# Aerodynamic Analysis of Tandem Square Cylinders

## A Physics-Informed XGBoost Regression Approach

Multidisciplinary Project Team

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# Introduction: The Square Cylinder Challenge

- **Configuration:** Two square cylinders in a tandem arrangement (upstream and downstream).
- **Geometric Difference:** Unlike circular cylinders, square shapes have **sharp corners**.
- **Aerodynamic Impact:**
  - Separation points are fixed at the corners.
  - No "Drag Crisis" at high Reynolds numbers.
  - Higher base pressure and wake-induced vibration (Galloping).
- **Objective:** Predict $C_{D1}$, $C_{D2}$, and $St$ using high-performance Gradient Boosting.

# Governing Parameters & Variables

Square shapes introduce specific interference regimes:

**Input Features:**

- $Re$: Reynolds Number ($UD/\nu$).
- $L/D$: Center-to-center Pitch Ratio.
- $\alpha$: Angle of Attack (fixed at $0^\circ$).

**Target Coefficients:**

- $C_{D1}$: Upstream Drag.
- $C_{D2}$: Downstream Drag.
- $St$: Strouhal Number (Shedding Frequency).

*Typical subcritical $C_D$ for a single square is $\approx 2.1$, significantly higher than circular sections ($\approx 1.2$).*

# The XGBoost Model Selection

Why use **Extreme Gradient Boosting (XGBoost)**?

- **Newton Boosting:** Uses second-order Taylor expansion to approximate the loss function, leading to faster convergence.
- **Regularization:** Includes $L1$ and $L2$ regularization to prevent overfitting on noisy experimental data.
- **Sparsity Awareness:** Efficiently handles missing data points often found in hydrodynamic literature.
- **Parallelism:** Highly optimized for large datasets (e.g., the 8,000-point database).

# The 10-Step Workflow for Square Cylinders

The project follows a "Physics-Informed" pipeline:

1. **Data Collection:** Collecting $C_D$ data from square bluff-body studies.
2. **Selection:** Filtering for "sharp" vs "rounded" corner effects.
3. **Correction:** Correcting for square-specific blockage in tunnels.
4. **Supplement:** Using LES simulations for gap flow validation.
5. **XGBoost Training:** Hyperparameter tuning (Learning Rate, Depth).
6. **Model Validation:** Checking for physical consistency.
7. **New Trends:** Mapping $C_D$ vs Spacing for square shapes.
8. **Improvement:** Median filtering for frequency stability.
9. **Database Generation:** Final engineering lookup tool.

# Data Selection & Preprocessing

- **Corner Sharpness:** $C_D$ can drop by $50\%$ if corners are slightly rounded. Data is strictly filtered for sharp-edged cases.
- **Blockage Correction:** Square sections generate larger wakes; correction is mandatory:

$$C_{D,corr} = C_{D,obs} \cdot (1 - \epsilon\beta)$$

- **Normalization:** Reynolds numbers are log-transformed ($\log_{10} Re$) to help XGBoost partition the feature space more effectively across orders of magnitude ($10^3$ to $10^6$).

# XGBoost Tuning & Training

Model performance is maximized using 5-fold cross-validation:

- **n_estimators:** 30–50 (Optimal balance of accuracy/speed).
- **max_depth:** 4 (Ensures global trends are captured without local overfitting).
- **learning_rate ($\eta$):** 0.1 (Stable gradient descent).

| **Target** | $R^2$ | $E_{mae}$ | $E_{rmse}$ |
|---|---|---|---|
| $C_{D1}$ | 0.96 | 0.044 | 0.066 |
| $St$ | 0.93 | 0.009 | 0.013 |

# Physical Analysis: Spacing Effects

The XGBoost model captures the three critical regimes for square shapes:

- **Regime I ($L/D < 2.5$):** Extended-body regime. The gap is small; no vortex shedding occurs from the upstream cylinder. $C_{D2}$ is negative (suction).
- **Regime II ($2.5 < L/D < 4$):** Reattachment regime. Shear layers from the upstream cylinder reattach to the downstream one.
- **Regime III ($L/D > 4$):** Co-shedding regime. Both cylinders shed independent vortices. $C_{D1}$ increases sharply due to gap flow destabilization.

# Step 9: Improving XGBoost Stability

Despite high accuracy, "Raw" XGBoost can produce non-physical noise:

- **The Issue:** Small discrepancies in experimental data cause "staircase" effects in the regression surface.
- **The Solution: Median Filtering** (Window size 5).
- **Bi-stable Branching:** For $St$, the model is trained on two separate groups ($St_{up}$ and $St_{low}$) to handle the frequency jump at the critical spacing ratio.

# Project Conclusion

- **Success:** Developed a robust aerodynamic database for tandem square cylinders using XGBoost.
- **Innovation:** Replaced standard "black-box" ML with a physics-informed approach that respects geometric constraints.
- **Finding:** Square cylinders exhibit much stronger interference effects and higher shielding sensitivity than circular cylinders.
- **Impact:** Provides structural engineers with a predictive tool for wind-load assessment on square-section high-rises and piers.