Effects of Flexible Fin on Low-Frequency Oscillation in Post-Stalled Flows

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Post-Stall Flow Control

Objectives

- Develop a simple passive device to suppress the natural low-frequency oscillation and reduce drag in deep stall
- Explore the physical mechanisms

Low-frequency oscillation in stall in Re-range of MAV and LPT blades, generating severe flutter [Zaman et al. (1989), Bragg et al. (1996), Broeren et al. (1999)]
From Flexible Trailing Edge to Flexible Fin

**Extended Trailing Edge**

**Two Original Goals:**

- **Lift Enhancement by Static Extended Trailing Edge**
  - ![Diagram](image1)
  - ![Diagram](image2)
  - ![Diagram](image3)
  - ![Diagram](image4)

- **Wake/Separation Control by Flexible Extended Trailing Edge**
  - ![Diagram](image5)
  - ![Diagram](image6)
Flexible Fin on NACA0012 Airfoil

Illustration of the fin concept

Aerodynamic & aeroelastic scaling:

\[ C_F = f(\alpha, Re_\infty, G_1, G_2, a_1/\tau, a_2\tau) \]

Similarity parameters:

- Rigidity: \( G_1 = \frac{D_E}{l^3 q_\infty} \)
- Mass distribution: \( G_2 = \frac{M l}{\tau^2 q_\infty} \)

Thin plate equation:

\[
L \left[ w(P,t) \right] + \frac{\partial}{\partial t} C \left[ w(P,t) \right] + M(P) \frac{\partial^2 w(P,t)}{\partial t^2} = F(P,t)
\]

Analytical solution is given for a rectangular fin

\[
D_E = Eh^2 / 12(1 - \nu^2)
\]

\[
C = a_1 L + a_2 M
\]
Experimental Setup

Connected to a support

Force balance

Plexglas end plates

Flexible fin

Fin: 0.1 mm Mylar film

Typical PIV image
Drag reduction and oscillation suppression were achieved for various lengths and arrangements of flexible fins from AoA = 12 to 20 deg at Re = 6.3x10^4

Typical case: 25%c fin at 10%c

Natural low-frequency oscillation (St = 0.025) was dominant for the baseline mode, and suppressed by the fin
Drag and Lift Coefficients vs AoA
Effects of Fin on Time-Averaged Flow Structures

**Typical Case: AoA of 18°**

- **Strong re-circulating flow, large vortex, or separation bubble**

- **Suppressed reversed flow, broken vortex, or separation bubble**
Velocity Profiles across the Separated Region at Several Locations

\[ x/c = 0.91 \]
\[ x/c = 0.79 \]
\[ x/c = 0.66 \]
\[ x/c = 0.51 \]
\[ x/c = 0.40 \]
Reduction of Momentum Loss in Separated Flow Region

**Momentum Thickness Evolution**

\[
\theta = \int_{y_s}^{\infty} \frac{\Delta U(y)}{U_e} \left[ 1 - \frac{\Delta U(y)}{U_e} \right] dy \\
\Delta U = \langle U \rangle - \min(\langle U \rangle)
\]
Evolution of Power Spectra of $U$ for Baseline Model

(A) 
$\frac{x}{c} = 0.42$, AoA = 18 deg

(B) 
$\frac{x}{c} = 0.66$, AoA = 18 deg

(C) 
$\frac{x}{c} = 0.90$, AoA = 18 deg

$St = 0.025$, the low-frequency oscillation
Evolution of Power Spectra of U for Model with 0.25c Fin

(A) $x/c = 0.42, \text{AoA} = 18\,\text{deg}$

(B) $x/c = 0.66, \text{AoA} = 18\,\text{deg}$

(C) $x/c = 0.90, \text{AoA} = 18\,\text{deg}$
Evolution of Zone-Averaged Power Spectra of $U$ in Shear Layer along X-Coordinate

Baseline, AoA 18°

Shear layer

Linear growth of the low-frequency component
Suppression of Reynolds Stress in Separated Flow Region

**Baseline model**

Baseline, AoA = 18 deg

**Model with a 25% c fin**

Airfoil with Fin, AoA = 18 deg
Coexistence of Vortex Shedding and Low-Frequency Oscillation

Low-frequency oscillation (global phenomenon), $St = 0.025$

Vortex shedding from the shear layer

$$St_{shed} = f c \sin(\alpha)/U_e = 0.31$$
Vortex Shedding and Preferred Mode in Shear Layer

Strouhal number based on the momentum thickness

The most amplified shear layer mode:

$$St_\theta = 0.032$$
Velocity U at a Reference Point and Zero-Crossing Point Position

Reference point: mean zero-crossing point

Time history of U at reference point

Instantaneous zero-crossing point position
Magnitude Squared Coherence between Velocity $U$ at a Reference Point and Zero-Crossing Point Position

$$C_{y_{cp}U} = \frac{\left| P_{y_{cp}U}(f) \right|^2}{P_{y_{cp}y_{cp}}(f)P_{UU}(f)}$$

- cross-power spectral density
- power spectral densities

**Low-frequency oscillation**

**Phase difference: 180 deg**

**Meaning of $C_{y_{cp}U}$:**

How well they correlate at each frequency

[Graph showing magnitude squared coherence as a function of frequency]
Flow Structure Related to Low-Frequency Oscillation

**Short-time averaged flow fields over a period of vortex shedding**

- **(a)**
- **(b)**
- **(c)**

**Time history of U at a reference point**

**Dual-Vortex Structure**
Global Instability of Dual-Vortex Structure as a Origin of Low-Frequency Oscillation

A dynamical system for the dual-vortex structure on a flat plate:

\[
\frac{dz_1^*}{dt^*} = \bar{V}_1(z_1^*, z_2^*; \Gamma_1^*, \Gamma_2^*, \alpha) \quad \frac{dz_2^*}{dt^*} = \bar{V}_2(z_1^*, z_2^*; \Gamma_1^*, \Gamma_2^*, \alpha)
\]

The equilibrium positions of the two point vortices are unstable for a finite-amplitude disturbance
The displacement of a thin plate:

\[ w( x_3 )/l = \eta_1(t)X_1( x_3 ) \]

where the first beam characteristic function is

\[ X_1( x_3 ) = \cos \gamma_1 \bar{x} - \cosh \gamma_1 \bar{x} + k_1(\sin \gamma_1 \bar{x} - \sinh \gamma_1 \bar{x}) \]
Interaction between Fin and Flow

Power Spectra of Velocities across the Fin

- The fin mainly responds to the shear layer mode (vortex shedding).
- The fin absorbs the kinetic energy from the shear layer instability.
Correlation between Fin Kinematics and Flow

High correlation between the fin amplitude and velocities in the shear layer or vortex shedding mode.
Conceptual Interpretation for Post-Stall Control by a Flexible Fin

Scenario

- Vortex shedding due to the shear layer (K-H) instability

- Organized strong vortices developed in the shear layer collectively induce a large vortical motion (re-circulating flow) near TE

- Formation of the dual-vortex structure in a sense of short-time average

- Low-frequency oscillation as a result of the global instability of dual-vortex structure

- The shear layer instability and then the low-frequency oscillation are suppressed by a flexible fin
Conclusions

• Drag reduction and oscillation suppression are achieved by using a flexible fin on a NACA0012 airfoil at high AoAs in stall

• The flexible fin suppresses the shear layer instability and the low-frequency oscillation, and reduces the momentum loss in the separated flow region.

• Applications in gust alleviation for MAV and separation control on LPT blades impinged by unsteady wake