The Hydroelastic Response of a Flexible Surface Piercing Hydrofoil in Multiphase Flow

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Example: Ventilated Surface-Piercing Hydrofoil (INSEAN)

\[ \alpha = 15^\circ, \ U = 3.3 \ m/s \ (Fn_h = 2.5), \ AR_h = h/c = 1 \]
Importance of Studying Hydroelasticity

- Natural ventilation is the entrainment of air into low-pressure regions of flow – often in the vicinity of lifting-surfaces.

- Many high-lift devices operate in a surface-piercing configuration
  - Hydrofoils and struts
  - Surface-piercing propellers

- Other lifting systems operate near the free surface and can unintentionally ventilate
  - Waterjet impellers
  - Shallow-depth propellers, hydrofoils, control surfaces

- Marine systems with non-metallic construction are increasingly common
  - Large elastic deformations possible
Implications of Hydroelasticity in Lifting-Surface Applications

- Results from ISROMAC ’16
- With varying immersion-depth, resonant modes of a flexible hydrofoil coalesced and changed order
- Energy-transfer between modes can be a precursor to hydroelastic instability
- FEM predicts that resonant frequencies change with ventilation
**Over-arching Objective:**
Characterize the steady/unsteady fluid-structure interaction between flexible lifting bodies and multiphase flows (ventilated and vaporous) through a series of experimental programs

**Specific Objectives:**
- Develop and validate a non-optical method by which to measure the 3D static and dynamic deflections of wing-like structures *in-situ*
- Explore the effects of wetted and ventilated flow regimes on elastic response and vibration characteristics of a flexible hydrofoil
- Quantify the effects of foil flexibility on hydrodynamic loads, flow regime stability, and transition mechanisms
- Present highlights from recent collaboration at CNR INSEAN with Dr. Mario Felli and Dr. Massimo Falchi
Experimental Setup

MHL Towing Tank
- 110 m x 6.7 m x 3.2 m (L x W x D)
- Speeds up to 6.1 m/s
- Yaw angles $-5^\circ < \alpha < 20^\circ$
- Two models
  - Model 1: PVC
  - Model 2: PVC with reinforced TE (6061-Al strip)
## Cross-Sections of Flexible Hydrofoils

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### Diagrams

**Model 1 Diagram:**
- Center of pressure
- SS Spar "B"
- Center of gravity
- Shear center
- SS Spar "A"
- 1.1 in (0.028 m)
- 6.114 in (0.155 m)
- 5 in (0.127 m)
- 4.3 in (0.109 m)
- 1.25 in (0.032 m)
- 11 in (0.279 m)

**Model 2 Diagram:**
- 2.65 in (0.067 m)
- 4.73 in (0.12 m)
- 2.5 in (0.066 m)
- 11 in (0.279 m)
- Aluminum strip
- 0.25 in (0.006 m)
Development of Shape-Sensing Spars

- Goal: Measure static & dynamic motions of the strut
- Optical methods (e.g. DIC, LDV) are poorly-suited to heterogeneous flows
  - Refraction, reflection, diffraction
- Aluminum spars instrumented with strain gauges
  - Strain distribution fitted by least squares and twice-integrated to yield polynomial $Y(Z)$ along spar’s length
  - Two spars fitted into PVC hydrofoil permit bend and twist to be inferred
  - Decomposition of LS Vandermonde matrix is “cheap” enough to run at 100’s of Hz
Real-Time 3D Shape Sensing
Optical Motion Tracking

- Markers detected automatically by image segmentation and sequential thresholding
- Dot centers computed at brightness-weighted centroid of each white region for sub-pixel accuracy
- “Naïve” implementation, but a good benchmark
Optical Tracking vs. Shape Sensing in a Challenging Flow

\[ \alpha = 5^\circ, \, Fn_h = 2.55, \, AR_h = 1, \, \sigma_v > 2 \]

Video played back at 1/20\textsuperscript{th} speed
Optical Tracking vs. Shape Sensing in a Challenging Flow

\[ \alpha = 5^\circ, \, Fn_h = 2.55, \, AR_h = 1, \, \sigma_v > 2 \]

