RQ23-23 High Work High Efficiency Low Pressure Turbine Aerodynamics

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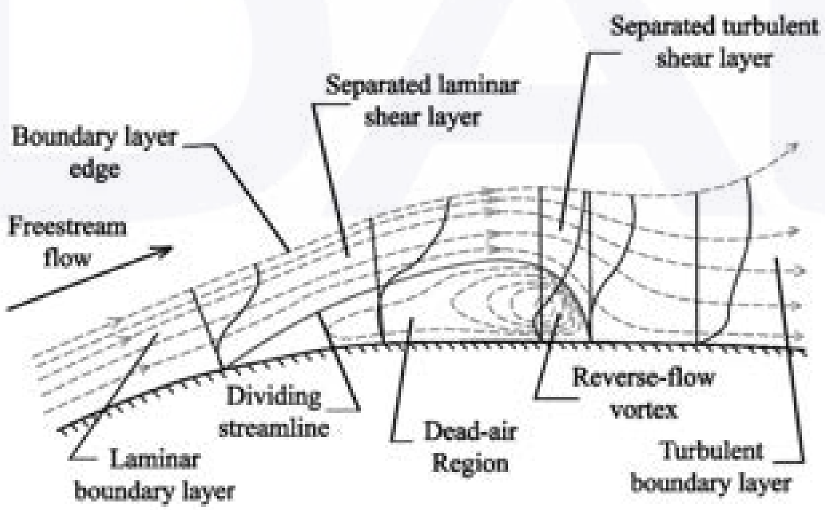
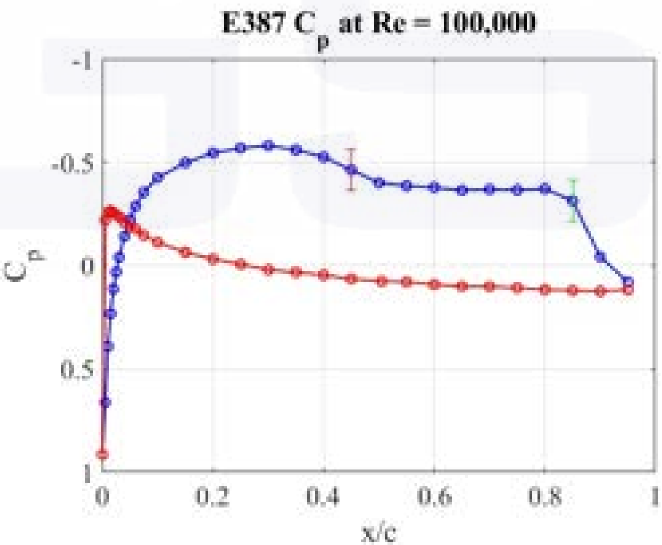
PA #: AFRL-2024-5599

Introduction - Laminar Boundary Layer Separation

- Laminar Boundary Layer Separation – characterized by an unstable separated shear layer and reversing flow, often occurs at low Reynolds number conditions
- Separation control well studied – want to optimize layout and operation of flow control systems
- Requires knowledge of ideal locations and frequencies for operation
- Eppler 387 experiences laminar separation at $\mathrm{Re} = 100000, \alpha = 0°$



