AIRFRAME NOISE MODELING APPROPRIATE FOR MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

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Introduction

- Aircraft noise: an important performance criterion and constraint in aircraft design
- Noise regulations limit growth of air transportation
- Reduction in noise needed
- To achieve noise reduction
  - Design revolutionary aircraft with innovative configurations
  - Improve conventional aircraft noise performance
  - Optimize flight performance parameters for minimum noise
- All these efforts require addressing noise in the aircraft conceptual design phase
Aircraft Noise Components

- Include aircraft noise as an objective function or constraint in MDO
  - Requires modeling of each noise source
- Airframe noise
  - Now comparable to engine noise at approach
  - Our current focus
Trailing Edge Noise

- Trailing Edge Noise
  - Airframe noise component
  - Main noise mechanism of a clean wing
  - Scattering of acoustic waves generated due to the passage of turbulent boundary layer over the trailing edge

- In our study, we have developed a new Trailing Edge Noise metric appropriate for MDO
Why Do We Model Trailing Edge Noise?

- Trailing Edge Noise: a lower bound value of airframe noise at approach (a measure of merit)

- Trailing Edge Noise can be significant contributor to the airframe noise for a non-conventional configuration
  - traditional high-lift devices not used on approach
  - A Blended-Wing-Body (BWB) Aircraft
    - Large Wing Area and span
  - A conventional aircraft or BWB with distributed propulsion
    - Jet-wing concept for high lift
  - An airplane with a morphing wing

- A Trailing Edge Noise Formulation based on proper physics may be used to model the noise from flap trailing edges or flap-side edges at high lift conditions

- First step towards a general MDO noise model
Outline of the Current Work

◆ Objective: To develop a trailing edge noise metric
  – construct response surfaces for aerodynamic noise minimization

◆ Noise metric
  – Should be a reliable indicator of noise
  – Not necessarily the magnitude of the absolute noise
  – Should be relatively inexpensive to compute
    • Computational Aeroacoustics too expensive to use
    • Still perform 3-D, RANS simulations with the CFD code GASP

◆ Parametric Noise Metric Studies
  – 2-D and 3-D cases
  – The effect of different wing design variables on the noise metric
The Trailing Edge Noise Metric

- Following classical aeroacoustics theories from Goldstein and Lilley, we derive a noise intensity indicator ($I_{NM}$)

$$I_{NM} = \frac{\rho_\infty}{2\pi^3 a_\infty^2} \int_0^b u_0^5(y)l_0(y)\cos^3(\beta(y)) D[\theta(y),\psi(y)] \, dy$$

- Noise Metric: $NM \ (dB) = 10\log\left(\frac{I_{NM}}{I_{ref}}\right)$, with $I_{ref}=10^{-12} \ (W/m^2)$

$$NM \ (dB) = 120 + 10\log(I_{NM})$$

$D[\theta,\psi] = 2\sin^2\left(\frac{\theta}{2}\right)\sin(\psi)$ (directivity term)

$u_0$ characteristic velocity for turbulence

$l_0$ characteristic length scale for turbulence

$\rho_\infty$ free-stream density

$a_\infty$ free-stream speed of sound

$H$ distance to the receiver

$\beta$ trailing edge sweep angle

$\theta$ polar directivity angle

$\psi$ azimuthal directivity angle
Modeling of $u_0$ and $l_0$

- Characteristic turbulence velocity scale at the trailing edge

$$u_0(y) = \text{Max} \left\{ \sqrt{\text{TKE}(z)} \right\}$$

- New characteristic turbulence length scale at the trailing edge

$$l_0(y) = \frac{\text{Max} \left\{ \sqrt{\text{TKE}(z)} \right\}}{\omega}$$

- $\omega$ is the turbulence frequency observed at the maximum TKE location for each spanwise location.

- $\text{TKE}$ and $\omega$ obtained from the solutions of $TKE-\omega$ ($k-\omega$) turbulence model equations used in RANS calculations

- Previous semi-empirical trailing edge noise prediction methods use $\delta$ or $\delta^*$ for the length scale
  - Related to mean flow
  - Do not capture the turbulence structure
Unique Features of the Noise Metric

- Expected to be an accurate relative noise measure suitable for MDO studies
- Applicable to any wing configuration
- Spanwise variation of the characteristic turbulence velocity and length scale taken into account
- Sensitive to changes in design variables (lift coefficient, speed, wing geometry *etc.*).
- The choice of turbulence length scale \(l_0\) more soundly based than previous ones used in semi-empirical noise predictions
Noise Metric Validation

- Experimental NACA 0012 cases from NASA RP 1218 (Brooks et al.)
- All cases subsonic
- Predicted Noise Metric (NM) compared with the experimental OASPL
- The agreement between the predictions and the experiment is very good

<table>
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<th>$\alpha$ (deg)</th>
<th>0.0</th>
<th>0.0</th>
<th>2.0</th>
<th>1.5</th>
<th>0.0</th>
<th>2.0</th>
<th>1.5</th>
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</thead>
<tbody>
<tr>
<td>$Re_c \times 10^6$</td>
<td>1.497</td>
<td>0.665</td>
<td>0.499</td>
<td>0.831</td>
<td>1.164</td>
<td>1.122</td>
<td>1.497</td>
</tr>
</tbody>
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$NM_{si}$ and $OASPL_{si}$ results are scaled with the values obtained for case 1.
**Parametric Noise Metric Studies**

