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# Numerical Study on Flow Separation of A Transonic Cascade

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**Objective:**

- Numerical prediction of the boundary layer separation for a transonic cascade

**Background:**

- Flow separation is one of the unsteady aerodynamic forcing sources exciting blade flutter

**Motivation:**

- Develop a CFD solver to predict the steady and unsteady flow separation for compressor

## Governing Equations

3D Reynolds averaged NS equations:

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = \frac{\partial R}{\partial x} + \frac{\partial S}{\partial y} + \frac{\partial T}{\partial z} \qquad (1)$$

where

$$Q = [\bar{\rho}, \bar{\rho}\tilde{u}, \bar{\rho}\tilde{v}, \bar{\rho}\tilde{w}, \bar{\rho}\tilde{e}]^T$$

$$E = [\bar{\rho}\tilde{u}, \tilde{p} + \bar{\rho}\tilde{u}^2, \bar{\rho}\tilde{u}\tilde{v}, \bar{\rho}\tilde{u}\tilde{w}, (\bar{\rho}\tilde{e} + \tilde{p})\tilde{u}]^T$$

$$F = [\bar{\rho}\tilde{v}, \bar{\rho}\tilde{u}\tilde{v}, \tilde{p} + \bar{\rho}\tilde{v}^2, \bar{\rho}\tilde{v}\tilde{w}, (\bar{\rho}\tilde{e} + \tilde{p})\tilde{v}]^T$$

$$G = [\bar{\rho}\tilde{w}, \bar{\rho}\tilde{u}\tilde{w}, \bar{\rho}\tilde{v}\tilde{w}, \tilde{p} + \bar{\rho}\tilde{w}^2, (\bar{\rho}\tilde{e} + \tilde{p})\tilde{w}]^T$$

$$R = \frac{1}{Re}[0, \bar{\tau}_{xx}, \bar{\tau}_{xy}, \bar{\tau}_{xz}, \beta_x]^T$$

$$S = \frac{1}{Re}[0, \bar{\tau}_{xy}, \bar{\tau}_{yy}, \bar{\tau}_{yz}, \beta_y]^T$$

$$T = \frac{1}{Re}[0, \bar{\tau}_{xz}, \bar{\tau}_{yz}, \bar{\tau}_{zz}, \beta_z]^T$$

shear stresses are expressed as,

$$\bar{\tau}_{ij} = -\frac{2}{3}(\tilde{\mu} + \mu_t)\frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij} + (\tilde{\mu} + \mu_t)\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

$\beta_x, \beta_y,$ and $\beta_z$ are expressed as,

$$\beta_i = (\tilde{\mu} + \mu_t)\tilde{u}_j\tau_{ij} + \frac{1}{\gamma - 1}\left(\frac{\tilde{\mu}}{Pr} + \frac{\mu_t}{Pr_t}\right)\frac{\partial \tilde{a}^2}{\partial x_i}$$

**Numerical Algorithms**

- Implicit Gauss-Seidel Relaxation Time Marching

- Roe and Van Leer Schemes for inviscid fluxes, 3rd Order MUSCL-type differencing

