Optimization of Blowing and Suction Control on NACA0012 Airfoil Using Genetic Algorithm with Diversity Control

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Outline

• Motivation
• Genetic Algorithm
  – Basic Continuous Parameter GA
  – EARND with Diversity Control
• Single Suction/Blowing Jet Study
• Two-jet Control System Optimization
  – A single suction jet and blowing jet system
  – A two suction jet system
• Conclusions
Synthetic-Jet Flow Control

Driver

Synthetic Jet
by
George Huang
Dept of Mech Eng
University of Kentucky
Plasma-Jet Flow Control

- Experiment Without Plasma Actuator
- Computation Without Plasma Actuator
- Computation With Plasma Actuator
Objectives


2. Improve convergence speed and robustness of genetic algorithm – with fewer population and generation numbers.

Genetic Algorithm

1. Challenges – fewer expensive CFD runs
   a. Fewer population
   b. Fewer generation

2. Basic Algorithm

3. Improved Algorithm
   EARND with Diversity Control
   (Explicit Adaptive Range Normal Distribution Algorithm)
Basic Continuous Parameter GA

- Ngood = Nbad = Npop/2
- Cost weighting pairing
- Mating and reproduce:

  father = \([x_{1,f}, x_{2,f}, \ldots, x_{\alpha,f}, \ldots, x_{Nvar-1,f}, x_{Nvar,f}]\)  
  
mather = \([x_{1,m}, x_{2,m}, \ldots, x_{\alpha,m}, \ldots, x_{Nvar-1,m}, x_{Nvar,m}]\)  
  where \(\alpha = \text{int}(\text{random}_1 * \text{Nvar}) + 1\)

  offspring\(_1\) = \([x_{1,f}, x_{2,f}, \ldots, x_{\text{new},1}, \ldots, x_{Nvar-1,m}, x_{Nvar,m}]\)  
  
  offspring\(_2\) = \([x_{1,m}, x_{2,m}, \ldots, x_{\text{new},2}, \ldots, x_{Nvar-1,f}, x_{Nvar,f}]\)  
  where \(x_{\text{new},1} = x_{\alpha,f} + \text{random}_2 (x_{\alpha,m} - x_{\alpha,f})\)  
  
  \(x_{\text{new},2} = x_{\alpha,m} - \text{random}_2 (x_{\alpha,m} - x_{\alpha,f})\)

- Mutation only applies to Nbad population
EARND with Diversity Control

1. Define: parameters
2. Cost function
3. Create population
4. Evaluate Cost
5. Sort
6. mate and reproduce
7. Converge?
8. Mutate

**EARND with DC**

Every N update step:

- **μ**: The best solution within the previous Nupdate step.
- **σ**: The standard derivation based on averaging all the population of the previous Nupdate generation.

- **Update is only applied to Nbad population.**
Test cases

1. \( f(x, y) = x \sin(4x) + 1.1y \sin(2y) \)

2. \( f(x_1, x_2) = -c_1 \exp \left( -c_2 \sqrt{\frac{1}{2} \sum_{j=1}^{2} x_j^2} \right) - \exp \left( \frac{1}{2} \sum_{j=1}^{2} \cos(c_3 x_j) \right) + c_1 + e \)

3. \( f(r) = \frac{1}{n} \sum_{i=1}^{n} \left[ x_i^2 - 10 \cos(2\pi x_i) + 10 \right] \)

4. \( f(r) = \sum_{i=1}^{N-1} (1 - x_i)^2 + 100(x_{i+1} - x_i)^2 \)

5. \( f(r) = 200 + \sum_{i=1}^{N} (x_i^2 - 10 \cos(2\pi x)) \)

6. \( f(r) = 1 + \sum_{j=1}^{N} (x_j^2 / 4000) - \prod_{j=1}^{N} \cos(x_j / \sqrt{j}) \)
Case 1  
Nvar=2