Laminar separation bubble schematic



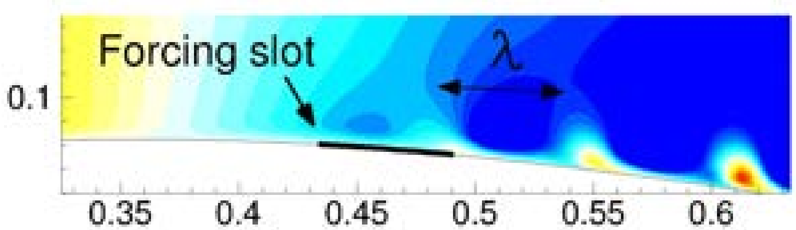
E387 Pressure Coefficient Plot

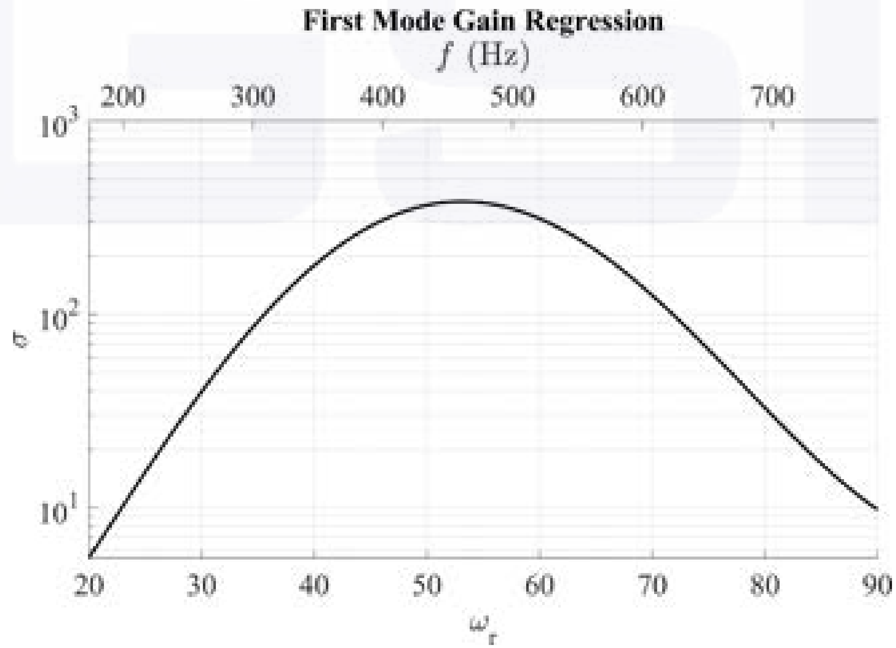
Determining Candidate Frequencies - Resolvent Analysis

- Resolvent Analysis performed by Prof. Andreas Gross (NMSU)
  - Built on similar equations as bi-global linear stability theory
  - Provides analysis of forcing modes and response modes of the flow
  - Examined 0% and 1% turbulence intensity
- First Mode peaks at $\omega_r = 53.1\ (461\text{Hz})$
- Active flow control analysis used a 5% freestream forcing amplitude at $w_r = 50\ (434Hz)$.

LES AFC Study Results[8]

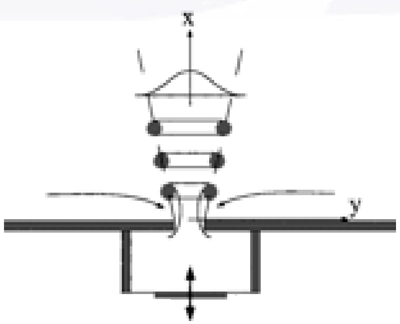
Case	c_l	c_d	c_l/c_d	c_m
FSTI = 0%	0.433	0.0191	22.7	−0.108
FSTI = 1%	0.399	0.0157	25.4	−0.0892
FSTI = 0%, AFC	0.371	0.0137	27.2 (+19.8%)	−0.0778
FSTI = 1%, AFC	0.361	0.0136	26.5 (+4.3%)	−0.0741

