Flow control
From quiet airplanes to robotic fish

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Overview

• What is flow control?
  • What is a fluid?
  • What is control?

• Quieter airplanes
  • Controlling sound waves

• Robotic fish
  • Controlling underwater vehicles

• Engineering in elementary school?
  • Princeton Engineering Education for Kids (PEEK) and LEGO engineering
What is flow control?

- What is a fluid?
  - A liquid or a gas
  - Water and air are both fluids
  - Fluid mechanics is the study of how fluids behave

- What is control?
  - Using sensors and actuators to alter the behavior of a system

- What is flow control?
  - Using sensors and actuators to change how a fluid behaves
Control: examples

• Example 1: cruise control on a car

Sensing + computation + actuation = Feedback

Actuate
Gas pedal

Sense
Speedometer

Compute
Control action
Control: early examples

• Watt governor (1788)
  • Regulate speed of steam engine
  • Reduce effects of variations in load

Balls fly out as speed increases, closing valve
Main idea of feedback

• Concept 1:
  • Feedback can reduce the effect of external disturbances
  • Cruise control: uphill, downhill
  • Steam engine: load on engine, temperature of boiler producing steam

```
Disturbances

Actuate
Gas pedal

S Sense
Speedometer

Compute
Control action
```

Other examples

• Balancing a stick

• Concept 2: Feedback can stabilize an unstable system

Actuate
Move hand

stick

hand

Sense
Eye/hand

Compute
Brain

Question: which is easier to balance, a short stick or a long stick?
Other examples

- Standing up

  All three components are critical: degrading any one hurts the system
Control: more examples

- **Aircraft** auto-pilot, auto-land
  - Commercial aircraft with auto-land are required to land on autopilot at least 1/3 of the time
  - **Sensors**: altitude, heading, airspeed, GPS
  - **Actuators**: engine throttle, ailerons, elevators, rudder

Boeing 777-200
From www.boeing.com
Controls course at Princeton

- MAE 433: Automatic control systems
- Princeton juniors

Pendulum (stick)  Ramp  Ball  Underpass
Cart
Cart
How do they do it?

• How do you design the controller?

  Actuate
  Gas pedal

  Sense
  Speedometer

• Need a mathematical description of how the system behaves: need a model
• Modeling concepts: state and dynamics
Modeling terminology

- **State**
  - Independent physical quantities that completely determine the future evolution (absent external excitation)

- **Inputs** describe external excitation
  - Inputs are extrinsic to the system (externally specified)

- **Dynamics** describes state evolution
  - Update rule for the system state
  - Function of current state and external inputs

- **Outputs** describe measured quantities
  - Outputs are functions of state and inputs -- not independent variables
  - Outputs are often a subset of state

**State:** position and velocities of each mass: \( q_1, q_2, \dot{q}_1, \dot{q}_2 \)

**Input:** position of spring at right end of chain: \( u \)

**Dynamics:** physics

**Output:** measured positions of the masses: \( q_1, q_2 \)
Modeling example

- Cart-pendulum
  - State:
    \[ x = (x, \theta, \dot{x}, \dot{\theta}) \]
  - Dynamics:
    \[
    \begin{bmatrix}
    \dot{x} \\
    \dot{\theta} \\
    \end{bmatrix} =
    \begin{bmatrix}
    \frac{-mg \sin \theta \cos \theta + ml \dot{\theta}^2 \sin \theta + F}{M + m (1 - \cos^2 \theta)} \\
    \frac{(M + m) g \sin \theta - ml \dot{\theta}^2 \sin \theta \cos \theta - F \cos \theta}{Ml + ml (1 - \cos^2 \theta)} \\
    \end{bmatrix}
    \]

4 differential equations for how the 4 states evolve
Control of fluids

• What is the state of a fluid?
  • Position/velocity of all fluid particles
  • Turns out only need to keep track of velocity since all fluid particles are the same
  • Infinite number of states!

• Dynamics for a fluid
  • Partial differential equations
  • Equivalent to an infinite number of ordinary differential equations
  • Usual tools for controls do not apply

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u}
\]

Conservation of momentum

\[
\nabla \cdot \mathbf{u} = 0
\]

Conservation of mass
Modeling of fluids

- **Key idea:**
  - We don’t necessarily care about the velocity of every single fluid particle.
  - Look for **patterns** (e.g. eddies, swirls), and make these patterns the new states. Write **dynamics** for how the patterns evolve.
  - **Reduce a huge problem** (millions of states) to a manageable one:

  Model reduction
Problem: reduce sound from a cavity

- **Motivation**: control of intense pressure fluctuations
  - Examples: car sunroof, aircraft landing gear, weapons bays

- **Previous strategies**
  - Passive (spoilers, etc): Effective at certain flow conditions
  - Can make things *worse* for other flow conditions

- **Low-order models**
  - Use numerical simulations to extract the patterns in the flow
Comparison of DNS with experiment

