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Full-Field Sonic Boom Simulation in Real Atmosphere

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Contents

Sonic Boom

Acoustic phenomenon by shocks

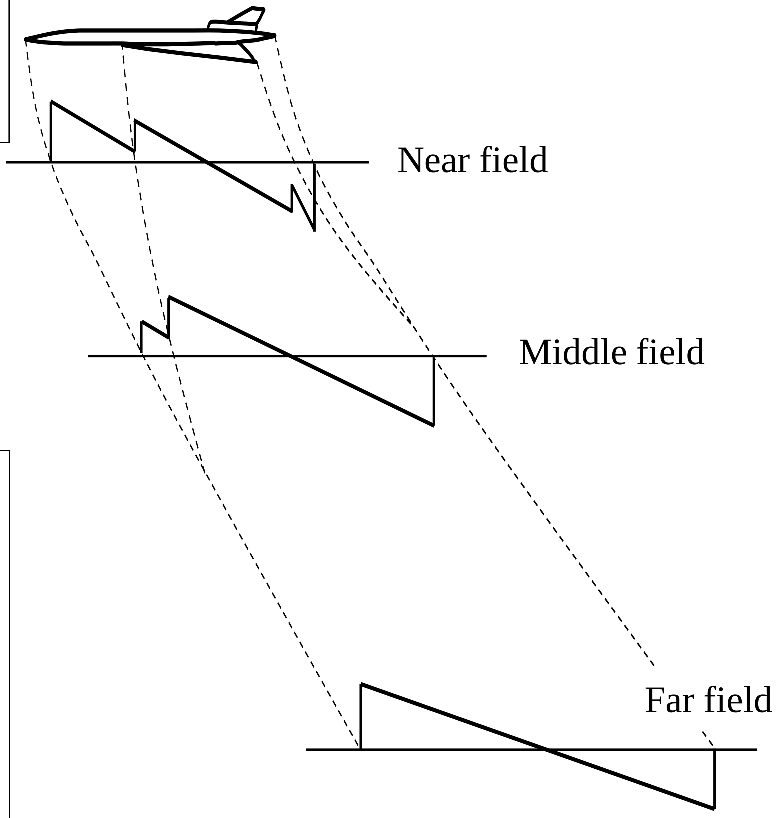
→ Sound of explosion

Sonic Boom reduction is essential

Sonic Boom Intensity

Depend on many factors

- Aircraft configuration
- Flight and atmos. conditions
- Ground topography



Related research

① Low boom design

To realize supersonic airplane

② Propagation mechanism

To clarify various effects

（Molecular relaxation, Atmospheric turbulence etc.）

③ Evaluation method

To predict sonic boom intensity precisely

Evaluation method

- Waveform parameter method
- Augmented burgers eq.
- Lossy nonlinear Tricomi eq.

→ It is possible to evaluate complex phenomena

(Focused sonic boom etc.)

Full-Field Simulation

CFD analysis in whole domain extending from airplane to ground

- Necessary to improve the following
  - ① Computational load
  - ② Solution adaptive technique
  - ③ Approach of real atmosphere
- Rigorous model can be solved in full-field simulation

Challenging and promising to clarify detailed phenomena

（Molecular relaxation, Ground effect, etc.）

- Potapkin, A. V. et al., "An Advanced Approach for Far-Field Sonic Boom Prediction," *AIAA Paper* 2009-1056, 2009.

  Axi-symmetric analysis in r/L (radial distance/Length of body) = 0-1000
  ⇒ CFD is feasible to predict sonic boom at far-field

- Yamashita, R. et al, "Numerical Analysis of Sonic Boom Cutoff Phenomena by Direct Simulation in Whole Domain Extending to Ground Level," *APISAT* 2013, No. 02-05-3.
  - Flight model : Axi-symmetric paraboloid
  - Flight Mach number : M = 1.1
  - Flight altitude : h = 10 km

  ⇒ Cutoff phenomena can be simulated by 3D Euler analysis in real (stratified) atmosphere

Accuracy of full-field simulation hasn't been fully confirmed

Objective

To investigate accuracy of full-field simulation as sonic boom prediction method from near-field around body to far-field (ground).