Shape-sensing offers:
- Improved resolution compared to rudimentary optical tracking
- Results that aren’t susceptible to dropouts in optical access during ventilated flow
- Improved fidelity of frequency content
- Negligible computational cost
Foil Flexibility Increases Loads Slightly \( (F_n h = 3; A R_h = 1) \)

- Results shown for Model 1 (bare PVC hydrofoil)

- There is a small – but consistent – increase in hydrodynamic lift and yawing moment with flexible hydrofoil
- Drag is fairly insensitive to foil flexibility
Scaling the Steady Twist Deformation

- Consider 2D, 2-DOF model
  \[ e = \frac{1}{c} (X_{CP} - X_{EA}) \]
- Steady twist given by:
  \[ \theta = \frac{a_0 \alpha e \frac{c}{2K_{s,\theta}} q c^2}{K_{s,\theta} - a_0 e \frac{c}{2K_{s,\theta}} q c^2} \]
- Manipulation yields:
  \[ \frac{\theta}{\theta + \alpha} = \frac{\theta}{\alpha_e} = \frac{c}{2K_{s,\theta}} q \propto e a_0 F n_h^2 \]
- Should be linear with \( F n_h^2 \), assuming \( e \) and \( a_0 \) are constant

\[ e \text{ and } a_0 \text{ both decrease with increasing cavity-length} \]
Review: Ventilation Formation and Elimination

Fully Wetted (FW)

Formation Mechanisms

Elimination Mechanisms

Fully Ventilated (FV)

Pressure Side Spray
Suction Side Spray
Cavitation-induced Ventilation Formation on Reinforced Hydrofoil

\[ \alpha = 5^\circ, \ Fn_h = 2.25, \ AR_h = 1, \ \sigma_v = 0.35 \ c \]

Video played back at 1/20\textsuperscript{th} speed
Ventilation Transition Boundaries are Shifted \((AR_h = 1.0)\)

- Induced increase in \(\alpha_{eff}\) advances ventilation inception and delays ventilation washout
- Shaker motor provides excitation force
- Frequency Response Function (FRF) vectors
  \[ H_{1i}(\omega) = \frac{XPS(U, Y_i)}{APS(Y_i)} \]
- Compliance frequency response function (FRF) vector from reconstructed surface displacements
  \[ H_{1}^{\text{comp}} \equiv \frac{\text{Displacement}}{\text{Force}} \]
- Inertance FRF vector from tip accelerations
  \[ H_{1}^{\text{inert}} \equiv \frac{\text{Acceleration}}{\text{Force}} \]
- Individual modes extracted from FRFs for parameter estimation.
Mode Separation for Hydrofoil Vibrations in Air
Mode Separation for Hydrofoil Vibrations in Still Water

\[(AR_h = 1)\]
“Waterfall” Plot of Compliance FRF – Raw

- DRY
- FW
- FV
- PC
“Waterfall” Plot of Compliance FRF – Denoised

- DRY
- FW
- FV
- PC

![Plot of Compliance FRF - Denoised](image)
Modal Frequencies and Damping

Modal Frequencies

Mode Shapes

Modal Damping Ratios

- Regime=DRY;
- Regime=FV;
- Regime=FW;
- Regime=PC;

$\omega_0$ vs $F_{n_h}$

$\xi$ vs $F_{n_h}$
Conclusions

• Foil flexibility does affect the hydrodynamic response, but the difference is small in the models tested.
  – Increased hydrodynamic loading commensurate with positive twist angle
  – Earlier ventilation inception and later washout → greater hysteresis
• Deformations scale appropriately with dynamic pressure

• Shape sensing spars are more robust than optical marker tracking

• Qualitative added mass behavior follows expected trends
  – Increases with foil wetting
  – Decreases with ventilation

• Natural frequencies increase with increased forward speed
  – Wake “stiffening” effect

• Damping increases with ventilation & cavitation in some modes
  – Cavity interfaces: alternate paths for energy deposition?
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