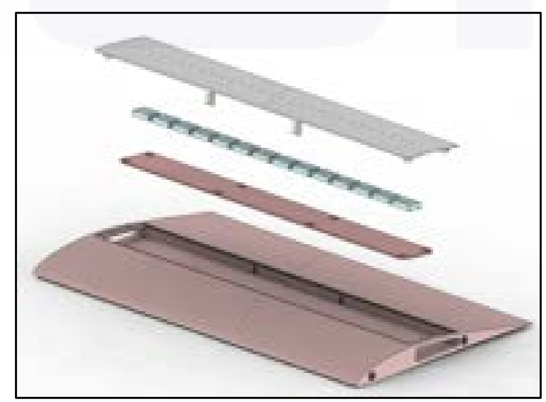




Facilities and Geometry

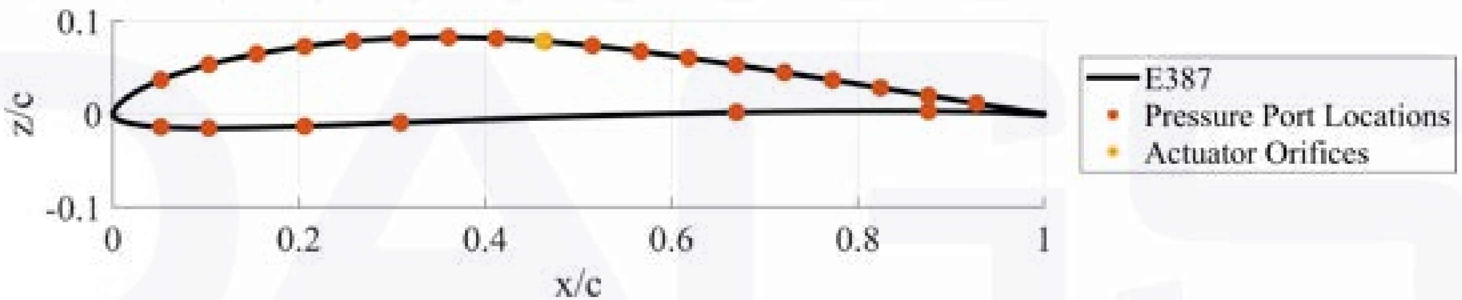
- Testing performed at AFRL's Low Speed Wind Tunnel facility (LSWT)
- Straight test section referred to as the Developmental Wind Tunnel
  - Airspeed range of $4.5 - 65\ \mathrm{m/s}$, $30\ \mathrm{cm}$. square by $60\ \mathrm{cm}$. test section
  - Turbulence intensity $\sim 0.6\%$
- Eppler 387 Airfoil
  - $16.5\ \mathrm{cm}$ chord
  - Max thickness $1.5\ \mathrm{cm}$ (~ 0.6 in.)
  - Using Acoustic speakers as driver for synthetic Jets

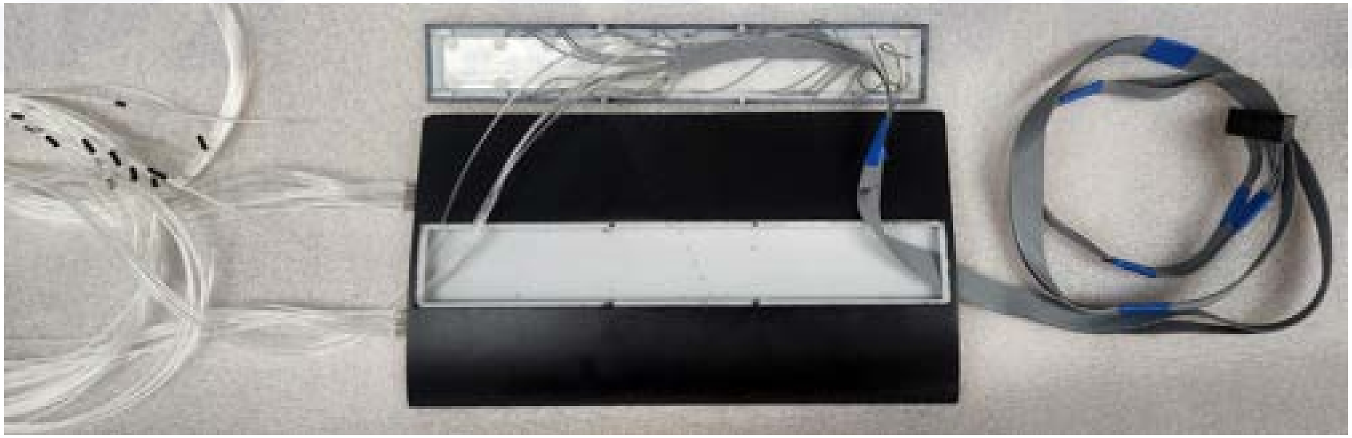




Test Article

- Coefficient of pressure measurements taken from selection of evenly spaced ports: $x/c = 5.15\%$ (18 SS, 6 PS)
- Actuators consisted of 14 speakers, 28 orifices of 1mm diameter
  - Spaced $y/\mathrm{b} = 0.0308$ covering 86% of the suction surface