Schlieren photographs
(Karamchetti 1955)

Density gradients from DNS

M = 0.6  M = 0.7  M = 0.8
Movie: short cavity

Vorticity

Dilatation
Movie: long cavity

Vorticity

Dilatation
Proper Orthogonal Decomposition

- Given an ensemble of data $u(x, t)$, approximate by an expansion in basis functions $\varphi_k$:
  \[ \hat{u}(x, t) = \sum_{k=1}^{n} a_k(t) \varphi_k(x) \]

- **Goal:** Given $u(x, t)$, find **optimal** orthonormal functions $\varphi_k(x)$, called **POD modes**, which minimize the time average of $\|u - \hat{u}\|_2$, for fixed $n$.

- **Low order models** may be obtained via **Galerkin projection** onto the basis functions: given a PDE $\dot{u} = D(u)$, where $D$ is a spatial differential operator,
  \[ \dot{a}_k = \langle D(\hat{u}), \varphi_k \rangle, \quad k = 1, \ldots, n. \]
POD modes (patterns)

- Vector-valued modes
  - Energy-based inner product
    - Kinematic and thermodynamic variables (u,v,a)
    - Weight both kinetic energy and internal energy
  - Vorticity and dilatation shown
    - Shear layer structures
    - Acoustic waves
- Over 90% of energy captured in the first 2 modes
  - Very low-dimensional!

Mode 1 (47.15%)
Mode 2 (44.67%)
Mode 3 (3.50%)
Mode 4 (3.42%)
4-mode Galerkin model

- **Vorticity**
- **Dilatation**

- 410,112 gridpoints
- 1,640,448 states

4-mode model
Control model

Using this model, design a controller to reduce the sensitivity to disturbances (noise that gets amplified by the cavity flow)
It works!

- Experiment at US Air Force Academy
- Large subsonic wind tunnel
- 20 dB noise reduction
Other applications

- Airplanes
  - Quieter
  - More efficient
  - Less emissions

Use active control to achieve these goals

- Rotating stall
- Combustion instabilities
- Mixing of cooling air
- Jet noise

Pratt & Whitney PW-4000
Swimming fish

- **Problem**
  - Easy to build a fish
  - Hard to build a fish that goes where you want it to go

- **Fluid mechanics**
  - Unsteady separation
  - Standard lift/drag models for aircraft not applicable

- **Controls**
  - Don’t care about details, just care about the effect of the flow on the motion of the fish/vehicle

**Modeling**

- For a potential flow, problem becomes finite-dimensional (Kirchhoff models)
- Add point vortices/vortex sheet: include lift, drag in a finite-dimensional way

**Student:** Juan Melli-Huber
Fish turning

- How do reef fish turn around so quickly?
- Falling cat problem
  - If you drop a cat upside down, with zero angular momentum, it is able to right itself before it lands
  - Angular momentum remains exactly zero the whole time! (No external forces)
  - This phase shift is called geometric phase
Experiment

- Experiment to model fish swimming
Part 2: Engineering in Elementary School

with lots of help from
Chris Rogers, Tufts University
What is the ultimate teaching goal?

- Curiosity
- Enthusiasm for learning
- How to find answers
- Test validity of answers
- Self-confidence
Learning Styles

- Learn by memory: Learn by doing
- Ability to focus: Ability to combine experiences
- Sits quietly: Cannot sit still
- Self-confident: Feels “it is above me”
## Learning styles (cont’d)

<table>
<thead>
<tr>
<th>Cooperative</th>
<th>Competitive</th>
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</thead>
<tbody>
<tr>
<td>Detail oriented</td>
<td>Zero in on one thing</td>
</tr>
<tr>
<td>Like to work in groups</td>
<td>Like to work alone</td>
</tr>
<tr>
<td>Design then build</td>
<td>Build then design</td>
</tr>
<tr>
<td>Like investigating</td>
<td>Know it all</td>
</tr>
</tbody>
</table>

**Goal:** Teach both cooperation and competition
What we teach

- Graphing
- Numeracy
- Statistics
- Decimals
- Modeling
- Reading
- Writing
- Estimation
- Engineering
- Science
PEEK
Princeton Engineering Education for Kids

- Princeton undergraduates help out in classrooms
- Started by Jim McQuade (P’03)
- Two models
  - Undergraduates teach engineering concepts in classrooms, and facilitate engineering projects
  - Teachers teach concepts, undergraduates facilitate projects
Benefits of PEEK program

- Helps teachers overcome technical hurdles
- Undergraduates learn about elementary education
- Kids get early exposure to engineering, before stereotypes set in
- Everybody has fun!
Example projects

Tug of war

Learn:
Engineering
Torque
Center of gravity
Friction
Teamwork
Stop-action movie

Harry Potter movie

Learn:
Reading
Writing
Engineering
Creativity
Acting!
The End

Thank you!