Control of Supersonic Impinging Jets Using Microjets

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Outline

- Motivation
- Mechanism
  - Feedback loop
  - Mechanism of microjet control
- Results and Discussion
- Conclusions
Motivation

JSF X-32B on the hover
Motivation

Flow schematic for a jet STOVL aircraft in hover

- Jet Flow
- Unsteady Structural Loads
- Lift Loss
- Jet Impinging Region
- Wall jet flow
- Lifting –jet flow
- Noise
- Ground plane

Ground Erosion Region
Motivation

Near field noise spectrum, NPR=3.7, h/d=4

Impinging tones

NPR=3.7, M_d=1.5, h/d=4
Feedback loop

Upstream propagating acoustic waves

Larger Scale Structures

Powell, Karamcheti, Tam & Ahuja, Krothapalli et al.
Goal

• To understand the characteristics of supersonic impinging jet flow

• To actively and efficiently control the jet behavior by disrupting the feedback loop
  ➢ Reduce: Tones, OASPL and other related adverse effects

• To understand the mechanism behind the microjets control method
Prior Attempts at Feedback Control

- Karamcheti et al. (1969): Edge tone suppression using baffles/plates
- Samimy et al. (1993): Screech tone suppression using tabs
- Sheplak & Spina (1994): Impinging tone suppression via coflow
- Shih et al. (1999): Screech tone suppression using counterflow
- Elavarasan et al. (1999): Impinging tone suppression via baffles

Present Approach

- Use supersonic microjets to disrupt the feedback loop:
  - High momentum, low mass flow
  - Relatively simple, can be actively manipulated to provide optimal control
Test Model and Facility

Lift plate

Ground plate

Mean pressure ports

Slots for Kulites

Microjets
Experimental Details

Microjets ($d_m = 400 \mu m$)

d = 27.5 mm

Lift plate

Kulite

$M_{design} = 1.5$, NPR = 2.5, 3.75

$h/d = 2 \sim 9$

$\alpha$: microjet angle

Lift plate

Ground plane

From Solenoid Valve

Primary Jet

From Solenoid Valve
Effect of Microjet Control

Shadowgraphs NPR = 3.7, h/d = 4

No Control

With Control

Large-scale Structures

Acoustic wave

Streaks
Effect of Microjet Control

NPR 3.7, h/D = 4

NPR=3.7, h/d=4
With and W/out control
**Pressure Spectra**

**Ground Plane**

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**NPR 3.7**

- **No Control**
- **With Control**

**NPR 5**

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**37-s-nc100-h4-GP.lay**

**35-s-nc100-h6-GP.lay**
**P_{rms} Reduction as a Function of Heights**

20°, 100 psi, 16 microjets

**NPR 3.7**

- Ground Plane
- Lift Plate
- Microphone

**NPR 5.0**
Why do the microjets work?

- Microjet **intercept** upstream-propagating acoustic disturbances
- Microjets **thicken** the nozzle shear layer, decreasing its receptivity to acoustic disturbances
- Microjets **disrupt** the axisymmetric coherent coupling between instability & acoustic waves
- Microjets **introduce** significant streamwise vorticity, thus weak the large-scale structures
Effect of Microjet Pressure

NPR=3.7, 60 deg. microjet

\[ \dot{M} = \gamma M_e^2 \frac{\rho_e}{\rho_0} \frac{a_e^2}{a_0^2} P_0 \]

- h/d=3.5
- h/d=4
- h/d=4.5

\[ \approx 35 \text{ psia} \]

\[ \Delta dB \]

\[ P (\text{psia}) \]
Effect of Microjet Angle

Microjet pressure @ 100psia

Delta dB vs h/d for 20°, 60°, and 90° microjets with NPR=3.7.
Effect of Microjet Spacing

NPR=3.7, 60 deg. Microjet @ fixed total momentum

8 microjets: Bank A
16 microjets: Bank A, C
32 microjets: Bank A, B, C
32 microjets: Bank A, B, C, D

NPR= 3.7
60 deg. Microjet (Same total momentum)
Lift Plate
Effect of Micro-tabs

NPR=3.7

90° Microjets

Micro-tabs

400 μm dia.
2.5 mm length

Tab.
90 deg. No Control
90 deg. With Control

NPR 3.7
Lift Plate

OASPL (dB)

180
176
172
168
164
160
156
152
148
144
140

1 2 3 4 5 6 7

h/d
Effect of Micro-tabs

NPR=5

Micro-tabs

90° Microjets

400 μm dia.
2.5 mm length

NPR=5
Lift Plate

Tabs
90 degree No Control
90 degree With Control (100psi)

