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How Shock Wave Interacts with a Vortex ?

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When a vortex diffracts upon encountering a vortex, many strong and weak waves are produced in the course of interaction. They are the cause of shock wave attenuation and noise production. This phenomenon is fundamental to understanding the more complex supersonic turbulent jet noise. In this paper we have reviewed the research on shock-vortex interaction we have carried on last seven years.

We have computationally investigated the parameter effect. When a shock is strong, shock diffraction pattern becomes complex since the slip lines from the triple points on Mach stem curl into the vortex, causing an entropy layer. When the vortex is unstable, vortexlets are brought about each of which make shock diffraction of a reduced intensity. Strong vortex produces quadrupole noise as it impinges into a vortex.

Elementary interaction models such as shock splitting, shock reflection, and shock penetration are presented based on shock tube experiment. These models are also verified by computational approach. They easily explain production and propagation of the aforementioned quadrupole noise. Diverging acoustics are explained in terms of shock-vortexlet interactions for which a computational model is constructed.

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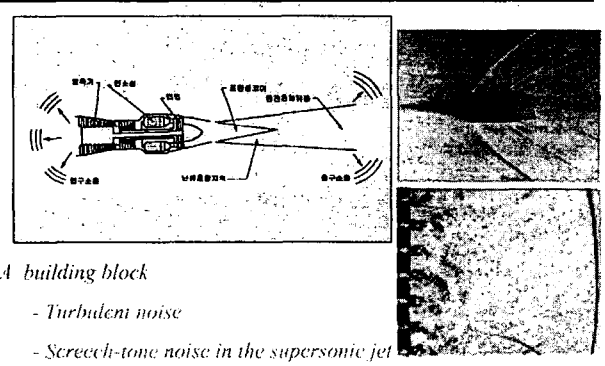
Content

1. Why shock-vortex interaction?



A building block

- *Turbulent noise*
- *Screech-tone noise in the supersonic jet*
- *Medical application of shock*

2. Why shock-vortex interaction?

Sound

- *Emission* (Aerodynamic Sources, nonlinear)
- *Propagation* (Wave Equation, linear)

Shock-Vortex Interaction

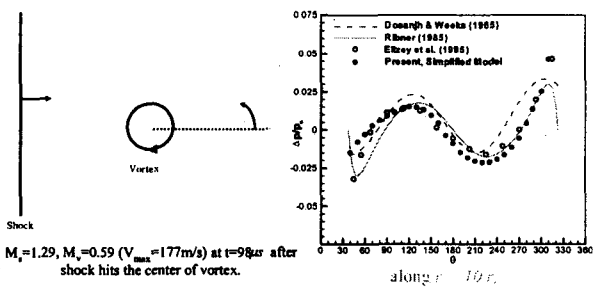
- *Shock distortion* (Shock Dynamics, nonlinear)
- *Sound Generation* (Acoustics, nonlinear + linear)

3. Why shock-vortex interaction?

- Dosanjh & Weeks (1965, 1967, *AIAA Journal*):
  - Experiment (Schilieren, Mach-Zehnder interferometry)
  - Acoustic analogy: *quadrupole* sound propagation
- Ellzey et al. (1995, *Phys. Fluids*):
  - Shock distortion
  - Quadrupole sound generation
- Inoue & Hattori (1999, *J. Fluid Mechanics*):
  - High-order sound components (2^{nd}, 3^{rd}, ... acoustic waves)

4. Why shock-vortex interaction?

Quadrupole Pressure Distribution

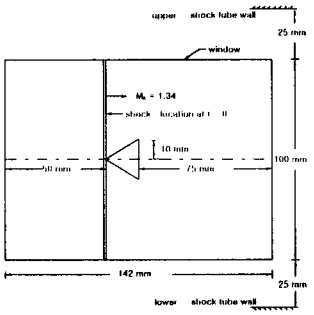


M_s=1.29, M_v=0.59 (V_{max}=177m/s) at t=98μs after shock hits the center of vortex.