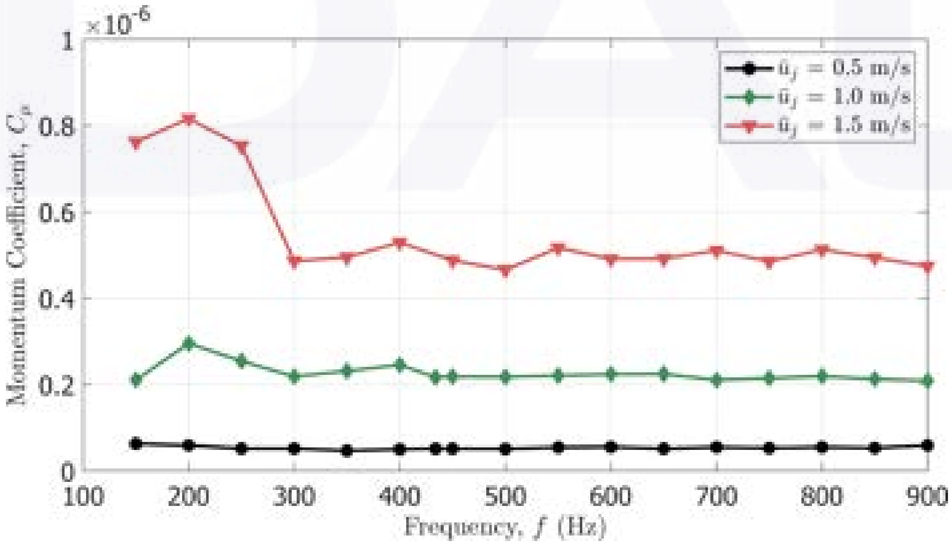


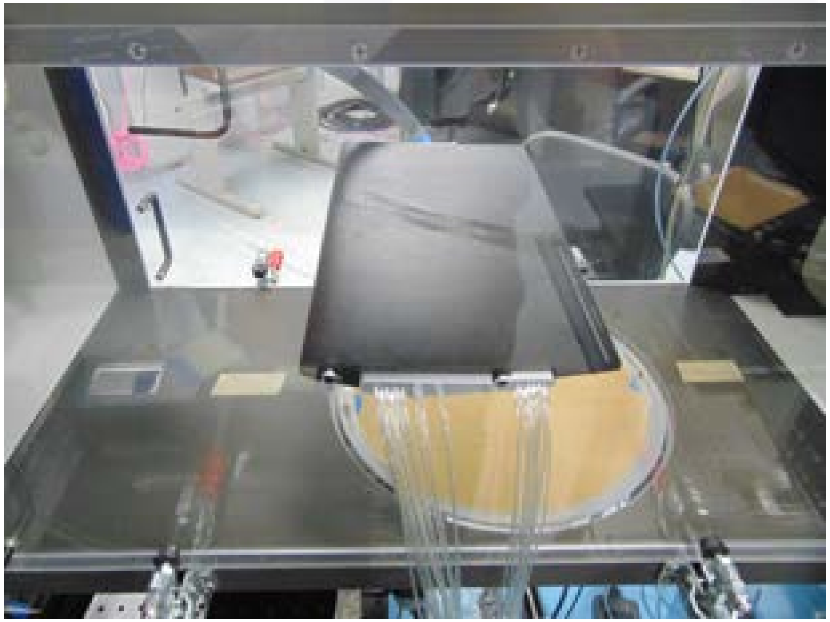


Actuator Characterization

- Actuators characterized using a hotwire in quiescent flow
- Lookup table created for jet velocities of $0.5, 1.0,$ and $1.5\ \mathrm{m/s}$
- Actuators give effective performance from $300\mathrm{Hz} - 900\mathrm{Hz}$
- Testing primarily occurred at 1.5m/s ($V_r \cong 15\%$), found to be most effective

$$C_\mu = J/q_{ref}A_{ref},\ \ J = \frac{\rho_{ref}}{T/2}\int_{T_1}^{T_2}\int_{A_{jet}} u_j^2(t)dt$$



