Wind tunnel experiments on wake-vortex decay in external turbulence

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Goal

Investigate the effect of external turbulence on wake-vortex decay with focus on experiments

Scope

– Single vortex with and without external turbulence
– Counter-rotating vortices without external turbulence
– Counter-rotating vortices with external turbulence
Experimental set up

Schematic top view of wind tunnel

- Typical Reynolds number: $\text{Re}_\Gamma = \Gamma / \nu_{\text{air}} = 4 \times 10^4$
- Typical tip spacing: $d_0 = 0.03 \text{ m}, 0.05 \text{ m and } 0.10 \text{ m}$
Turbulence generation and measurement

- No grid: $\varepsilon = 2 \times 10^{-6} \, \text{m}^2 \, \text{s}^{-3}$
- Open grid: $\varepsilon = 1.0 \, \text{m}^2 \, \text{s}^{-3}$
- Partially closed grid: $\varepsilon = 4.9 \, \text{m}^2 \, \text{s}^{-3}$

Velocity fluctuations measured with hot-wires → turbulent dissipation rate $\varepsilon$
Airfoil model

Clark-Y 11.7%

Wings are twisted to obtain constant load and optimized for $d_0 = 0.10$ m
Particle Image Velocimetry (PIV)

Delay time $\tau$ between subsequent laser pulses
Particle Image Velocimetry

I: Core region
- velocities are large
- small focus area

II: Outer region
- velocities are small
- large focus area
Azimuthal velocity profile for single vortex (no grid)
Vortex core growth for single vortex

\[ r_1 \approx 1.12 \sqrt{4 \nu_{eff} t} \]

\( \nu_{eff} \approx 1.5 \nu_{air} \) \rightarrow flow in vortex core is close to laminar
Circulation profile for single vortex (with and without grid)

$\Delta x = 2.82$ m

$\Gamma_0$

without grid

with grid (different $\alpha$)

region I data (no grid)

$\rightarrow$ External turbulence has only a marginal effect
Vortex core wandering (single vortex)

Wandering amplitude:

\[
\frac{S_R}{r_{1,0}} = \left( \frac{S_y^2 + S_z^2}{r_{1,0}} \right)^{1/2}
\]

Distance from airfoil:

\[
t = \frac{\Delta \chi}{U}
\]

\[\Rightarrow \text{External turbulence enhances wandering}
\]

\[\Rightarrow \text{Increasing } \Gamma_0 \text{ decreases wandering}\]
Decay of circulation for counter-rotating vortices (no grid)

\[ \frac{\Gamma_{total}}{\Gamma_0} = \text{erf} \left( \sqrt{\frac{\Gamma_0}{4D_{eff} t^*}} \right) \]

\[ t^* = \frac{t \Gamma_0}{2\pi b_0^2} \]

\[ \nu_{air} = 1.5 \times 10^{-5} \text{ m}^2 \text{ s}^{-1} \]

\[ D_{eff} = (4 \pm 0.5) \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \]

\[ \rightarrow D_{eff} >> \nu_{air} \rightarrow \text{turbulent cross-diffusion} \]
Increase vortex separation (no grid)

- $b$ grows and $\Gamma$ decays $\Rightarrow \Gamma b$ remains constant $\Rightarrow$ evolution is 2D
- large deviations for $t^* = 12$
Crow instability and vortex linking (smoke visualization)
Crow instability and vortex linking (no grid)

$\theta = 33^0$ (Crow: $\theta = 48^0$)

- vortex center positions oscillate symmetrically
At fixed $\Delta x$ the total circulation $\Gamma_{total}$ decreases due to vortex linking.
Crow instability and vortex linking (with grid)

- Crow instability at $t^* < 12$
- Angle of oscillation $\theta \rightarrow 33^0$ (Crow: $48^0$)
- Growth $b_{rms} \sim \exp(0.41 \ t^*)$ (Crow: $\sim \exp (0.83 \ t^*)$)
Effect of external turbulence on vortex life time

→ Turbulence promotes onset of Crow instability and vortex linking
Effect of external turbulence on decay of circulation

\[ \Gamma_{\text{total}} \]

\[ b \]

\[ D_{\text{eff}} \]

exchange of vorticity

\[ \rightarrow \text{positive correlation between } D_{\text{eff}} \text{ and } \varepsilon^* \]
Summary

Single vortex:

- Vortex core is close to laminar independent of external turbulence; outer region is marginally effected by external turbulence.
- Turbulence increases vortex wandering

Vortex pair:

- Initial decay of circulation due to cross-diffusion of vorticity, followed by the Crow instability and vortex linking leading to the final destruction of the vortex pair.
- External turbulence enhances the cross-diffusion of vorticity and promotes the onset of the Crow instability.
- Deviations from theory are still unclear (other modes?, cut-off radius?)