＜Full-Field Simulation＞

- Consideration of real (stratified) atmosphere
- Construction of adaptive grid aligned to shock waves

＜Validation＞

- Comparison with
  - D-SEND#1 flight test data by JAXA (JAXA：Japan Aerospace Exploration Agency)
  - Waveform Parameter Method (WPM)

Waveform Parameter Method（WPM）

Representative prediction method of sonic boom

Geometric Acoustics	Isentropic wave theory
To approximate shock by acoustic wave	To account for nonlinear waveform distortion

Far-field waveform is obtained by propagation along ray

Input Parameter

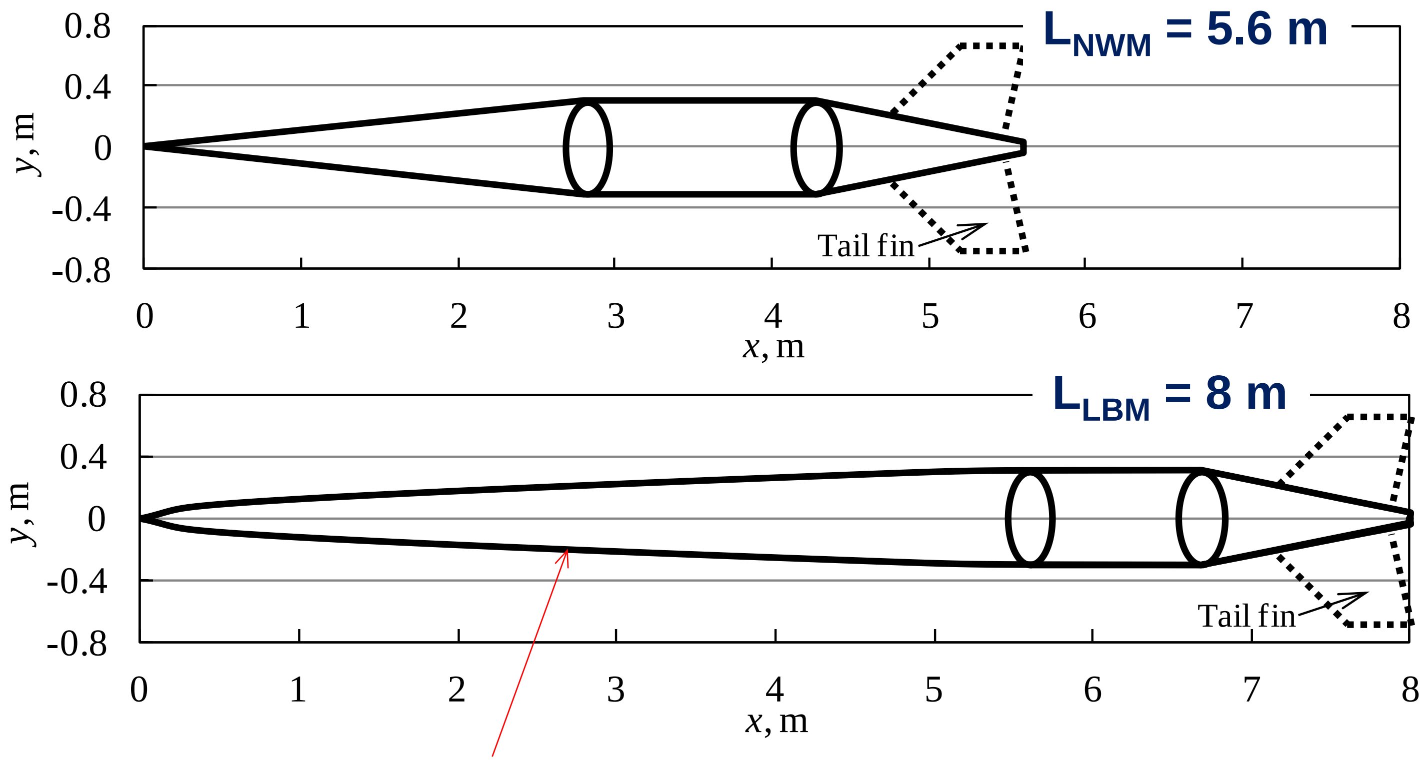
- Near-filed pressure waveform
- Flight condition（Mach number, Flight altitude and etc.）
- Atmos. condition（Temperature, wind distributions）