- 2nd order central differencing for viscous terms

- Baldwin-Lomax Turbulence model

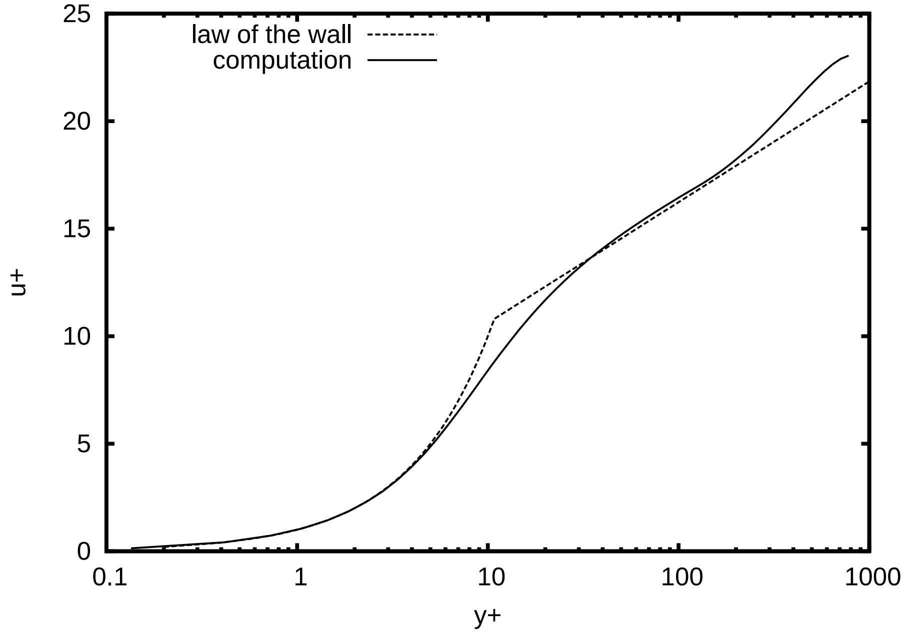



Figure 1: Computed velocity profile comparison with the law of the wall

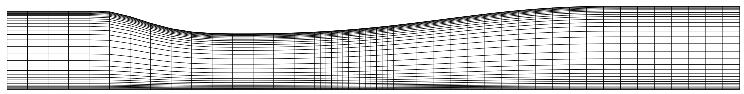


