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Prediction of Noise from Turbulent Boundary Layers with Suction

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Overview

- Introduction and Background
- Methodology
- Results
  - Aerodynamic
  - Aeroacoustics
- Summary and Conclusions
- Scope of Future Work

Boundary Layer Control Mechanisms

- Methods of controlling behavior of boundary layers
- Laminar flow - to delay transition to turbulence
- Turbulent flows - to reduce drag or to delay separation from the wall
- Mechanisms used:
  - Suction
  - Cooling of the wall
  - Blowing
  - Injection of another gas
  - Motion of the solid wall

Fig. 1 Airflow separating from a wing at a high angle of attack [1].

Example of Suction on a Wing

Used in wings, inlets and wind tunnels.

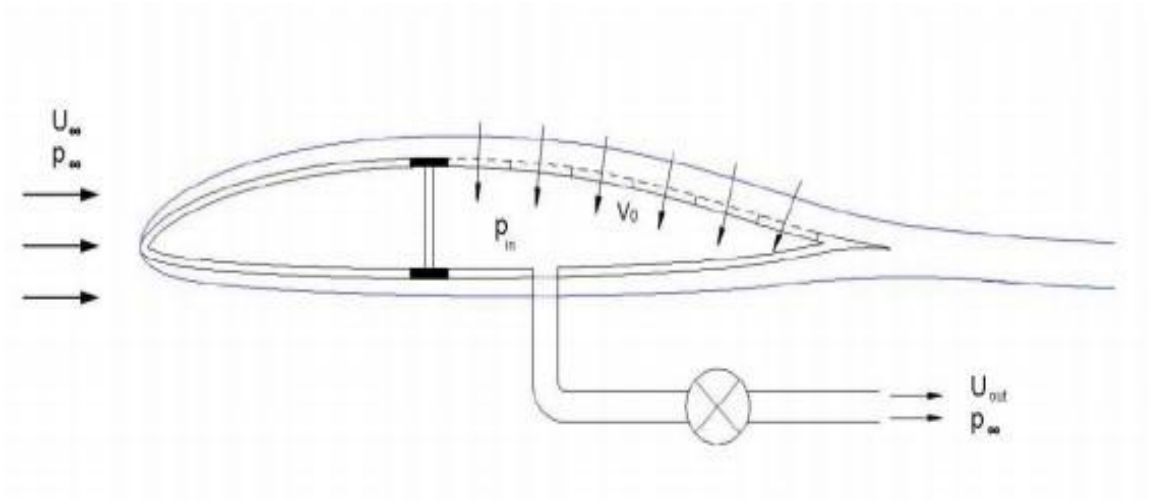


Fig. 2 Schematic representation of suction on wing of aircraft (Boermans[2008][2]).

Previous Work in Suction

- Experimental Work
  - **Reynolds and Saric (1986)[3]**
    - discrete suction being as effective as continuous suction.
  - **Zhu and Antonia (1995)[4]**
    - reduction in Reynolds shear stress.
  - **Djenidi et al. (2002)[5]**
    - reduction in three-dimensional turbulent features.
  - **Oyewola et al. (2003)[6]** :
    - quantified reduction in C_f; pseudo-relaminarization.

Previous Work in Suction (cont.)

- Numerical Investigations
  - **Park and Choi (1999)[7]**:
    - DNS; streamwise turbulent intensity recovers quickly, while other components recover over longer distance.
  - **Kametani et al. (2015)[8]**:
    - LES; more than 10% drag reduction.
  - **Bobke et al. (2015)[9]**:
    - LES; components of the Reynolds stress tensors were overall reduced.

Motivation and Present Approach

- Previous research: makes strong case for using suction as a form of boundary layer control.
- However, no studies have been performed to study the acoustic radiation.
- Important as designing wings with low noise is key to communities near airports.
- We predict acoustics from simplified numerical simulations of flat plate turbulent boundary layers with and without suction ports.

Objectives

- Examining change in acoustic radiation on a flat plate when suction is applied.
- Change in acoustic radiation for M = 0.30, 0.50 and 0.70.
- Quantify the acoustic source.
- Find correlations between change in noise and turbulence statistics (TKE).