Case 2  
Nvar=2

Case 3  
Nvar=5

Case 4  
Nvar=10

Case 5  
Nvar=20

Case 6  
Nvar=10

f_{min}  

# of generation  

Npop=16
Npop=16 n ew
Npop=32
Npop=32 new
Single Jet Study

Establishing a benchmark solution of a single jet flow control by performing a carpet search of three parameters:

1. Suction/Blowing jet location ($L_j$)
2. Suction/Blowing jet amplitude ($A$)
3. Suction/Blowing jet angle ($\theta$)

NACA 0012 Airfoil Suction/Blowing Control

$Re = 500,000$
$\alpha = 18^\circ$

Control Parameters
1. Jet Location ($L_j$)
2. Amplitude ($A$)
3. Angle ($\theta$)
Single Jet Study

Incompressible CFD Code: Ghost
Finite Volume Structure 2-D
Convective Terms: Quick
Diffusive Terms: Central Difference
SST turbulence model

210,000 Chimera grid points
Re=500,000
\( \alpha = 18^0 \)
<table>
<thead>
<tr>
<th>Block number</th>
<th>1(i*j)</th>
<th>2(G*j)</th>
<th>3(i*j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55*70</td>
<td>110*140</td>
<td>110*200</td>
</tr>
<tr>
<td>2 (background)</td>
<td>70*70</td>
<td>140*140</td>
<td>200*200</td>
</tr>
<tr>
<td>3 (background)</td>
<td>55*70</td>
<td>110*140</td>
<td>150*200</td>
</tr>
<tr>
<td>4 (background)</td>
<td>70*70</td>
<td>140*140</td>
<td>200*200</td>
</tr>
<tr>
<td>5</td>
<td>55*70</td>
<td>110*140</td>
<td>110*200</td>
</tr>
<tr>
<td>6 (airfoil)</td>
<td>54*25</td>
<td>107*50</td>
<td>148*75</td>
</tr>
<tr>
<td>7 (airfoil)</td>
<td>54*25</td>
<td>107*50</td>
<td>148*75</td>
</tr>
<tr>
<td>8 (airfoil)</td>
<td>70*25</td>
<td>120*50</td>
<td>220*75</td>
</tr>
<tr>
<td>9 (airfoil)</td>
<td>70*25</td>
<td>120*50</td>
<td>220*75</td>
</tr>
<tr>
<td>10</td>
<td>55*70</td>
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<td>110*140</td>
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<tr>
<td>11</td>
<td>70*70</td>
<td>140*140</td>
<td>140*140</td>
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<tr>
<td>12</td>
<td>55*70</td>
<td>110*140</td>
<td>110*140</td>
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<tr>
<td>13</td>
<td>70*70</td>
<td>110*140</td>
<td>110*140</td>
</tr>
<tr>
<td>14</td>
<td>70*70</td>
<td>140*140</td>
<td>140*140</td>
</tr>
<tr>
<td>15</td>
<td>55*70</td>
<td>110*140</td>
<td>110*140</td>
</tr>
</tbody>
</table>
1. Coarse Grid
2. Mid-Dense Grid*
3. Dense Grid

Lift Coefficients

\[ C_l = \frac{L}{\frac{1}{2} \cdot \rho \cdot u_{\infty}^2 \cdot c} \]

Drag Coefficients

\[ C_d = \frac{D}{\frac{1}{2} \cdot \rho \cdot u_{\infty}^2 \cdot c} \]
Comparison with other data

- Reynolds Number Effects
  - Laminar, Turbulence
- 3-D effects
- Installation Errors
- Wall Effects
- Effective Angle of attack

Graph shows comparisons with different experiments and computations, including:
- Computation, Present
- Experiment, Sheldahl (1981)
- Experiment, Critzos (1955)
- Experiment, E. Jacobs (1937)
- Computation, Jiezhi Wu (1998)

Legend indicates different datasets with symbols and colors.
Exhaustive Search

NACA 0012 Airfoil Suction/Blowing Control

Control Parameters
1. Jet Location ($L_j$)
2. Amplitude ($A$)
3. Angle ($\theta$)