Tab.
90 deg. No Control
90 deg. With Control
Summary of Parametric Effects

- Microjet control suppresses the flow unsteadiness and reduces the noise level:
  - Impinging tones are completely eliminated or significantly reduced
  - Overall noise/dynamic pressures are reduced by 5-12 dB
- The substantial improvement on the reduction was achieved when the microjet angle changed from 20º to 60º or 90º
- The effectiveness of microjet control strongly depend on the microjet pressure for NPR=3.7, but less sensitive for NPR=5
- The effectiveness of microjet control also depend on microjet spacing
- Micro-tabs show no effect at NPR=3.7, but have almost same effect as microjet control for NPR=5.
Experiment Setup
Effect of Microjet Control on Mean Velocity

NPR=3.7, h/d=4, 90 deg. μjet

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</table>

No Control

With Control
Effect of Microjet Control on Centerline Velocity

$NPR = 3.7$, $h/d = 4$, 90 deg. $\mu_{jet}$

**Graph:**
- No Control, $h/d = 4$
- With Control, $h/d = 4$
- No Control, Free jet

**Legend:**
- Red: No Control
- Green: With Control
- Blue: No Control, Free jet

**Axes:**
- $x/d$ on the x-axis
- $U_{center}$ (m/sec) on the y-axis

**Legend:**
- Red: No Control
- Green: With Control
- Blue: Free Jet
Effect of Microjet Control on Shear Layer Thickness

NPR=3.7, h/d=4, 90 deg. µjet
Effect of Microjet Pressure on Shear Layer Thickness

NPR=3.7, h/d=4, 60 deg. \( \mu \)jet

25 ~ 100 psia
Effect of Microjet Control on Velocity Profile

NPR = 3.7, h/d = 4, 90 deg. µjet

No Control

With Control
**Instantaneous Vorticity Distribution**

NPR=3.7, h/d=4, 90 deg. \( \mu \text{jet} \)

**No Control**

**With Control**
Effect of Microjet Control on Azimuthal Vorticity

NPR=3.7, h/d=4, 90 deg. \( \mu \text{jet} \)

No Control

With Control
Effect of Microjet Control on Azimuthal Vorticity

$h/d=4, 90$ deg. $\mu$jet

$NPR=3.7$

$NPR=5$

Vorticity

Velocity
Effect of Microjet Control on Peak Azimuthal Vorticity

**No Control**

**With Control**

$h/d=4$, $90\, \text{deg.} \, \mu\text{jet}$

**NPR=3.7**

**NPR=5**
Phase-Averaged Shadowgraphs

*M = 1.5 nozzle, NPR = 3.7*

*With Control*
**Cross Section PLS & PIV Setup**

- **Nd-Yag Laser**
- **Nozzle**
- **Lift Plate**
- **Light sheet optics**
- **Laser sheet**
- **CCD Camera**
- **Glass Plate plate**
- **Ground plane**
- **Mirror**
PLS Images, Averaged

NPR=5  h/D=4

No Control

With Control
3D PIV Setup
Instantaneous 3D Images

Image A  Image B
Effect of Microjet Control on Mean Axial Velocity

NPR=3.7, h/d=4, 90 deg. μjet

With Control

No Control
Close-up on Velocity Field

\[ \text{NPR} = 3.7, \ h/d = 4, \ x/d = 1 \]

\( r/d = 0.5 \)

\( r/d = 0.85 \)

No Control

With Control
Effect of Microjet Control on Streamwise Vorticity

\[ \text{NPR=3.7, } h/d = 4, \text{ 90 deg. } \mu \text{jets} \]

No Control

With Control

\[ \text{NPR=3.7, } h/d = 4 \]
\[ \text{With Control (60 deg. } \mu \text{jets)} \]
Effect of Microjet Control on Streamwise Vorticity

_NPR=5, h/d = 4, x/d = 1, 90 deg. µjets_

No Control

With Control
Effect of Microjet Control on Streamwise Vorticity

\( h/d = 4, x/d = 1, 90 \text{ deg. } \mu\text{jets} \)

- **NPR = 3.7**
  - No Control
  - With Control (3D PIV)
  - With Control (2D PIV)

- **NPR = 5**
  - No Control
  - With Control

\[ \frac{\Omega_{x}/U_j}{\text{No Control}} \]

\[ \frac{\Omega_{x}/U_j}{\text{With Control (3D PIV)}} \]

\[ \frac{\Omega_{x}/U_j}{\text{With Control (2D PIV)}} \]
Streamwise Development of the Average Circulation