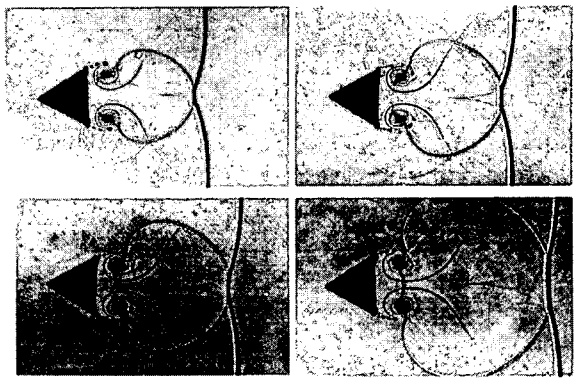
along r = 10 r.

5. Why shock-vortex interaction?

Benchmarking Schardin's Experiment (1957)

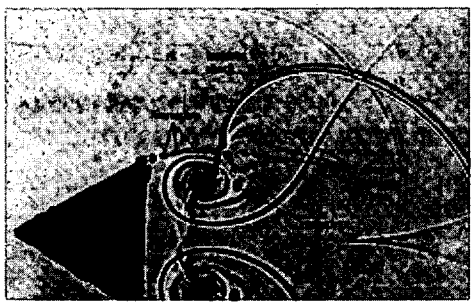


6. Why shock-vortex interaction?



7. Why shock-vortex interaction?

Diverging Acoustics



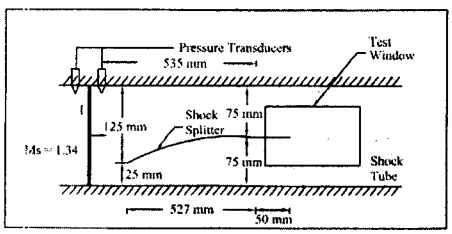
Chang and Chang: *Shock Waves, an Inter. J.* (2000)

8. Why shock-vortex interaction?

How Acoustic Waves are generated by Shock-Vortex Interaction?

Shock Diffraction → **Sound Generation**

A simple experimental model



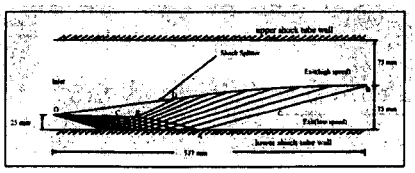
Experiment:

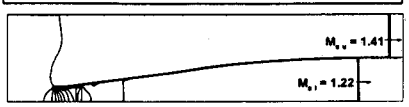
shock tube, shadowgraphy, holographic interferometry

(Computation:

N-S equations, TVD method, QUAG)

Design of a Shock Splitter





Whitham's ray shock theory, MOC

$$K_{-OA} = \theta_O + \omega_O = \theta_A + \omega_A$$

$$K_{-AB} = \theta_A - \omega_A = \theta_B - \omega_B$$

$$\theta_O = \omega_B - \omega_C = \int_{M_\infty}^{M_B} \left[\frac{\lambda(M)}{M^2-1}\right]^{1/2} dM$$

$$\lambda(M) = \left(1 + \frac{2}{\gamma+1}\frac{1-\mu^2}{\mu}\right)\left(1 + 2\mu + \frac{1}{M^2}\right)$$

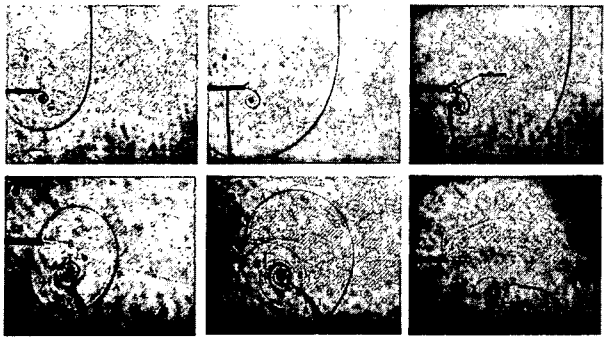
$$\mu^2 = \frac{(\gamma-1)M^2+2}{2\gamma M^2-(\gamma-1)}$$

$$\frac{dy}{dx}_{CE} = -\frac{1}{2}\left[\tan(\theta_O + m_O) + \tan(\theta_E + m_E)\right]$$