<table>
<thead>
<tr>
<th>Round</th>
<th>Jet Location $L_j$</th>
<th>Amplitude $A$</th>
<th>Angle $\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Round (64)</td>
<td>0.1, 0.333, 0.567, 0.8</td>
<td>0.01, 0.173, 0.337, 0.5</td>
<td>-90, -30, 30, 90</td>
</tr>
<tr>
<td>Second Round (64)</td>
<td>0.05, 0.075, 0.1, 0.125</td>
<td>0.01, 0.073, 0.137, 0.2</td>
<td>-90, -30, 30, 90</td>
</tr>
<tr>
<td>Third Round (64)</td>
<td>0.03, 0.04, 0.05, 0.06</td>
<td>0.01, 0.073, 0.137, 0.2</td>
<td>0, 30, 60, 90</td>
</tr>
<tr>
<td>Fourth Round (128)</td>
<td>0.2, 0.286, 0.371, 0.457, 0.543, 0.629, 0.714, 0.8</td>
<td>0.01, 0.073, 0.137, 0.2</td>
<td>0, 30, 60, 90</td>
</tr>
</tbody>
</table>

Re = 500,000
$\alpha = 18^\circ$

NACA 0012 Airfoil Suction/Blowing Control

Exhaustive Search
Suction Jet Study

Normalized Lift: $C_L/C_{LB}$

Normalized Drag: $C_d/C_{dB}$

$0.1=L_j=0.8$, $0.01=A=0.5$, $\theta=-90^0$, $-30^0$
Suction Jet Study: Location

Baseline

\[ L_j = 0.1 \]

\[ A = 0.173, \theta = -90^\circ \]

\[ L_j = 0.333 \]

\[ L_j = 0.567 \]
Suction Jet Study: Amplitude

$L_j=0.1, \tau = -90^0$
Blowing Jet Study

Normalized Lift: $C_L/C_{LB}$

Normalized Drag: $C_d/C_{dB}$

$0.1 = L_j = 0.8, 0.01 = A = 0.5, \theta = 30^0, 90^0$
Blowing Jet Study - Location

\[ A = 0.173, \ ? = 90^0 \]
Single Jet Study

• Suction:
  – Suction has a strong impact than blowing.
  – Leading edge (L/c < 0.1) position and perpendicular suction are better.
  – Separation bubble disappears when amplitude A > 0.2

• Blowing:
  – Blowing can have negative impact when amplitude is large.
  – avoid leading edge blowing and keep A < 0.1.
  – Tangential blowing is better.
  – Only when L/c>0.2,  A < 0.2 and the blowing angle is small do we observe a slightly positive influence of the blowing jet.
Two Jet System Optimization

- **Goal**
  - Examine the combined GA and CFD approach

- **Test Cases**
  - A combined suction and blowing jet system
  - A two suction jets system (1 run)
A Combined Suction and Blowing System

Two-Jet Control System: Suction Jet + Blowing Jet

5 Control Variable

- **Suction Location:** $0.05 \leq L^s_j \leq 0.8$
- **Suction Angle:** $-90^0 \leq \theta^s \leq 0^0$
- **Blowing Location:** $0.05 \leq L^b_j \leq 0.8$
- **Blowing Angle:** $0^0 \leq \theta^b \leq 90^0$
- **Blowing Amplitude:** $0 \leq A^b \leq 0.2$

Suction Amplitude: 0.03
A Combined Suction and Blowing System

Genetic Coefficient

\[ N_{\text{Generation}} = 100 \]
\[ N_{\text{PopSize}} = 32 \]
\[ N_{\text{Variable}} = 5 \]
\[ N_{\text{Update}} = 8 \]
\[ P_m = 0.1 \]

Aggregate Fitness Function

\[ (Fit_A)_{\text{max}} = a \cdot C_l / C_{lB} + b \cdot C_{dB} / C_d \]
\[ a = 1.0 \quad b = 1.0 \]
Parallel GA-CFD Computation