Contents

D-SEND#1 model by JAXA

NWM
(N Wave Model)

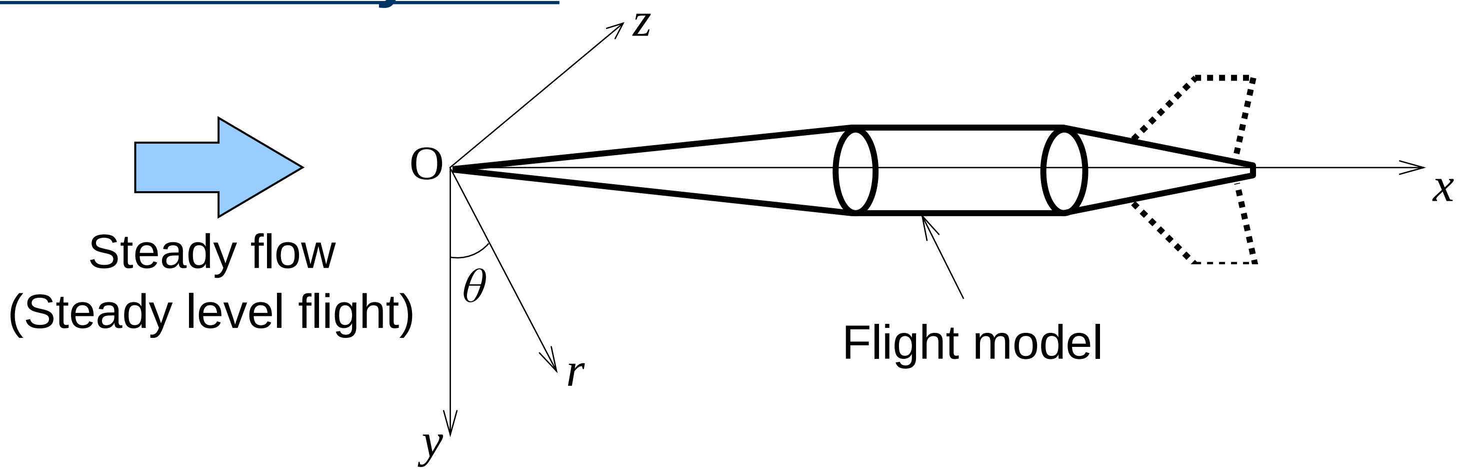
LBM
(Low Boom Model)



Designed by Seebass-George-Darden (S-G-D) method
to suppress the pressure fluctuation behind front shock wave

(Darden, C. M., “Sonic-Boom Minimization with Nose-bluntness Relaxation,” NASA TP-1348, 1979.)