Reference Computational Domain

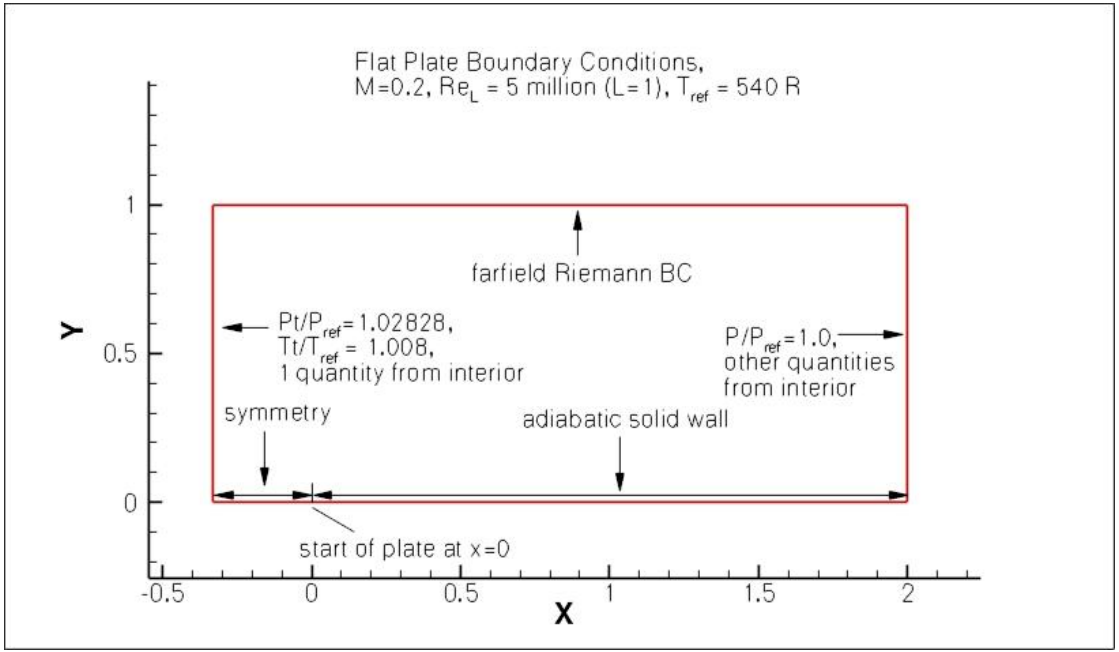


Fig. 3 Reference computational domain from NASA Turbulence Modeling Resource (TMR).

Computational Grids

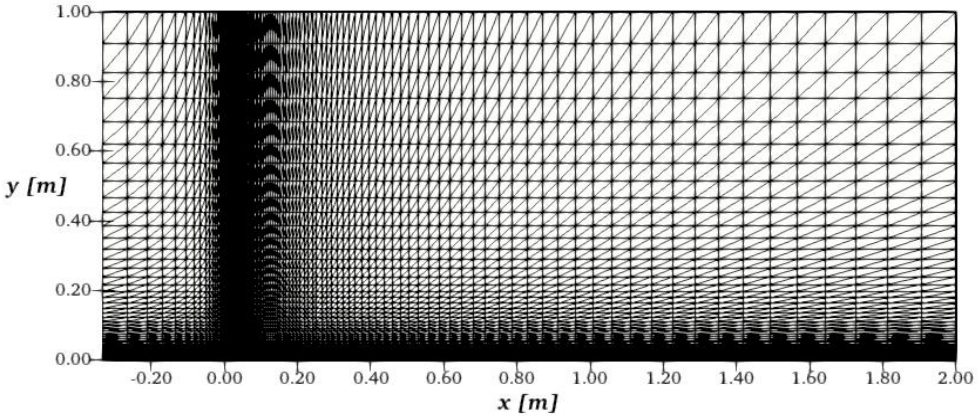


Fig. 4 Computational grid of flat plate.

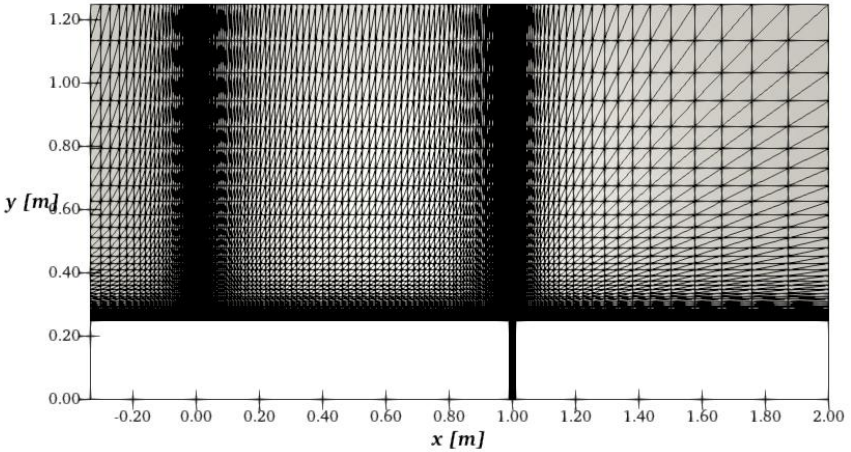


Fig. 5 Computational grid of flat plate with suction port.

