{\frac{1}{2} \rho U^2 d} \quad C_y = \frac{L(t)}{\frac{1}{2} \rho U^2 d} \]
Alternate Vortex shedding causes oscillatory forces which induce structural vibrations.

Rigid cylinder is now similar to a spring-mass system with a harmonic forcing term.

\[ z(t) = z_0 \cos \omega t \]
\[ \dot{z}(t) = -z_0 \omega \sin \omega t \]
\[ \ddot{z}(t) = -z_0 \omega^2 \cos \omega t \]

LIFT = \( L(t) = L_0 \cos (\omega_s t + \psi) \)

DRAG = \( D(t) = D_0 \cos (2\omega_s t + \psi) \)

\[ \omega_s = 2\pi f_s \]
“Lock-in”

A cylinder is said to be “locked in” when the frequency of oscillation is equal to the frequency of vortex shedding. In this region the largest amplitude oscillations occur:

\[ \omega_v = 2\pi f_v = 2\pi S_t (U/d) \]

Shedding frequency

\[ \omega_n = \sqrt{\frac{k}{m + m_a}} \]
Natural frequency of oscillation

Equation of Cylinder Heave due to Vortex shedding

\[ m\ddot{z} + b\dot{z} + kz = L(t) \]

\[ L(t) = -L_a \ddot{z}(t) + L_v \dot{z}(t) \]

\[ m\ddot{z}(t) + b\dot{z}(t) + kz(t) = -L_a \ddot{z}(t) + L_v \dot{z}(t) \]

\[ (m + L_a)\ddot{z}(t) + (b - L_v)\dot{z}(t) + kz(t) = 0 \]

Added mass term

Restoring force

Damping

If \( L_v > b \) system is UNSTABLE
Lift Force on a Cylinder

Lift force is sinusoidal component and residual force. Filtering the recorded lift data will give the sinusoidal term which can be subtracted from the total force.

**LIFT FORCE:** \( L(t) = L_o \cos(\omega t + \psi_o) \) \( \text{if } \omega < \omega_v \)

\[
L(t) = L_o \cos \omega t \cos \psi_o - L_o \sin \omega t \sin \psi_o
\]

\[
L(t) = -\frac{L_o \cos \psi_o}{z_o \omega} \ddot{z}(t) + \frac{L_o \sin \psi_o}{z_o \omega} \dot{z}(t)
\]

where \( \omega_v \) is the frequency of vortex shedding.

**Lift Force Components:**

Two components of lift can be analyzed:

Lift in phase with acceleration (added mass):

\[
M_a(\omega, a) = \frac{L_o}{a \omega^3} \cos \psi_o
\]

Lift in-phase with velocity:

\[
L_v = -\frac{L_o \sin \psi_o}{a \omega}
\]

Total lift:

\[
L(t) = -M_a(\omega, a) \ddot{z}(t) + L_v(\omega, a) \dot{z}(t)
\]

\( (a = z_o \) is cylinder heave amplitude)
Total Force:

\[ L(t) = -M_a(\omega, a)\ddot{z}(t) + L_v(\omega, a)\dot{z}(t) \]
\[ = -\left(\frac{\pi}{4}\rho d^2\right)C_{ma}(\omega, a)\dot{z}(t) \]
\[ + \left(\frac{\sqrt{2}}{2}\rho dU^2\right)C_{Lv}(\omega, a)\dot{z}(t) \]

- If \( C_{Lv} > 0 \) then the fluid force amplifies the motion instead of opposing it. This is self-excited oscillation.
- \( C_{ma}, C_{Lv} \) are dependent on \( \omega \) and \( a \).