Coordinate system

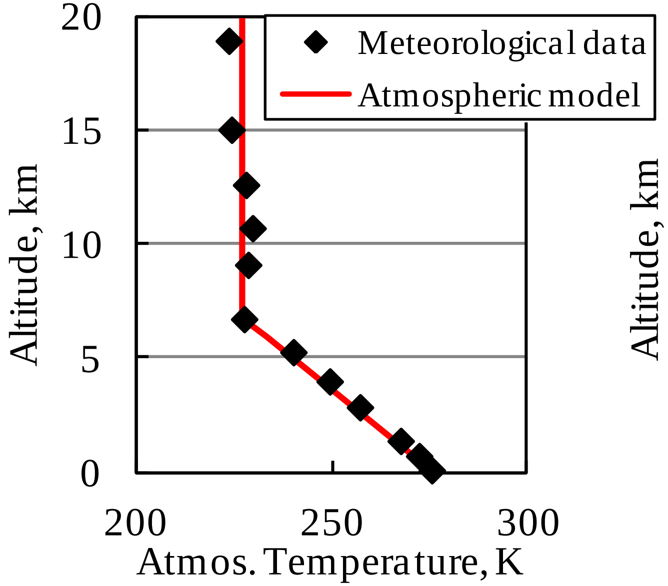


Numerical condition

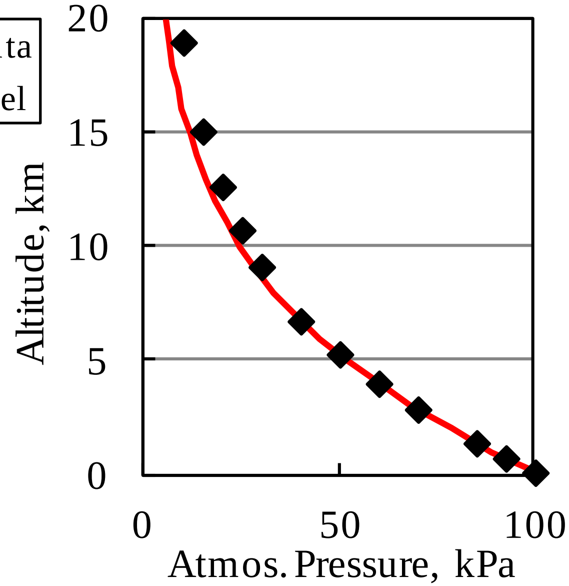
	NWM	LBM
Mach number	1.43	1.42
Flight altitude	6.03 km	6.015 km
Computational domain	r/L_{NWM} = 0～1100 (r = 6.16 km)	r/L_{LBM} = 0～800 (r = 6.4 km)
Observation point （D-SEND#1 flight test）	0.5 km altitude ⇒Ground topography has little effect	

Atmospheric Model

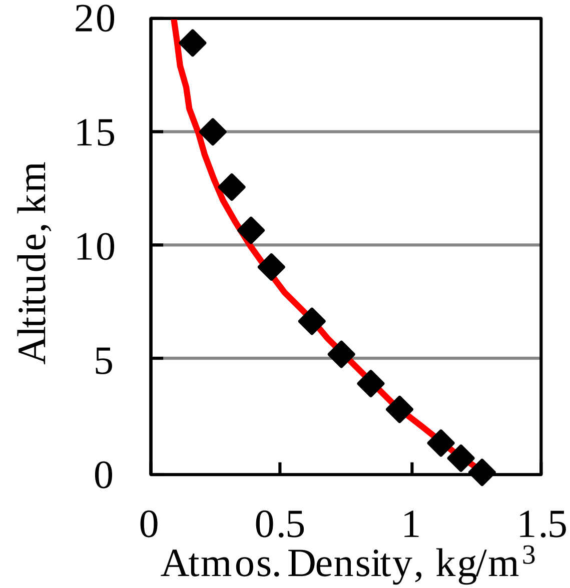
Temperature



Pressure



Density



- Atmos. Temperature : $T_\infty = T_0 - \beta h \quad (h \le 6.75km)$ $T_\infty = const \quad (6.75km \le h)$
- Hydrostatic Eq. : $\dfrac{dp_\infty}{dh} = -g\rho_\infty$
- Eq. of state of ideal gas : $p_\infty = \rho_\infty R T_\infty$

Governing Equation

$$\underline{\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}} = \underline{S_G} + \underline{S_C}$$