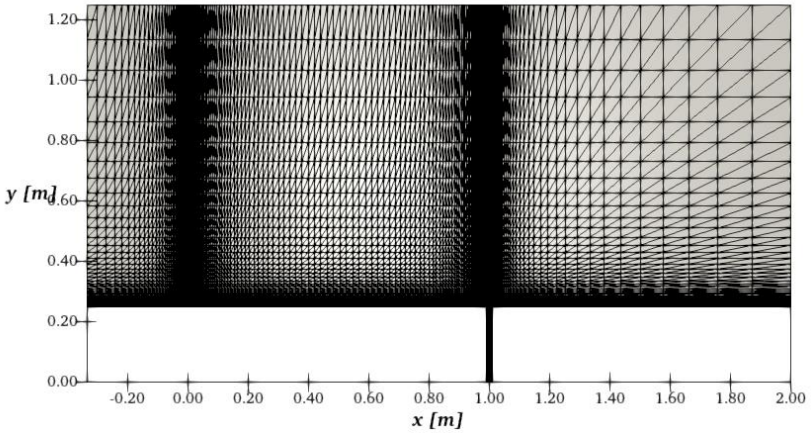
- 50x70 grid point mesh used for Fig. 3.
- 50x145 with 70x10 (suction port) used for Fig. 4.
- Grids created in Gmsh with y^+ set to 1.

Boundary Conditions

- Inlet
  - Total temperature and pressure inlet
  - T = 298 K; P = 101325 Pa
- Outlet
  - ZPG flat plate; P = 101325 Pa
  - Suction port outlet: P = 10 kPa
- Free-stream BC at the top.
- No-slip adiabatic wall at plate surface.
- Eulerian slip wall at x<0.

Mach Number (M_∞)	P_0 (Pa)	T_0 (K)
0.30	107849.92	303.69
0.50	120195.73	312.89
0.70	140553.48	327.221

Table 1. Total pressure and temperature for varying *M* cases.



Turbulence Model

- RANS k-ω SST Turbulence model of Menter[10]

$$\frac{\partial(\rho k)}{\partial t}+\frac{(\partial \rho u_j k)}{\partial x_j}=P-\beta^*\rho\omega k+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right]$$

$$\frac{\partial \rho\omega}{\partial t}+\frac{\partial \rho u_j\omega}{\partial x_j}=\frac{\gamma}{\nu_t}P-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\right]+2(1-F_1)\frac{\rho\sigma\omega_2}{\omega}\frac{\partial \omega}{\partial x_j}$$

- Blending function F_1 shifts between k-ε and k-ω models.
- k-ε model not preferred for applications where viscous sub-layer is resolved.
- k-ω model sensitive to inlet free-stream properties.

Mesh Verification

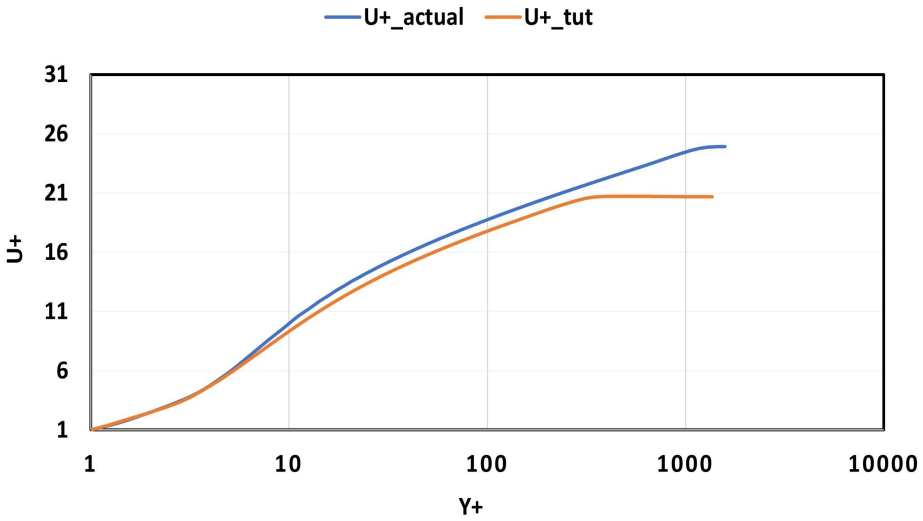


Fig. 6 Prediction compared to composite boundary layer profile at $M = 0.30$.

- Comparison made with benchmark mesh from NASA TMR.
- Error of 5 units.
- Error stems from 'log-layer' of the profile.

Acoustics Model

- Spectral density of acoustic pressure calculated by Cross spectral acoustic analogy (CSAA) of Miller [11].

$$S(X,\omega) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_{ijlm} l_{sy} l_{sz} F_t \mathcal{I} d\xi d\eta \qquad (1)$$

- Sound pressure level (SPL) per unit frequency (f) calculated by:

$$\mathrm{SPL_f} = 20 \log_{10} \frac{S^{1/2}(X,\omega)}{2 \times 10^{-5}} \qquad (2)$$

- Acoustics calculated from TBL profile at x = 1.03 m (one port diameter distance away from suction port).