Figure 2: **The transonic inlet-diffuser mesh**

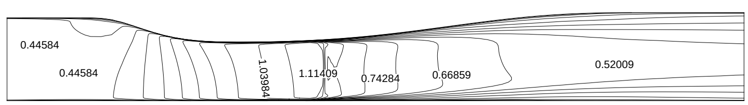



Figure 3: **Mach number contours of the transonic inlet-diffuser**

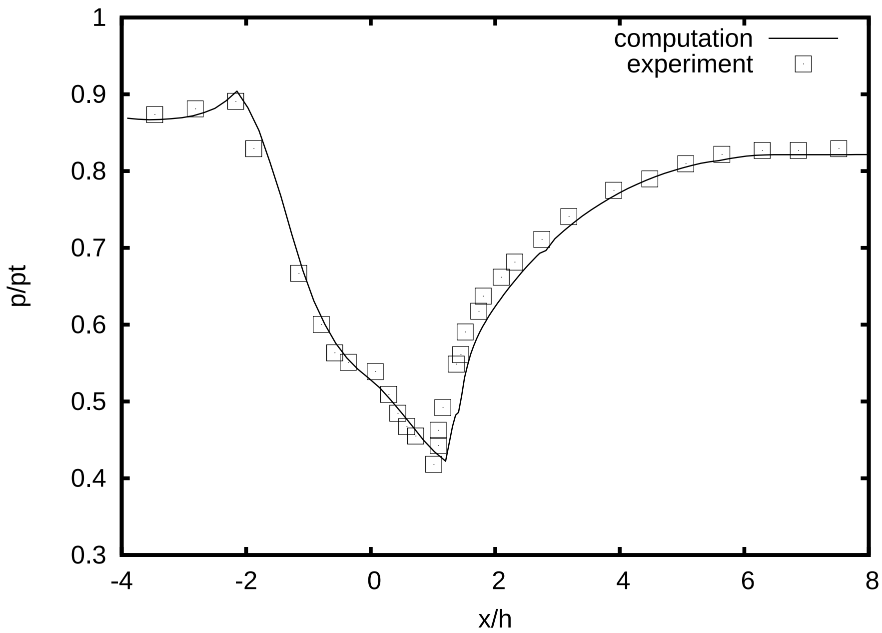



Figure 4: Upper wall pressure distribution of the transonic inlet-diffuser