Computation Time

**Computation Time/Case (chromosome):**
- 2.5 Hour on 16 AMD XP 1800+ processors (KFC2)
- 1.5 Hour on 16 Intel Xeon 2.66G Processors (CFDME)

**Total Time (100 Generation):**
- 30 days on 48 AMD XP 1800+ processors (KFC2)
- 10 days on 64 Intel Xeon 2.66G Processors (CFDME)
A Combined Suction and Blowing System

Generation: 0

Diagram showing the relationship between suction and blowing locations and angles.
A combined Suction and Blowing System

- **Suction Location**
- **Suction Angle**
- **Blowing Location**
- **Blowing Angle**
- **Blowing Amplitude**
EARND with Diversity Control
EARND with Diversity Control

Basic GA

EARND with Diversity Control
A Combined Suction and Blowing System

\[ L_{JS} = 0.137383 \]
\[ \theta_S = -89.3069 \]
\[ L_{JB} = 0.741999 \]
\[ \theta_B = 45.4739 \]
\[ A_B = 0.195951 \]
A Two Suction-Jet System

Suction Location 1: 0.05 = L_{js1} = 0.8
Suction Angle 1: -90^0 = ?_{s1} = 0^0
Suction Location 2: 0.05 = L_{js2} = 0.8
Suction Angle 2: -90^0 = ?_{s2} = 0^0
A Two Suction-Jet System

Genetic Coefficient

\[ \text{NGeneration} = 100 \]
\[ \text{NPopSize} = 16 \]
\[ \text{NVariable} = 4 \Rightarrow \text{NUpdate} = 8 \]
\[ P_m = 0.1 \]

Aggregate Fitness Function

\[ (\text{Fit}_A)_{\text{max}} = a \cdot C_i / C_{iB} + b \cdot C_{dB} / C_d \]
\[ a = 1.0 \quad b = 1.0 \]

Suction Location 1:
Suction Angle 1:
Suction Location 2:
Suction Angle 2:
A Two Suction-Jet System
A Two Suction-Jet System

Top 100 fit Individuals
A Two Suction Jets System

Discussion of Optimized Result

<table>
<thead>
<tr>
<th>Case</th>
<th>( L_{jS1} )</th>
<th>( \theta_{S1} )</th>
<th>( L_{jS2} )</th>
<th>( \theta_{S2} )</th>
<th>( C_L/C_{LB} )</th>
<th>( C_{dB}/C_d )</th>
<th>( \text{Fit}_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>0.101834</td>
<td>-89.9168</td>
<td>0.140014</td>
<td>-86.0520</td>
<td>1.10318</td>
<td>1.13470</td>
<td>2.23789</td>
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<tr>
<td>1</td>
<td>0.101834</td>
<td>-90</td>
<td>0.140014</td>
<td>-90</td>
<td>1.10330</td>
<td>1.13473</td>
<td>2.23802</td>
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<tr>
<td>2</td>
<td>0.101834</td>
<td>-90</td>
<td>Double Width</td>
<td></td>
<td>1.09786</td>
<td>1.13897</td>
<td>2.23683</td>
</tr>
</tbody>
</table>
Concluding Remarks

- GA Algorithm
  - EARND with diversity control yields greater efficiency and robustness than the basic algorithm.
  - GA combined with CFD can be used for preliminary design optimization.
  - GA can identify and optimize control factors in sequence.
Conclusions and Discussions

A Combined Suction and Blowing Jet System
- Suction/Blowing Jet Control
  1. Suction jet is dominant.
  2. Blowing jet is secondary.

- Control Parameters
  1. Suction location and angle are most important and fastest converging parameters.
  2. The blowing location is of secondary importance.
  3. The blowing angle and blowing amplitude are least well-constrained and least critical.
Conclusions and Discussions

A Two Suction Jet System

- Both suction jets locate on the optimum location range and both suction angle approach to the ideal -$90^0$.
- A double width jet is no better than two suction jets separated with certain distance, but the difference is small.