Residual History

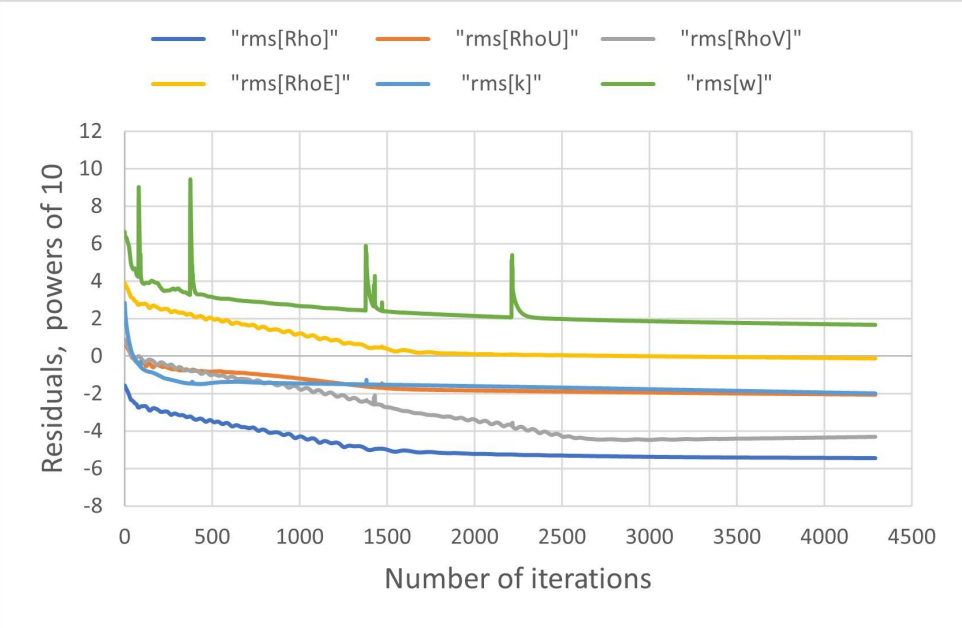
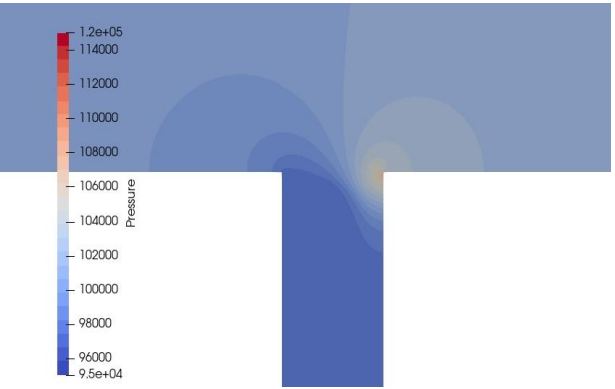


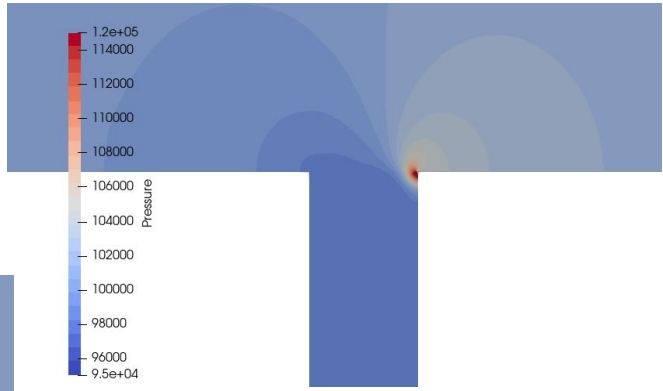
Fig. 7 Residual history of flat plate solution at M = 0.30