Coefficient of Lift in Phase with Velocity

\[ Cl_v = L_v/\left(1/2 \rho U^2 d\right) \]

Vortex Induced Vibrations are

SELF LIMITED

In air: \( \rho_{\text{air}} \sim \text{small}, \ z_{\text{max}} \sim 0.2 \text{ diameter} \)

In water: \( \rho_{\text{water}} \sim \text{large}, \ z_{\text{max}} \sim 1 \text{ diameter} \)
Lift in phase with velocity

\[ C_{Lv} \]

\[ d/a = 0.3 \]

Gopalkrishnan (1993)

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Amplitude Estimation

Blevins (1990)

\[
\frac{a}{d} \approx \frac{1.29}{[1 + 0.43 S_G]^{3.35}}
\]

\[
S_G = 2\pi \frac{\hat{f}_n}{f_n^2} \frac{2\bar{m} (2\pi \zeta)}{\rho d^2}
\]

\[
\hat{f}_n = \frac{f_n}{f_s}; \quad \bar{m} = m + m_a^*
\]

\[
\zeta = \frac{b}{2\sqrt{k(m+m_a^*)}}
\]

\[
m_a^* = \rho \bar{C}_{ma}; \quad \text{where } C_{ma} = 1.0
\]
Drag Amplification

VIV tends to increase the effective drag coefficient. This increase has been investigated experimentally.

\[ C_d = 1.2 + 1.1 \left( \frac{a}{d} \right) \]

Gopalkrishnan (1993)

\[ \frac{a}{d} = 0.75 \]

Mean drag:  
Fluctuating Drag:

\[ \overline{C_d} \]

\[ \sim \]

\[ C_d \text{ occurs at twice the shedding frequency.} \]

Single Rigid Cylinder Results

- a) One-tenth highest transverse oscillation amplitude ratio
- b) Mean drag coefficient
- c) Fluctuating drag coefficient
- d) Ratio of transverse oscillation frequency to natural frequency of cylinder
Flexible Cylinders

Mooring lines and towing cables act in similar fashion to rigid cylinders except that their motion is not spanwise uniform.

\[ m \frac{d^2 y}{dt^2} = T_{(s)} \frac{d^2 y}{dt^2} + L_{(s,t)} \]

Tension in the cable must be considered when determining equations of motion.

Flexible Cylinder Motion Trajectories

Long flexible cylinders can move in two directions and tend to trace a figure-8 motion. The motion is dictated by the tension in the cable and the speed of towing.
Wake Patterns Behind Heaving Cylinders

- Shedding patterns in the wake of oscillating cylinders are distinct and exist for a certain range of heave frequencies and amplitudes.
- The different modes have a great impact on structural loading.

Transition in Shedding Patterns

[Graph showing transition in shedding patterns with parameters A/d and Vr = U/fd, f* = fd/U]
Formation of ‘2P’ shedding pattern

End Force Correlation

Hover, Tcheta, Triantafyllou (JFM 1998)
VIV in the Ocean

- Non-uniform currents effect the spanwise vortex shedding on a cable or riser.
- The frequency of shedding can be different along length.
- This leads to “cells” of vortex shedding with some length, $l_c$.

Three Dimensional Effects

Shear layer instabilities as well as longitudinal (braid) vortices lead to transition from laminar to turbulent flow in cylinder wakes.

Longitudinal vortices appear at $Re = 230$. 
The presence of longitudinal vortices leads to rapid breakdown of the wake behind a cylinder.

C.H.K. Williamson (1992)
Oscillating Tapered Cylinder

Strouhal Number for the tapered cylinder:

\[ S_t = \frac{f\bar{d}}{U} \]

where \( \bar{d} \) is the average cylinder diameter.

Spanwise Vortex Shedding from 40:1 Tapered Cylinder

\( R_d = 400; \quad St = 0.198; \quad A/d = 0.5 \)

\( R_d = 1500; \quad St = 0.198; \quad A/d = 0.5 \)

\( R_d = 1500; \quad St = 0.198; \quad A/d = 1.0 \)

Flow Visualization Reveals:  
*A Hybrid Shedding Mode*

- ‘2P’ pattern results at the smaller end  
- ‘2S’ pattern at the larger end  
- This mode is seen to be repeatable over multiple cycles


DPIV of Tapered Cylinder Wake

Digital particle image velocimetry (DPIV) in the horizontal plane leads to a clear picture of two distinct shedding modes along the cylinder.