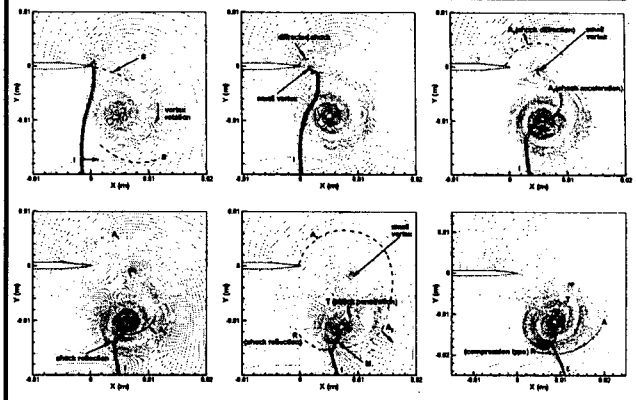
$$\frac{dy}{dx}_{ED} = -\frac{1}{2}\left[\tan(\theta_E - m_E) + \tan(\theta_D - m_D)\right]$$

$$m = \tan^{-1}\left[\frac{M^2-1}{M^2\lambda(M)}\right]^{1/2}$$

Shadowgraphs

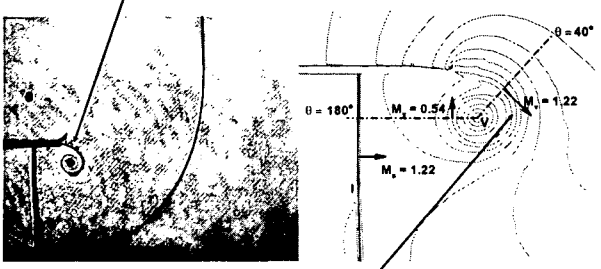


Numerical results: an enlarged view



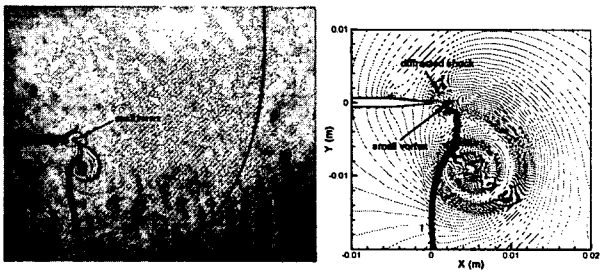
Shock interacts with a vortex

Supersonic Wave Structure

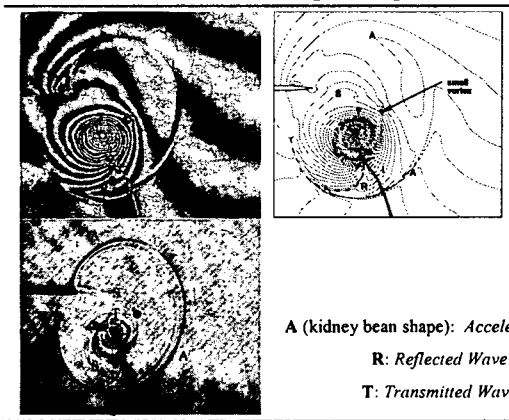


Locally Supersonic vortical flow

Shock diffraction



Shock Splitting



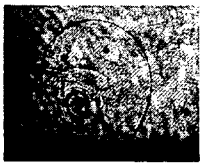
A (kidney bean shape): *Accelerated wave*