Pressure Contours



(a) $M = 0.30$

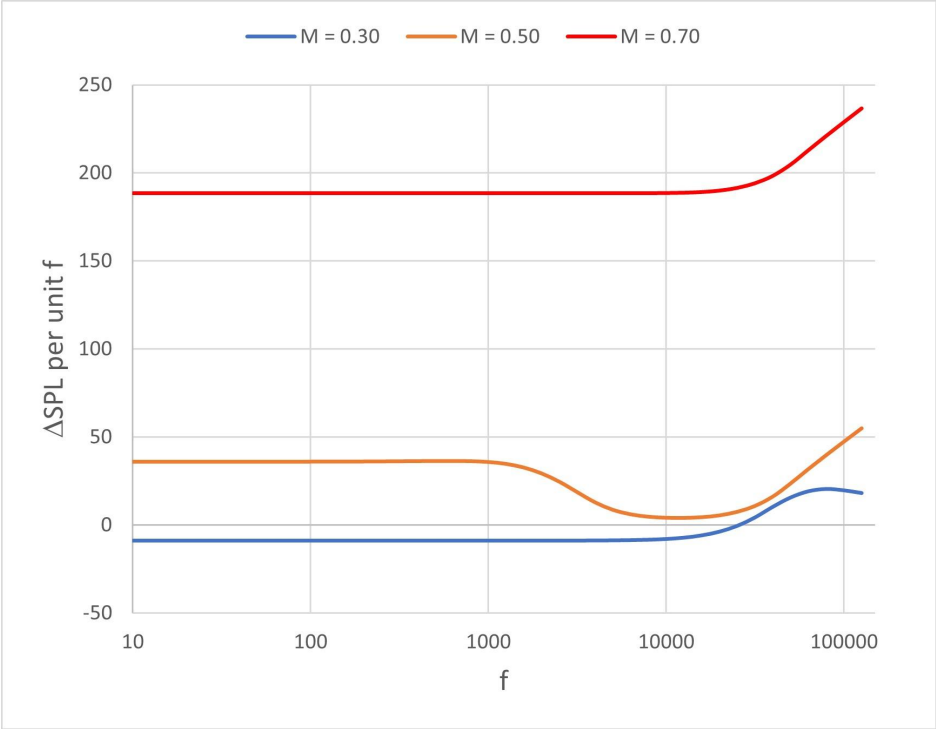
(b) $M = 0.50$



(c) $M = 0.70$

Fig. 8 Pressure contours around the suction port at various M

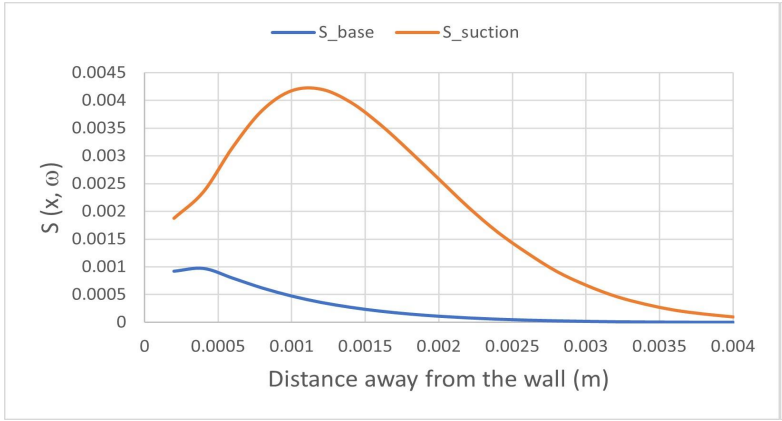
ΔSPL Variation with *f*

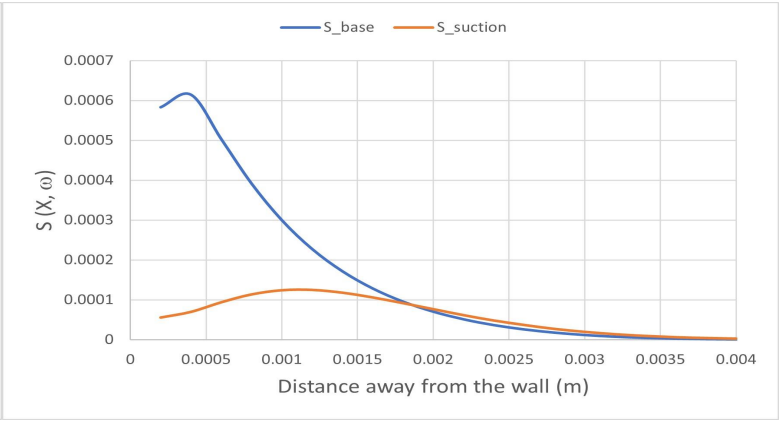


- $\triangle SPL = SPL_{NO\ SUCTION} - SPL_{SUCTION}$
- For $M = 0.30$, suction leads to increased noise.
- At $M = 0.50$ and 0.70, suction is observed to lead to reduced noise.
- Negligible noise with suction at $M = 0.70$.

Fig. 9 ΔSPL with *f* for $M = 0.30$, 0.50 and 0.70.