\[ \text{Rd} = 1500; \, \text{St} = 0.198; \, A/d = 0.5 \]
Evolution of the Hybrid Shedding Mode

‘2P’
$z/d = 7.9$

‘2S’
$z/d = 22.9$

$Rd = 1500; St = 0.198; A/d = 0.5$

Evolution of the Hybrid Shedding Mode

‘2P’
$z/d = 7.9$

‘2S’
$z/d = 22.9$

$Rd = 1500; St = 0.198; A/d = 0.5$
Evolution of the Hybrid Shedding Mode

\[ \begin{align*}
Rd &= 1500; \quad St = 0.198; \quad A/d = 0.5 \\
z/d &= 7.9 \quad (\text{‘}2P\text{’}) \quad z/d = 22.9 \quad (\text{‘}2S\text{’})
\end{align*} \]
Objectives:
• Confirm numerically the existence of a stable, periodic hybrid shedding mode 2S–2P in the wake of a straight, rigid, oscillating cylinder

Approach:
• DNS - Similar conditions as the MIT experiment (Triantafyllou et al.)
• Harmonically forced oscillating straight rigid cylinder in linear shear inflow
• Average Reynolds number is 400

Methodology:
• Parallel simulations using spectral/hp methods implemented in the incompressible Navier-Stokes solver NEKTAR

Principal Investigator:
• Prof. George Em Karniadakis, Division of Applied Mathematics, Brown University

Results:
• Existence and periodicity of hybrid mode confirmed by near wake visualizations and spectral analysis of flow velocity in the cylinder wake and of hydrodynamic forces

VIV Suppression
• Helical strake
• Shroud
• Axial slats
• Streamlined fairing
• Splitter plate
• Ribbed cable
• Pivoted guiding vane
• Spoiler plates
VIV Suppression by Helical Strakes

Helical strakes are a common VIV suppression device.

Galloping

Galloping is a result of a wake instability.

Resultant velocity is a combination of the heave velocity and horizontal inflow.

If $\omega_n << 2\pi f_v$ then the wake is quasi-static.
Lift Force, $Y(\alpha)$

\[ C_y = \frac{Y(t)}{\frac{1}{2} \rho U^2 A_p} \]

Galloping motion

\[ m\ddot{z} + b\dot{z} + kz = L(t) \]

\[ L(t) = \frac{1}{2} \rho U^2 a C_{1v} - m_y y(t) \]

\[ C_1(\alpha) = C_1(0) + \frac{\partial C_1(0)}{\partial \alpha} + \ldots \]

Assuming small angles, $\alpha$:

\[ \alpha \sim \tan \alpha = -\frac{\dot{z}}{U} \]

\[ \beta = \frac{\partial C_1(0)}{\partial \alpha} \quad V \sim U \]
Instability Criterion

$$(m+m_a)\ddot{z} + (b + \frac{1}{2} \rho U^2 a \frac{\beta}{U})\dot{z} + kz = 0$$

If $b + \frac{1}{2} \rho U^2 a \frac{\beta}{U} < 0$

Then the motion is unstable!
This is the criterion for galloping.

β is shape dependent

<table>
<thead>
<tr>
<th>Shape</th>
<th>$\frac{\partial C_1}{\partial \alpha} \mid (0)$</th>
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<tbody>
<tr>
<td>1</td>
<td>-2.7</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-0.66</td>
</tr>
<tr>
<td>4</td>
<td>-10</td>
</tr>
</tbody>
</table>
Instability:

\[ \beta = \frac{\partial C_l}{\partial \alpha} (0) < \frac{-b}{1/2 \rho U a} \]

Critical speed for galloping:

\[ U > \frac{b}{1/2 \rho a \left( -\frac{\partial C_l}{\partial \alpha} (0) \right)} \]

Torsional Galloping

Both torsional and lateral galloping are possible. FLUTTER occurs when the frequency of the torsional and lateral vibrations are very close.
Galloping vs. VIV

- Galloping is low frequency
- Galloping is NOT self-limiting
- Once $U > U_{\text{critical}}$ then the instability occurs irregardless of frequencies.

References