R: *Reflected Wave*

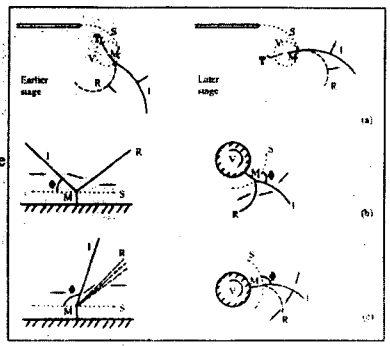
T: *Transmitted Wave*

Shock reflection

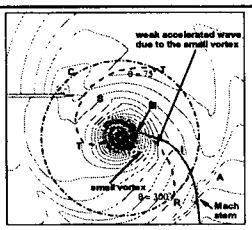
Earlier, Compressive Type

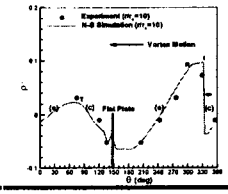


Later, Expansive Type



Shock penetration



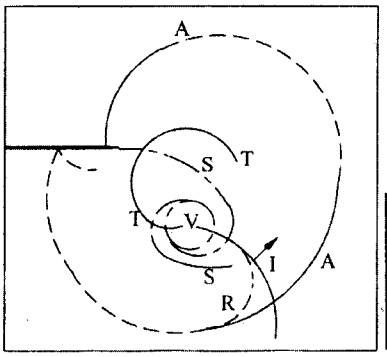


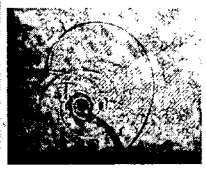
Quadrupole:

Double compressions (c) &

Double expansions (e)

Wave Structure

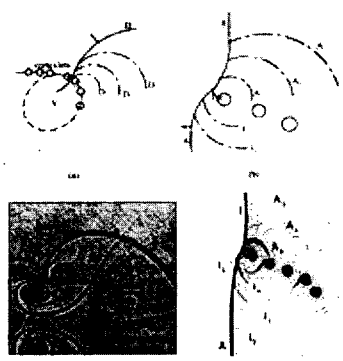




Shock interacts with a shock

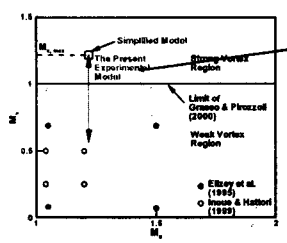
Shock reflection on Mach Stem

Shock interacts with a vortexlet



Why others overlooked?

Literature on computational modeling has skipped 'reflection and penetration of shock'



Supersonic Vortical Flow!!

So far, other researches have been limited to subsonic vortex.

Parameters

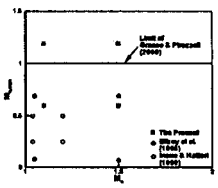
- Shock Strength
- Vortex Strength

Computational models

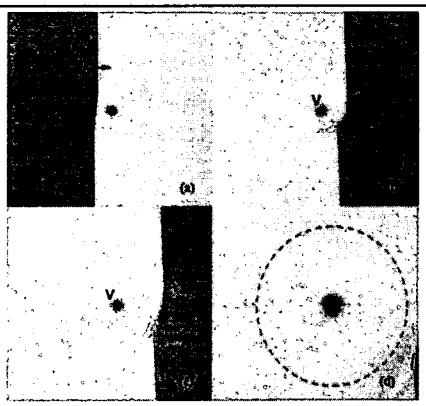
- Navier-Stokes Equations
- Classical Rankin Vortex Model
- Foppl's Idea (for Multiple Vortex Model)

Four combinations

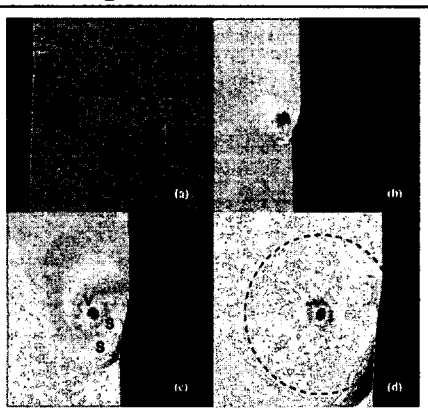
Weak Shock + Weak Vortex (WSWV) M_s=1.1, M_v=0.58	*Strong Shock + Weak Vortex (SSWV)* M_s=1.5, M_v=0.58
Weak Shock + Strong Vortex (WSSV) M_s=1.1, M_v=1.17	*Strong Shock + Strong Vortex (SSSV)* M_s=1.5, M_v=1.17