Noise Source Distribution at M = 0.30





(a)10 Hz

(b)31 kHz

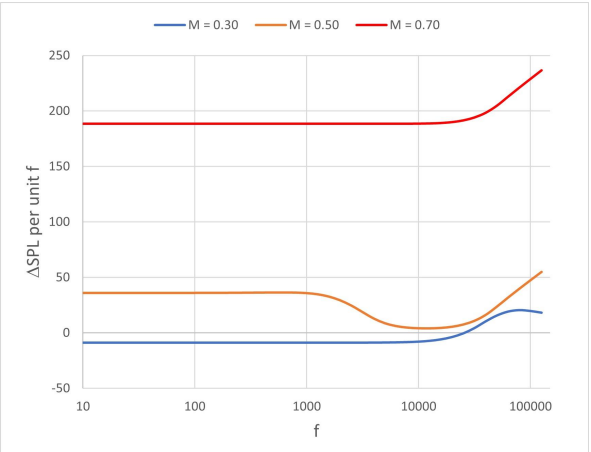
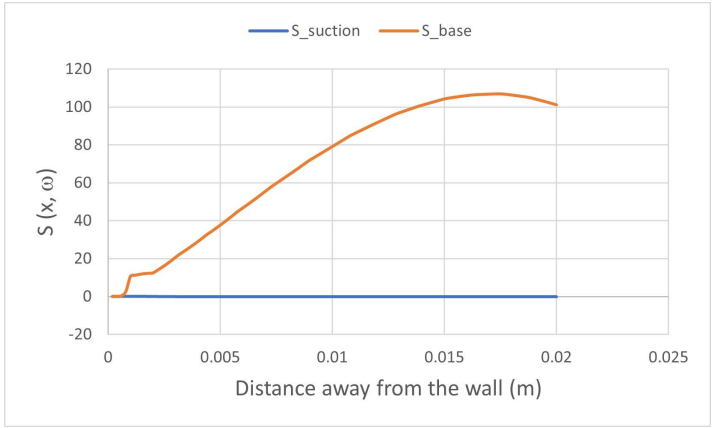
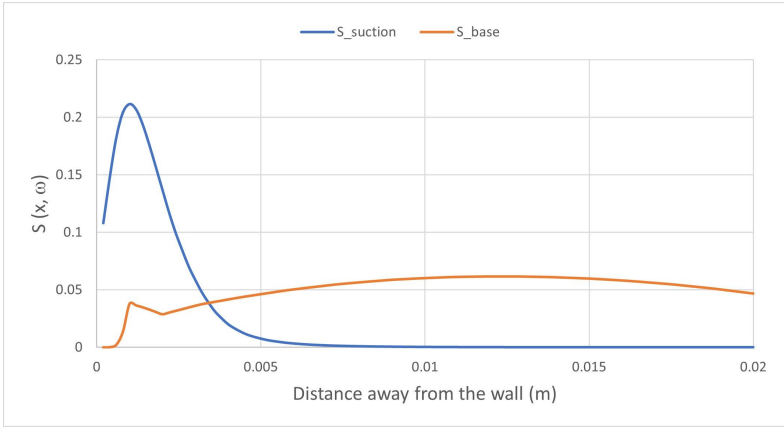


Fig. 10 Noise source distribution for M = 0.30 at f = (a) 10 Hz (b) 31 kHz.

Noise Source Distribution at M = 0.50



(a)100 Hz



(b)10 kHz

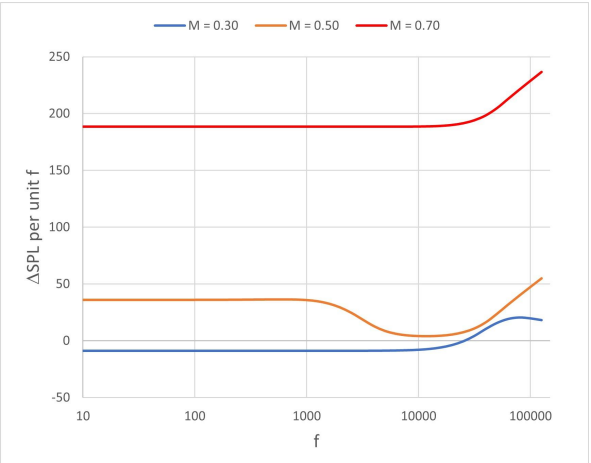
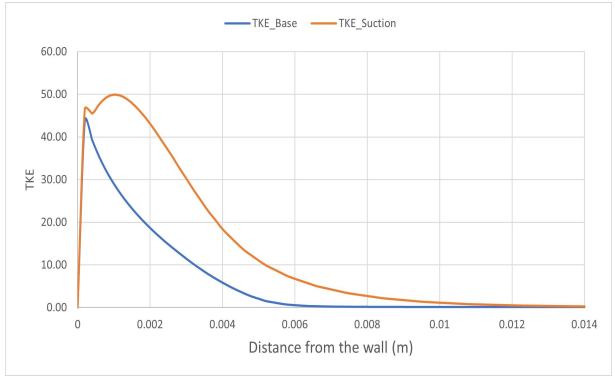
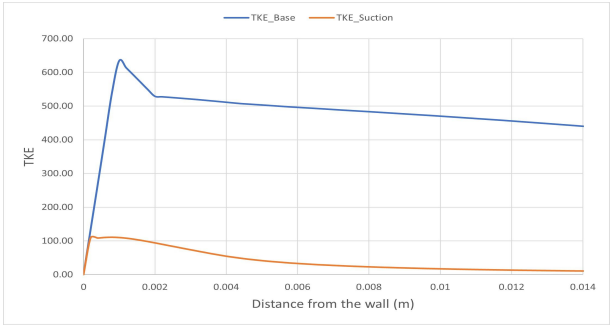


Fig. 11 Noise source distribution for M = 0.50 at f = (a) 100 Hz (b) 10 kHz.

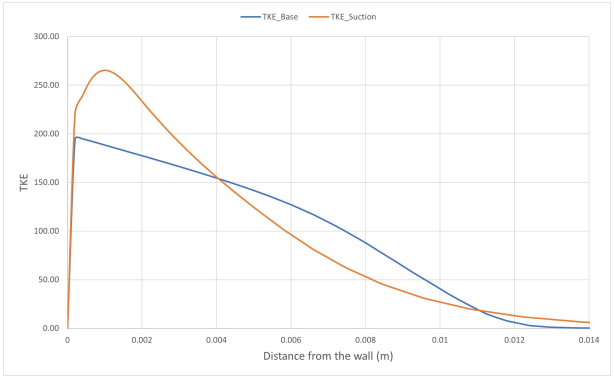
Turbulent kinetic energy (TKE) Variation



(a) $M = 0.30$



(b) $M = 0.50$



(c) $M = 0.70$

Fig. 12 Variation of TKE with distance away from the wall for M = (a) 0.30, (b) 0.50 and (c) 0.70.