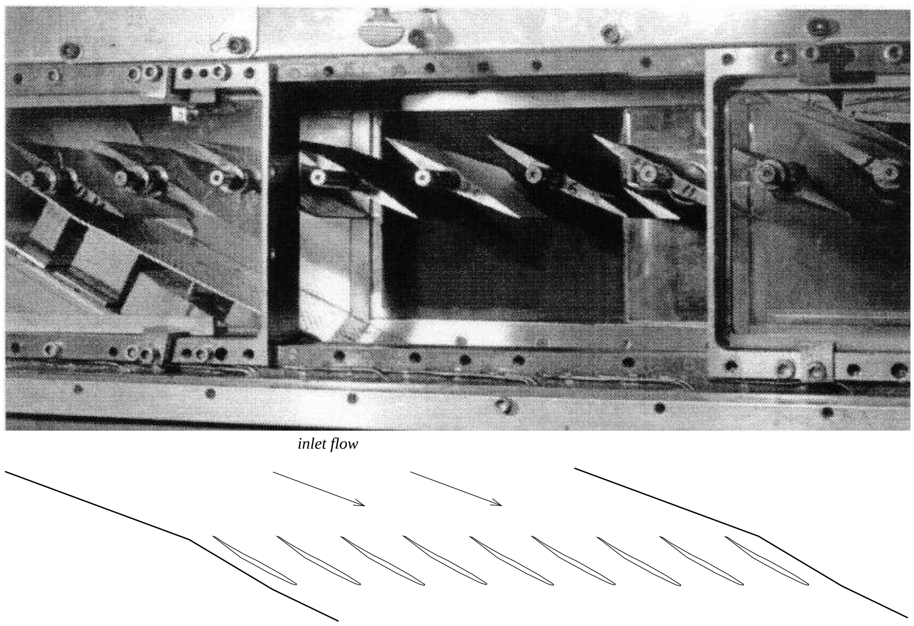



Figure 5: **NASA transonic flutter cascade tunnel**

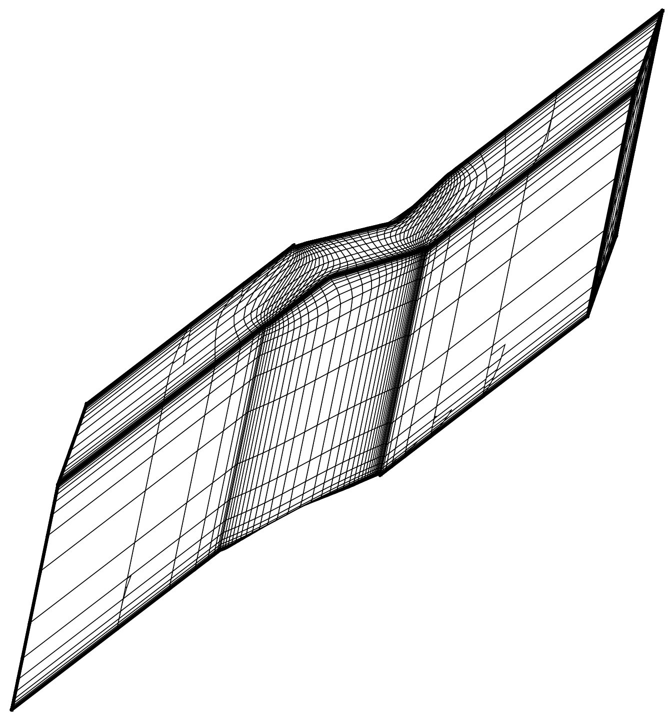


Figure 6: **Cascade 3D mesh**

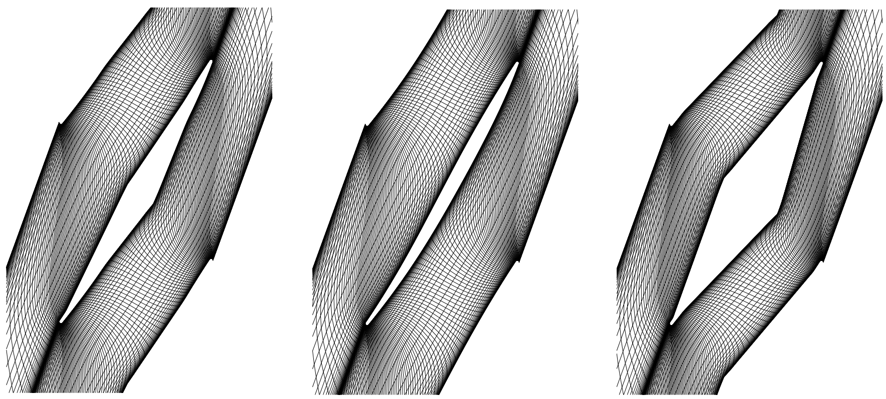