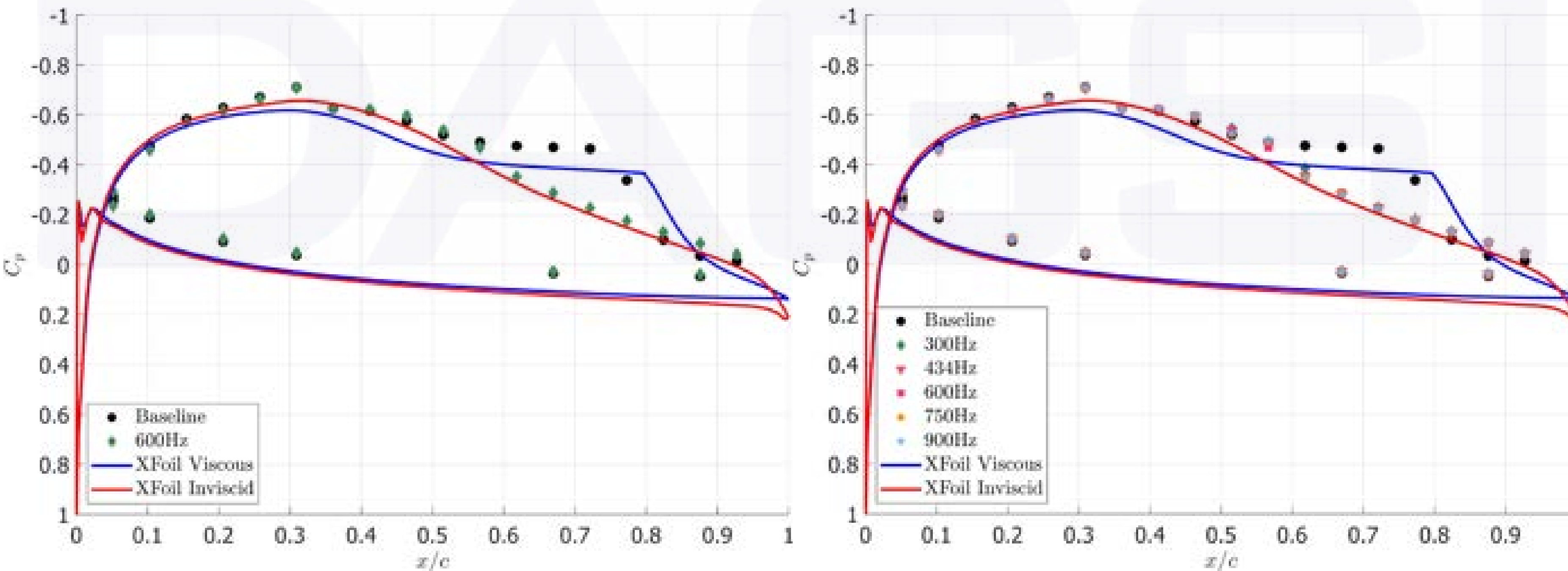


Coefficient of Pressure Measurements

- Measurements taken using Allsensor transducers and a selector valve

$$C_p = 1 - \left(\frac{P_{T,in} - p_{s,local}}{P_{T,in} - p_{s,in}}\right)$$

- Actuators have clear effect on separation bubble length

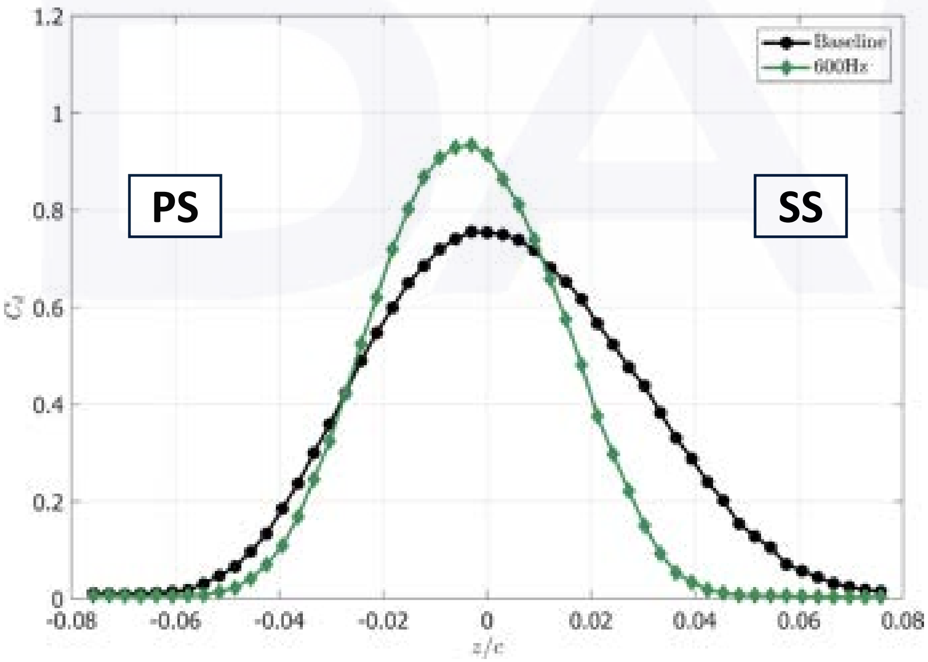


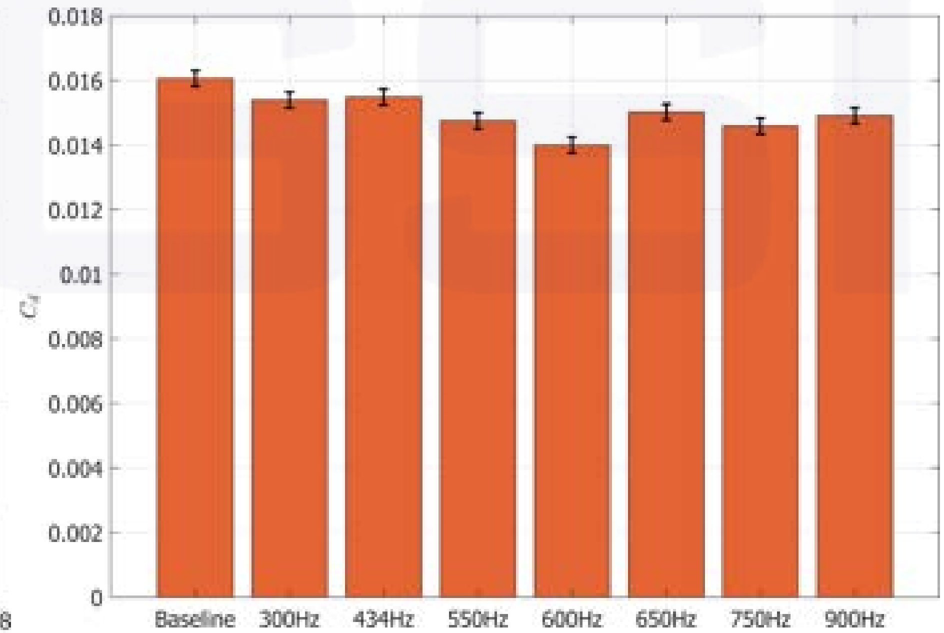
Drag Measurements

- Coefficient of drag estimated using the method of Jones (Goett 1939)

$$C_d = \frac{2}{C_x}\int^{w} \frac{\sqrt{P_{T,w} - p_w}}{\sqrt{P_{T,in} - p_{in}}}\left(1 - \frac{\sqrt{P_{T,w} - p_{in}}}{\sqrt{P_{T,in} - p_{in}}}\right) dz$$

- Measurements performed using a stationary upstream probe and 2 axis traversable downstream probe