**Two-Dimensional Cases**
- **Subsonic Airfoils**
  - NACA 0012 and NACA 0009
- **Supercritical Airfoils**
  - SC(2)-0710 (t/c=10%)
  - SC(2)-0714 (t/c=14%)
- **C-grid topology (388×64 cells)**

**Three-Dimensional Cases**
- **Energy Efficient Transport (EET) Wing**
  - S_{ref}=511 m², MAC=9.54 m
  - AR=8.16, Λ=30° at c/4
  - t/c=14% at the root
    - t/c=12% at the break
    - t/c=10% at the tip
  - **C-O topology, 4 blocks (884,736 cells)**

**Steady RANS simulations with GASP**
- Menter’s SST k-ω turbulence model
Parametric Noise Metric Studies with NACA 0012 and NACA 0009

- $V_\infty=71.3$ m/s, $Mach=0.2$, $Re_c=1.497 \times 10^6$ & $1.837 \times 10^6$
- Investigated noise reduction by decreasing $C_l$ and $t/c$
  - Increased chord length to keep lift and speed constant
  - Total noise reduction=3.617 dB

- Simplified representation of increasing the wing area and reducing the overall lift coefficient at constant lift and speed
  - Additional benefit: eliminating or minimizing the use of high lift devices
Parametric Noise Metric Studies with SC(2)-0710 and SC(2)-0714

- Realistic approach conditions
  - \(Re_c = 44 \times 10^6\)
  - \(V_\infty = 68 \text{ m/s, } Mach=0.2\)
- Corresponds to typical transport aircraft
  - With \(MAC=9.54 \text{ m}\)
  - Flying at \(H=120 \text{ m}\)
  - Approximately the point for the noise certification at the approach before landing
- Directivity terms
  - Directivity term=1.0
    \((\theta=90^\circ \text{ and } \psi=90^\circ)\)
- Investigate the effect of the thickness ratio and the lift coefficient
Noise Metric Values for the Supercritical Airfoils at different $C_l$ values

- At relatively lower lift coefficients ($C_l < 1.3$)
  - Noise metric almost constant
  - The thicker airfoil has a larger noise metric

- At higher lift coefficients ($C_l > 1.3$)
  - Sharp increase in the noise metric
  - The thinner airfoil has a larger noise metric
3-D Parametric Noise Metric Studies with the EET Wing

- Realistic approach conditions
  - $Re_c=44 \times 10^6$, $V_\infty=68$ m/s, $M=0.2$
  - Flying at $H=120$ m
- Stall observed at the highest $C_L$
  - $CL_{max}=1.106$
  - $W/S_{max}=315.7$ kg/m$^2$ (64.8 lb/ft$^2$)
  - Less than realistic $C_L$ and $W/S$ (~430 kg/m$^2$) values
- Investigate the effect of the lift coefficient on the noise metric with a realistic geometry
- Investigate spanwise variation of $u_0$ and $l_0$
Section $C_l$ and Spanload distributions for the EET Wing

- Loss of lift on the outboard sections at the highest lift coefficient
- Large region of separated flow
- Shows the value to increase the wing area of a clean wing
  - To obtain the required lift on approach with lower $C_L$
  - Lower noise
Skin Friction Contours at the Upper Surface of the EET Wing for different $C_L$ values

$C_L=0.375$, $\alpha=2^\circ$

$C_L=0.689$, $\alpha=6^\circ$

$C_L=0.970$, $\alpha=10^\circ$

$C_L=1.106$, $\alpha=14^\circ$
**TKE** ($u_0^2$) and $l_0$ Distributions at the Trailing Edge of the EET Wing for different $C_L$ values

- Maximum **$TKE$** and $l_0$ get larger starting from CL=0.836, especially at the outboard section
- Dramatic increase for the separated flow case
- Maximum **$TKE$** and $l_0$ not constant along the span at high $C_L$
Noise Metric Values for the EET Wing at different $C_L$ values

- At lower lift coefficients
  - Noise metric almost constant
  - Contribution to the total noise from the lower surface significant

- At higher lift coefficients
  - Noise metric gets larger
    - Dramatic increase for the separated flow case
  - Upper surface is the dominant contributor to the total noise
Conclusions

◆ A new trailing edge noise metric has been developed
  – For noise response surfaces in MDO
  – For any wing geometry
  – Introduced a length scale directly related to the turbulence structure
  – Spanwise variation of characteristic velocity and length scales considered

◆ Noise metric an accurate relative noise measure as shown by validation studies

◆ Parametric noise metric studies performed
  – Studied the effect of the lift coefficient and the thickness ratio
  – Noise reduction possible with decreasing the lift coefficient
    • Leads to increase in chord length (wing area) for constant lift and speed
    • Leads to decrease in thickness ratio (further reduction in noise)
  – Noise constant at lower lift coefficients and gets larger at higher lift coefficients. Sharp increase when there is large separation
  – Characteristic velocity and length scales not constant along the span at high lift coefficients due to 3-D effects
Future Work

- Trailing Edge Noise
  - Investigate the effect of other design parameters
    - Twist distribution
  - Wider parameter space
  - Extend approach to flaps and slats

- Consider other noise components