Figure 7: **Cascade 3D mesh**

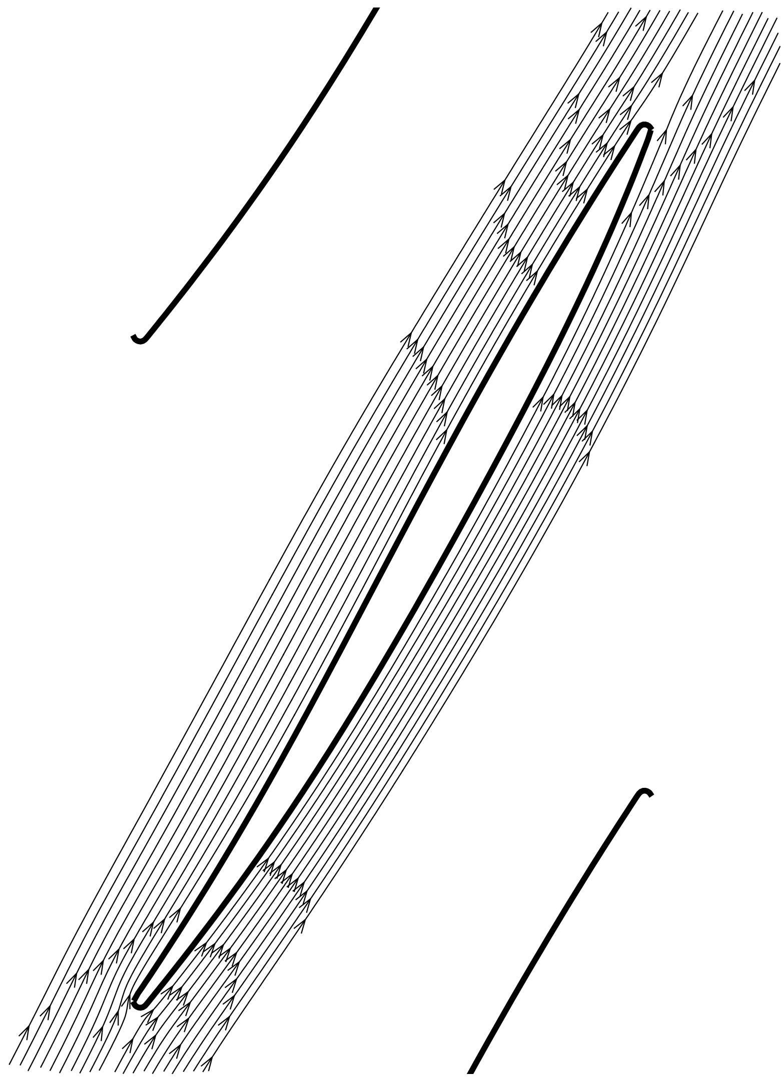


Figure 8: **Flow pattern of the inlet-diffuser at incidence**

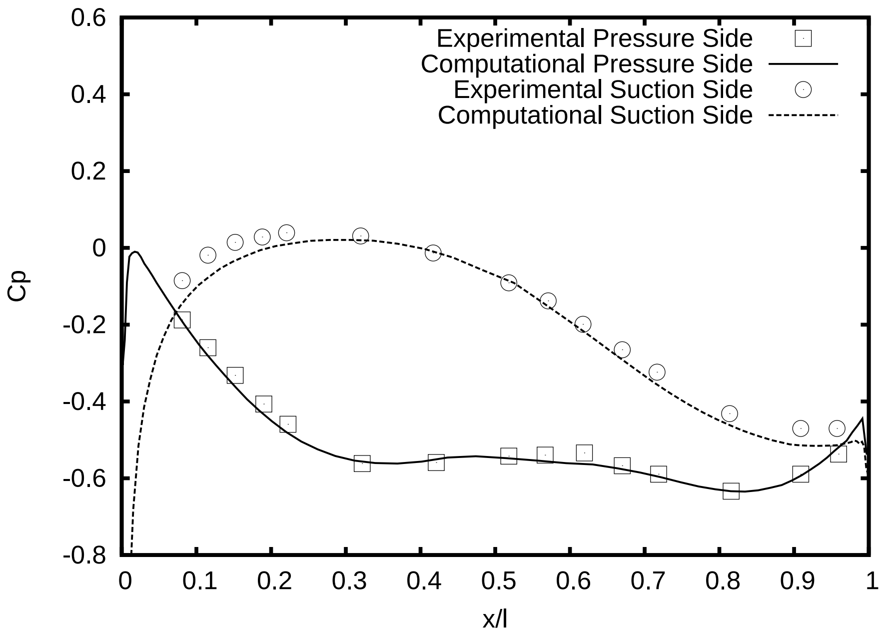
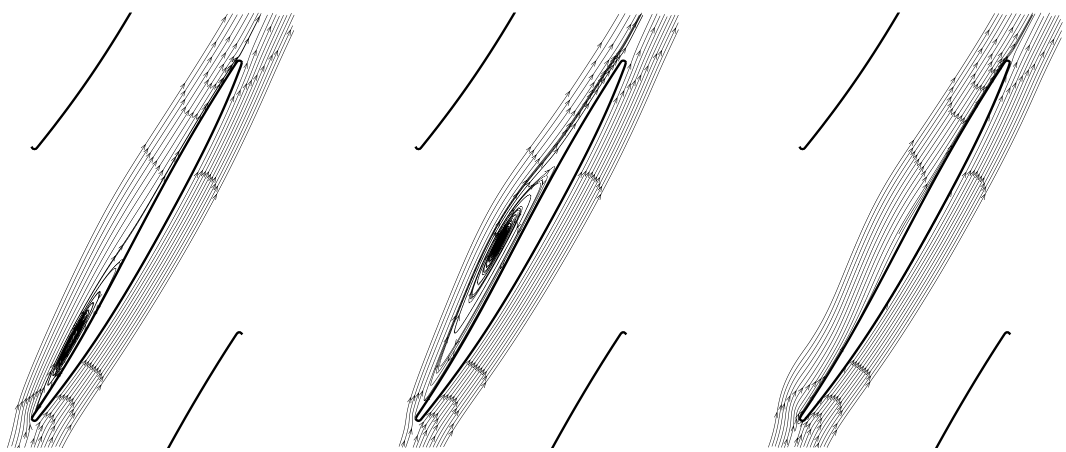
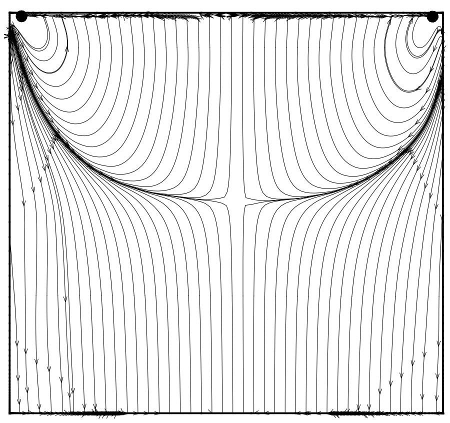