Lift To Drag Ratio

- Coefficient of lift estimated by integration of coefficient of pressure

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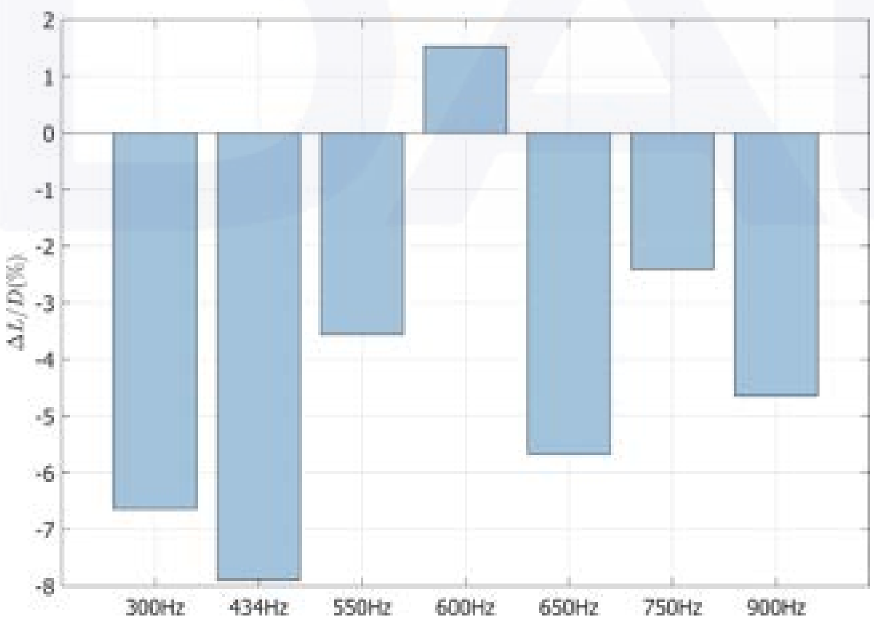
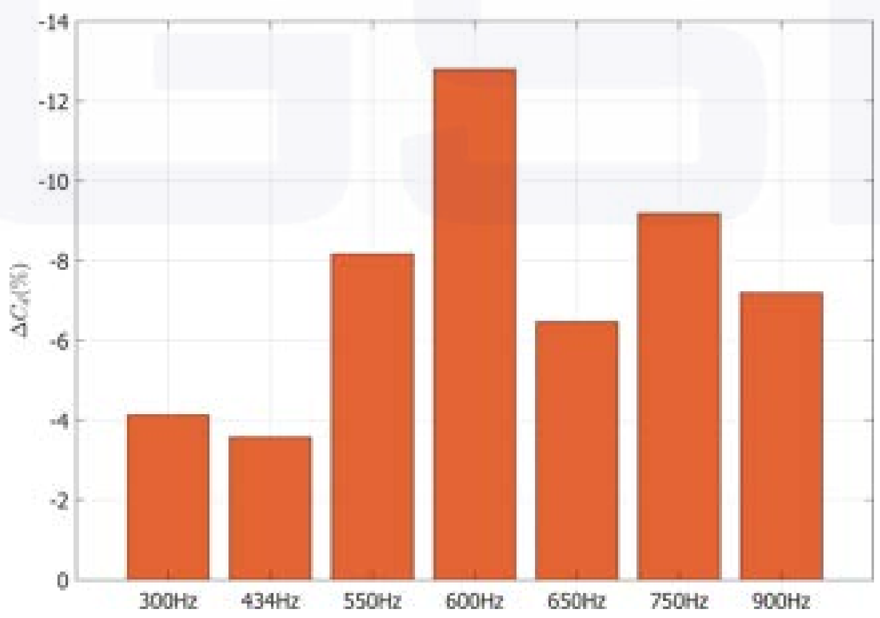
Experimental Results

Case	c_l	c_d	c_l/c_d
Baseline	0.3844	0.01606	23.36
434Hz	0.3414	0.01548	22.05 (-7.90%)
600Hz	0.3403	0.01400	24.30 (+1.52%)





Conclusions

- Used acoustic synthetic jets to verify a frequency dependence predicted by resolvent analysis
- Hotwire used to construct lookup table and ensure equal amplitude (momentum coefficient) used when sweeping frequency
- Actuators caused peak loss to increase, but lowers overall drag
- Largest drag reduction occurred at 600Hz
- Frequency dependence is evident, but a smooth curve as described by the resolvent analysis did not emerge

Future Work:

- Passive resonators designed at ideal frequencies
- Flow visualization of synthetic jet model
- Potential application in linear cascade on high zweifel airfoils.