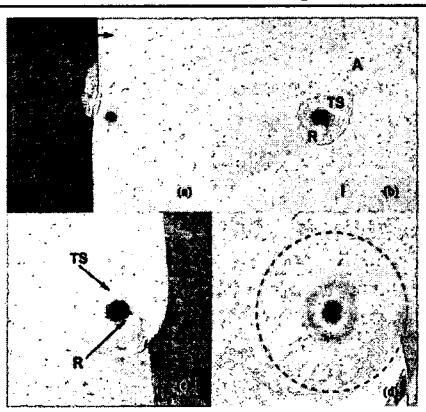
Weak shock + Weak vortex



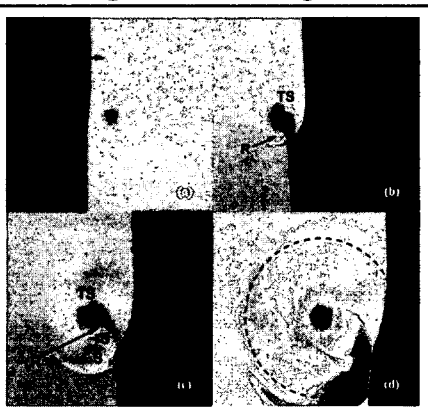
Strong shock + Weak vortex



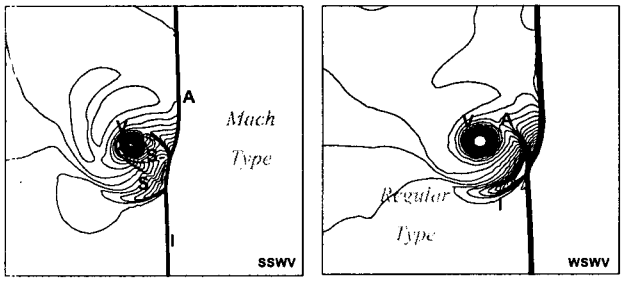
Weak shock + Strong vortex



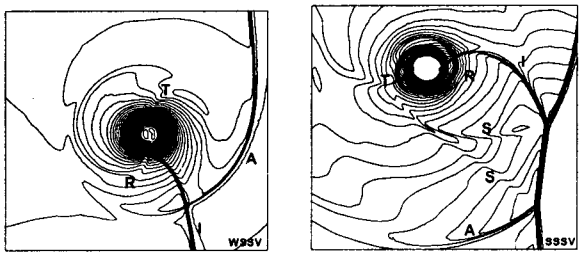
Strong shock + Strong vortex



Shock strength

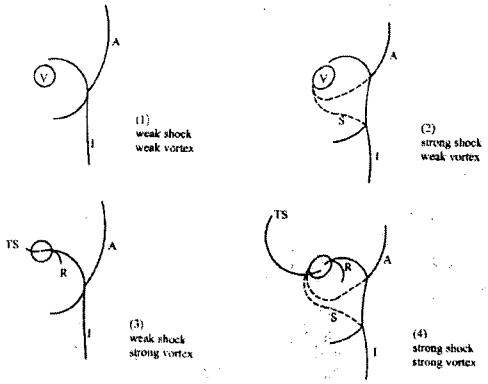


Vortex strength

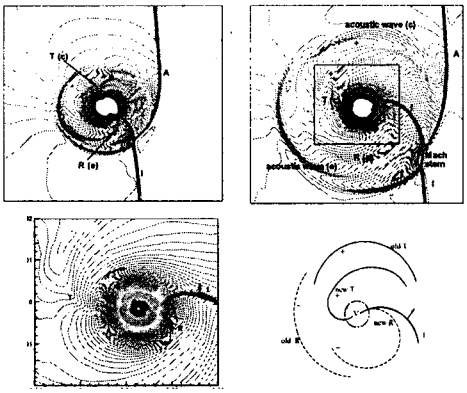


Strong vortex produces weak waves, R and T!!

Summary: Schematic Diagram



Quadrupole acoustic source



Conclusions

1. Shock splitting, penetration, and reflection constitutes quadrapole noise source.
2. These observation is valid for the strong vortex.
3. For the strong shock, double slip lines spiral into the vortex, forming an entropy layer.
4. The accelerated shock is not uniform but of quadrupolar structure.
5. Shock-vortexlet interaction constitutes diverging acoustics.