Figure 9: Mid-span static pressure distribution at Mach number 0.5

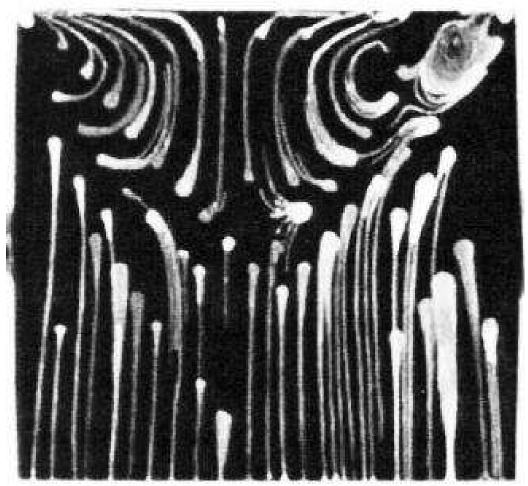


(a) Ma=0.5 (b) Ma=0.8 (c) Ma=1.18

Figure 10: Mid-span fbw pattern under different inlet Mach numbers

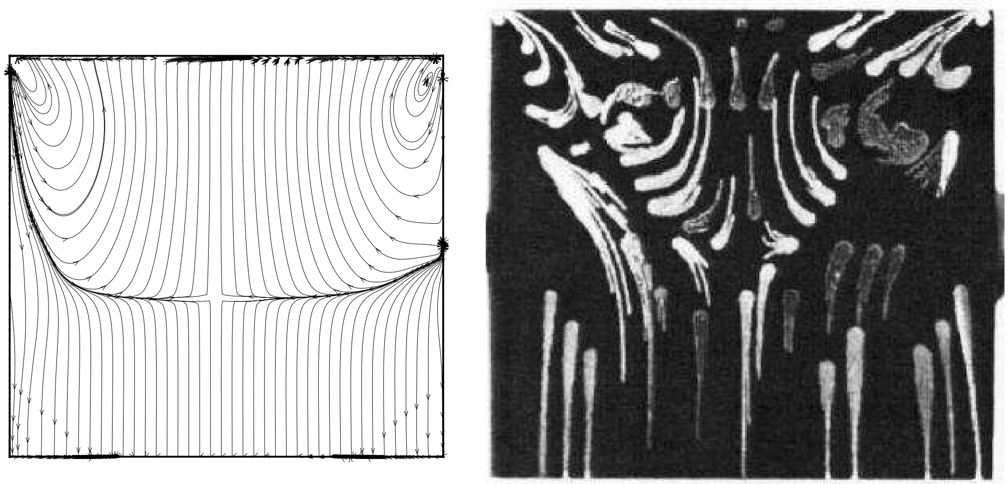


(a) Computed fbw pattern



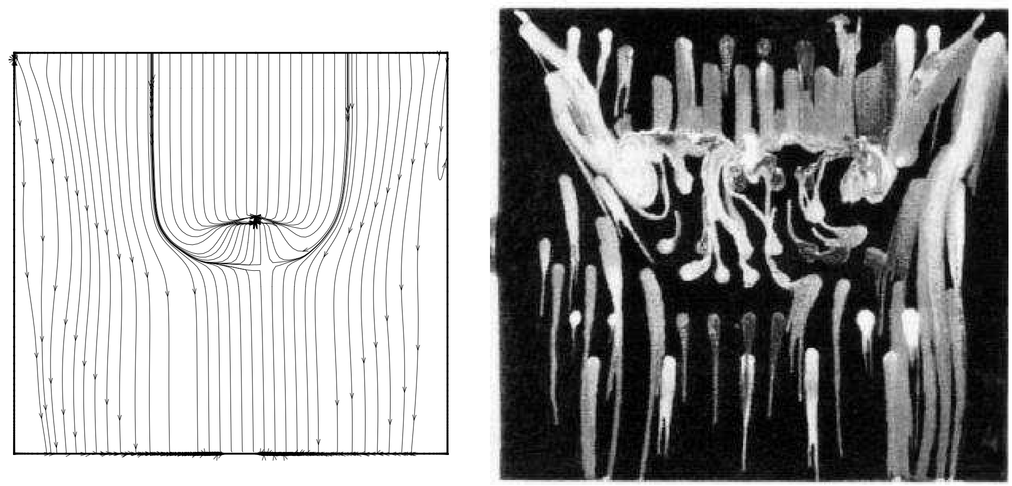
(b) Experiment visualization

Figure 11: Suction surface fbw pattern at Mach number 0.5



(a) Computed fbw pattern (b) Experiment visualization

Figure 12: Suction surface fbw pattern at Mach number 0.8



(a) Computed fbw pattern (b) Experiment visualization