- No linear correlation between TKE variation and change in noise.

Summary and Conclusions

- Predicted acoustic radiation with and without the presence of suction employing the CSAA of Miller.
- Showed source distributions at certain frequencies.
- Plotted variation in TKE.
- Conclusions:
  - Suction leads to more noise at lower subsonic M and reduced noise at higher subsonic M.
  - Threshold M between 0.30 and 0.50 where there is no change in noise.
  - No linear correlation between TKE and change in noise observed.

Scope of Future Work

- Better correlation models between change in noise and TBL statistics.
- Noise with more complicated suction geometries/ back pressure cases..
- Effect of multiple ports or uniform suction.
- Noise spectra from asymptotic turbulent boundary layer.
- Noise development further away from the port.

References

I. By DLR, CC-BY 3.0, CC BY 3.0 de, https://commons.wikimedia.org/w/index.php?curid=61072555
II. Boermans, L. M. M. (2008). Practical implementations of boundary layer suction for drag reduction and lift enhancement at low speed. In Presentation at KATnet II Workshop, Ascot UK.
III. Reynolds, G. A., & Saric, W. S. (1986). Experiments on the stability of the flat-plate boundary layer with suction. AIAA Journal, 24(2), 202–207.
IV. Zhu, Y., & Antonia, R. A. (1995, December). Effect of concentrated wall suction on the structure of a turbulent boundary layer. In Proceedings of the 12th Australasian fluid mechanics conference, Sydney, Australia (pp. 215-218).
V. Djenidi, L., Gall, P. E., Vincent, A., & Antonia, R. A. (2002, July). Effect of wall suction on the structure of a turbulent boundary layer. In 11th international symposium on applications of laser techniques in fluid mechanics. Paper (No. 23.1).
VI. Oyewola, O., Djenidi, L., & Antonia, R. A. (2003). Combined influence of the Reynolds number and localised wall suction on a turbulent boundary layer. Experiments in fluids, 35(2), 199-206.

References (cont.)

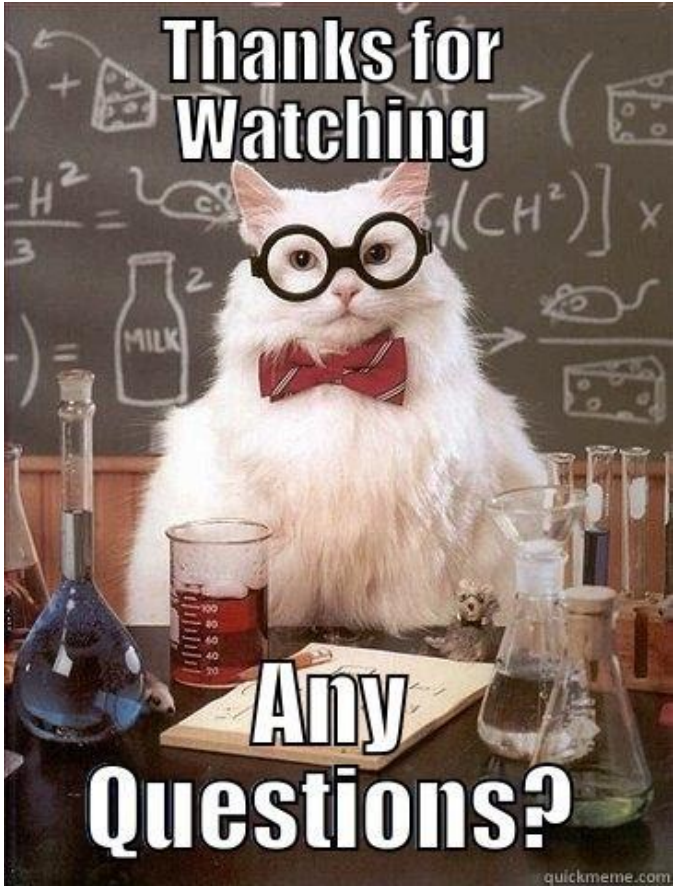
VII. Park, J., & Choi, H. (1999). Effects of uniform blowing or suction from a spanwise slot on a turbulent boundary layer flow. Physics of Fluids, 11(10), 3095-3105.

VIII. Kametani, Y., Fukagata, K., Örlü, R., & Schlatter, P. (2015). Effect of uniform blowing/suction in a turbulent boundary layer at moderate Reynolds number. International Journal of Heat and Fluid Flow, 55, 132-142

IX. Bobke, A., Örlü, R., & Schlatter, P. (2016). Simulations of turbulent asymptotic suction boundary layers. Journal of Turbulence, 17(2), 157-180.

X. Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. AIAA journal, 32(8), 1598-1605.

XI. Miller, S. A. E. (2015). Prediction of near-field jet cross spectra. AIAA Journal, 53(8), 2130-2150.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Any Questions?
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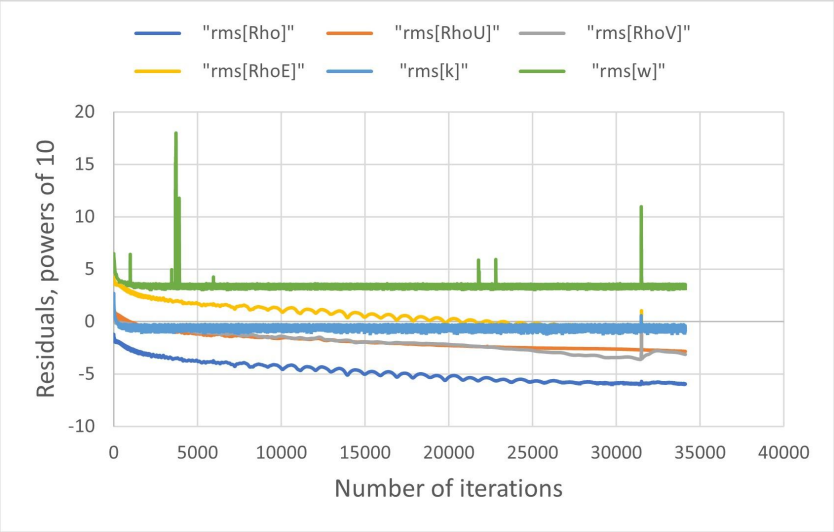

Fig. 5 Residual history of flat plate with suction port solution at M = 0.30

Numerical Method in Solver

- Convective Numerical Method - ROE
- 2nd Order Upwind
- Numerical method for spatial gradients - Weighted Least Squares
- Venkatakrishnan slope limiter

Velocity Profile at Suction Outlet

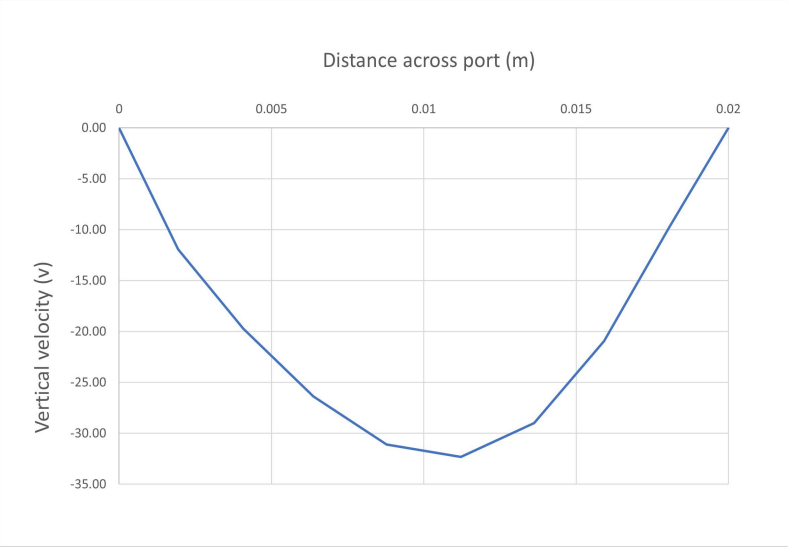

Fig. Inlet of suction port for $M = 0.30$.

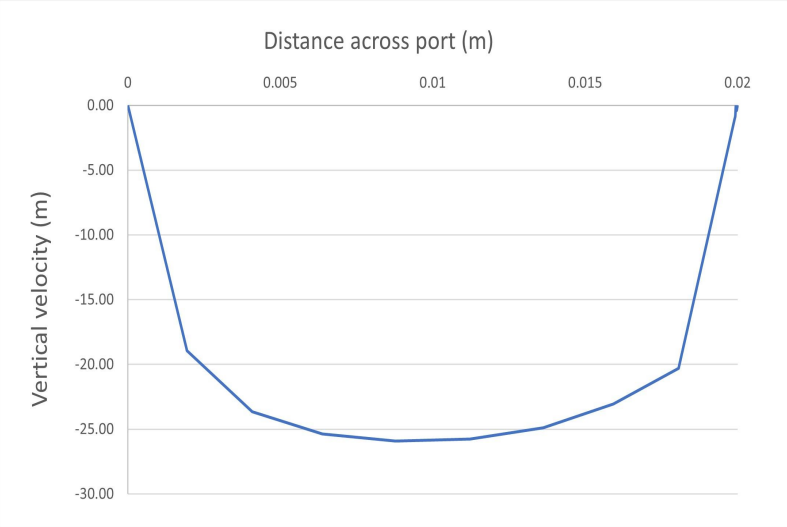

Fig. Outlet of suction port for $M = 0.30$.