$\text{NPR}=3.7$ and $5$, $h/d = 4$, $x/d = 1$, 90 deg. $\mu$jets

$$\Gamma = \int \bar{\Omega} \cdot \bar{n} \, dA$$

![Graph showing streamwise development of the average circulation with NPR=3.7 and 5, h/d = 4, x/d = 1, 90 deg. $\mu$jets.](image)
Circulation of Azimuthal Vorticity

For NPR=3.7

0.16/0.52 ≈ 31%
Streamwise Vorticity Formation Mechanism

Vorticity Transportation Equation:

\[ \frac{D\tilde{\Omega}}{Dt} = \tilde{\Omega} \cdot \nabla \tilde{U} - \nabla \left( \frac{1}{\rho} \nabla \cdot \nabla \times \nabla P \right) + \text{Stress term} + \nu \nabla^2 \tilde{\Omega} \]

Streamwise vorticity component

\[ \frac{D\Omega_x}{Dt} = \frac{\partial}{\partial x} \left( \frac{\partial \tilde{u}' v'}{\partial z} - \frac{\partial \tilde{u}' w'}{\partial y} \right) + \frac{\partial^2}{\partial y \partial z} \left( \tilde{v}'^2 - \tilde{w}'^2 \right) + \left( \frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2} \right) \tilde{v}' \tilde{w}' \]
Streamwise Vorticity Formation Mechanism

**Vorticity Transportation Equation:**

\[
\frac{D\vec{\Omega}}{Dt} = \vec{\Omega} \cdot \nabla \vec{U}
\]

- \( \Omega_x \) Streamwise vorticity
- \( \Omega_r \) Radial vorticity
- \( \Omega_\theta \) Azimuthal vorticity

Streamwise vorticity component

\[
\frac{D\Omega^x}{Dt} = \Omega_x \frac{\partial U^x}{\partial x} + \Omega_\theta \left( \frac{1}{r} \frac{\partial U^x}{\partial \theta} \right) + \Omega_r \frac{\partial U^x}{\partial r}
\]

- Stretching
- Tilting
Titling of Azimuthal Vorticity

\[ \Omega_\theta \left( \frac{1}{r} \frac{\partial U_x}{\partial \theta} \right) \]

\[ \text{NPR}=3.7 \ h/d = 4, \ x/d = 1, \ 90 \ deg. \ \mu\text{jets} \]

- No Control
- With Control

\[ r/d=0.35 \]

\[ r/d=0.55 \]
Titling and Stretching of Azimuthal Vorticity

\[ \frac{\partial U_x}{\partial r} \Omega_r \]

\[ \frac{D \Omega_r}{Dt} = \Omega_\theta \left( \frac{1}{r} \frac{\partial V_r}{\partial \theta} \right) + \Omega_r \frac{\partial V_r}{\partial r} + \Omega_x \frac{\partial V_r}{\partial x} \]

\( \Omega_x \) Streamwise vorticity

\( \Omega_r \) Radial vorticity

\( \Omega_\theta \) Azimuthal vorticity
Effect of Microjet Angle

NPR = 3.7, h/d = 4, x/d = 1, 60, 90 deg. \( \mu \)jets @ 100 psia

\[
\frac{\partial U}{\partial r} \quad 60 \text{ deg.} \quad \frac{\partial U}{r \partial \theta} \quad 90 \text{ deg.}
\]
Effect of Microjet Spacing

NPR=3.7 h/d = 4, x/d = 1, 60 deg. \( \mu \)jets @ constant momentum

\[ \frac{\Omega_x d}{U_j} \]

- 16 \( \mu \)jets
- 32 \( \mu \)jets

16 microjets, \( \lambda_{3D} \approx 0.19d \)

Widnall et al. (1974) and Tsai & Widnall (1976), \( \lambda_{3D} \approx 0.23d \)
Summary

• Microjet control successfully disrupts the feedback loop and leads to:
  - Eliminate or significantly reduce the impinging tones
  - Reduce the overall sound pressure level
  - Reduce the unsteady loads

• PIV measurement clearly show microjet control:
  - Reduce in the azimuthal vorticity
  - Increase in the streamwise vorticity
  - Thicken the shear layer at nozzle exit

• The plausible mechanism of microjet control -
  *Redirect the azimuthal vorticity into streamwise direction* through:
  - Tilting
  - Stretching
Thank you !!!