Figure 13: Suction surface fbw pattern at Mach number 1.18

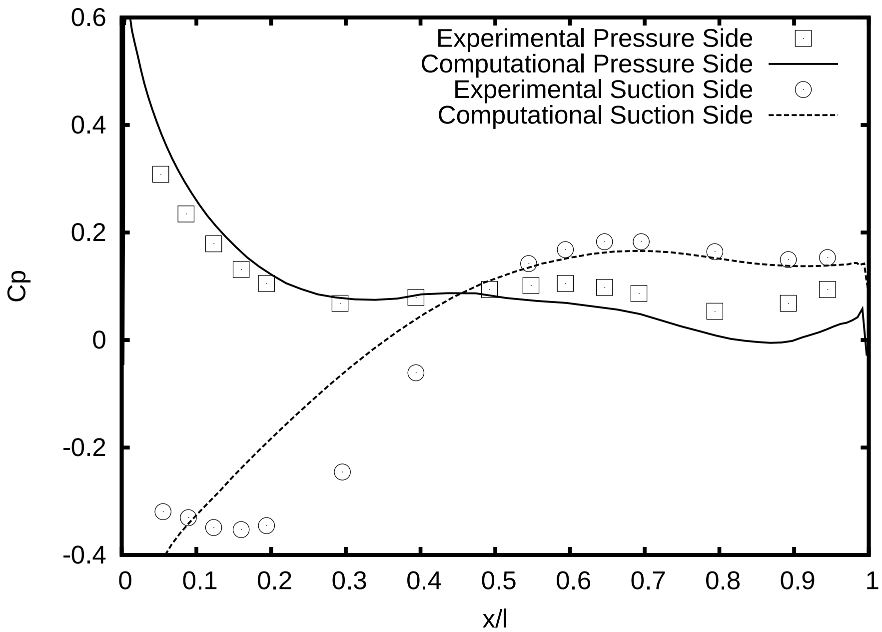



Figure 14: Mid-span static pressure distribution at Mach number 0.5

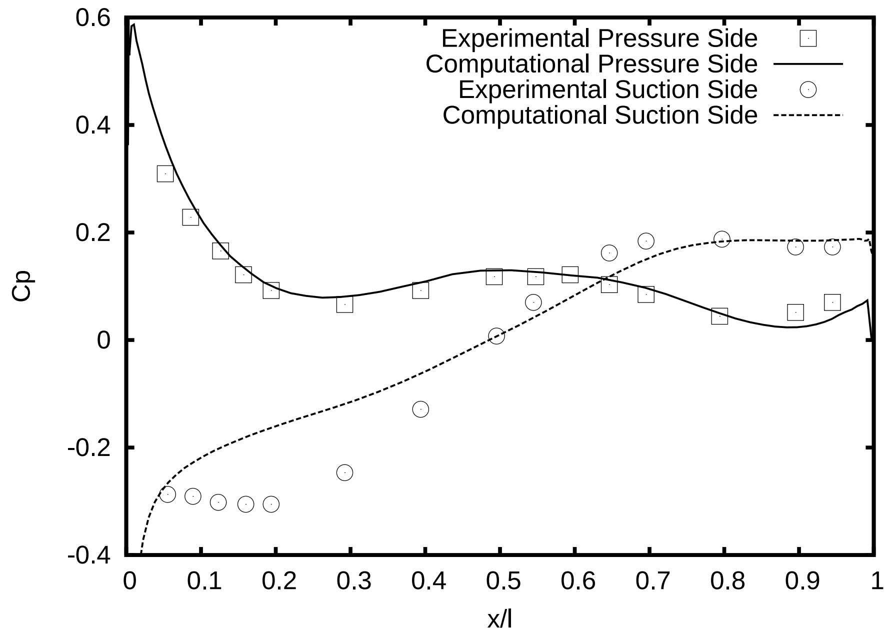



Figure 15: Mid-span static pressure distribution at Mach number 0.8

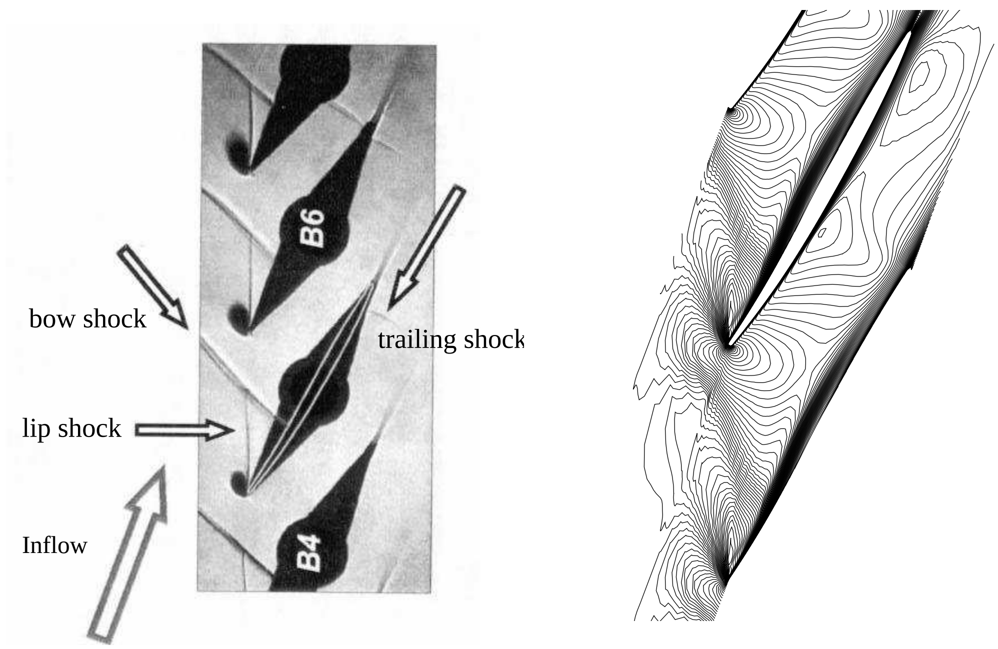



Figure 16: Experimental shock structure of the NASA transonic cascade at Mach number 1.18

**Conclusions:**

- NASA GRD flutter compressor cascade calculated at incidence of $0°$ and $10°$, inlet M=0.5, 0.8, 1.0
- The surface pressure distribution agrees well with the experiment with no flow separation.
- At high incidence and subsonic, flow separation starts at leading edge.
- The separation bubble length predicted agree well with the experiment.
- The computed surface pressure with separation rises more steeply than that at experiment, overall agreement is reasonable.
- At supersonic, the flow is attached-separated-reattached. The separation is due to the shock wave/boundary layer interaction.
- With Baldwin-Lomax turbulence model, the Van Leer scheme predicts the separation region agreeing better than the Roe scheme.