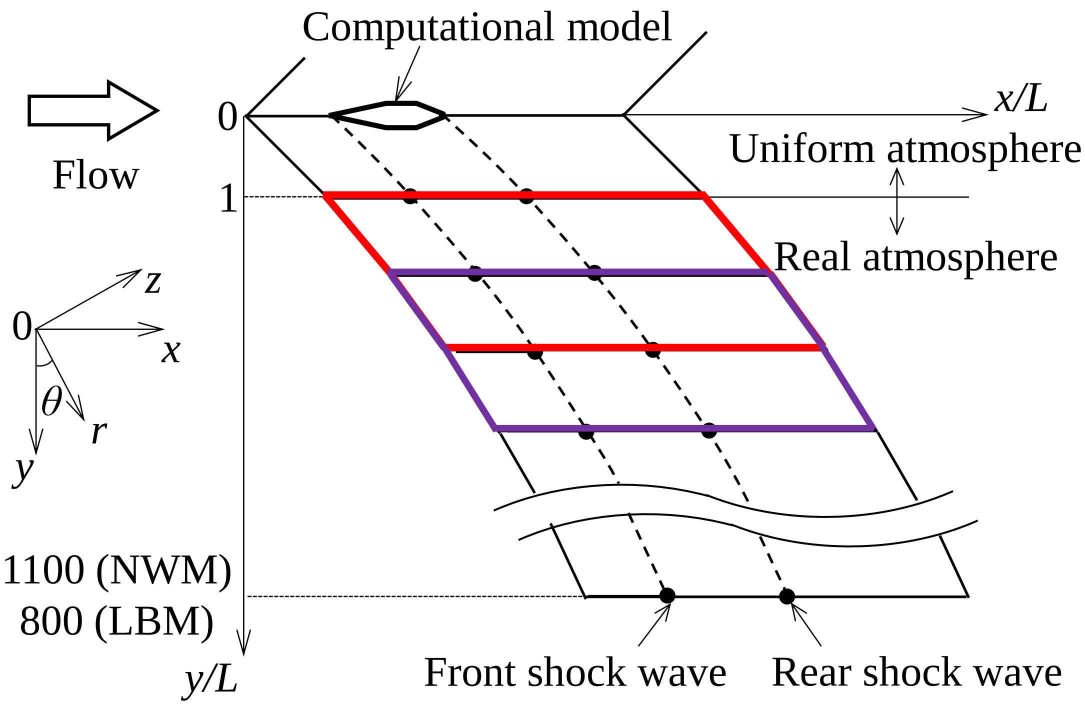
3D Euler Eq. Gravity term Correction term (approach is discussed later)

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E_t\end{bmatrix}, E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (E_t+p)u\end{bmatrix}, F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (E_t+p)v\end{bmatrix}, G=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (E_t+p)w\end{bmatrix}, S_G=\begin{bmatrix}0\\ 0\\ \rho g\\ 0\\ \rho gv\end{bmatrix}, S_C=\begin{bmatrix}s_1\\ s_2\\ s_3\\ s_4\\ s_5\end{bmatrix}$$

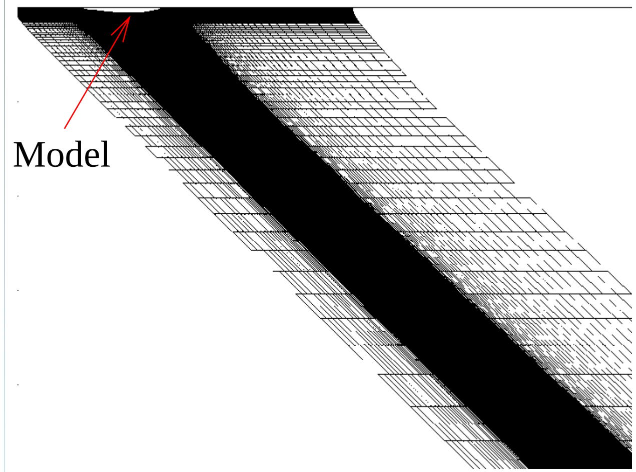
Numerical approach

- Convective term : SHUS(Simple High-resolution Upwind Scheme)
  ＋third order MUSCL interpolation
- Gravity term : Source term
- Time integration : MFGS(Matrix Free Gauss-Seidel) implicit method

Computational Grid



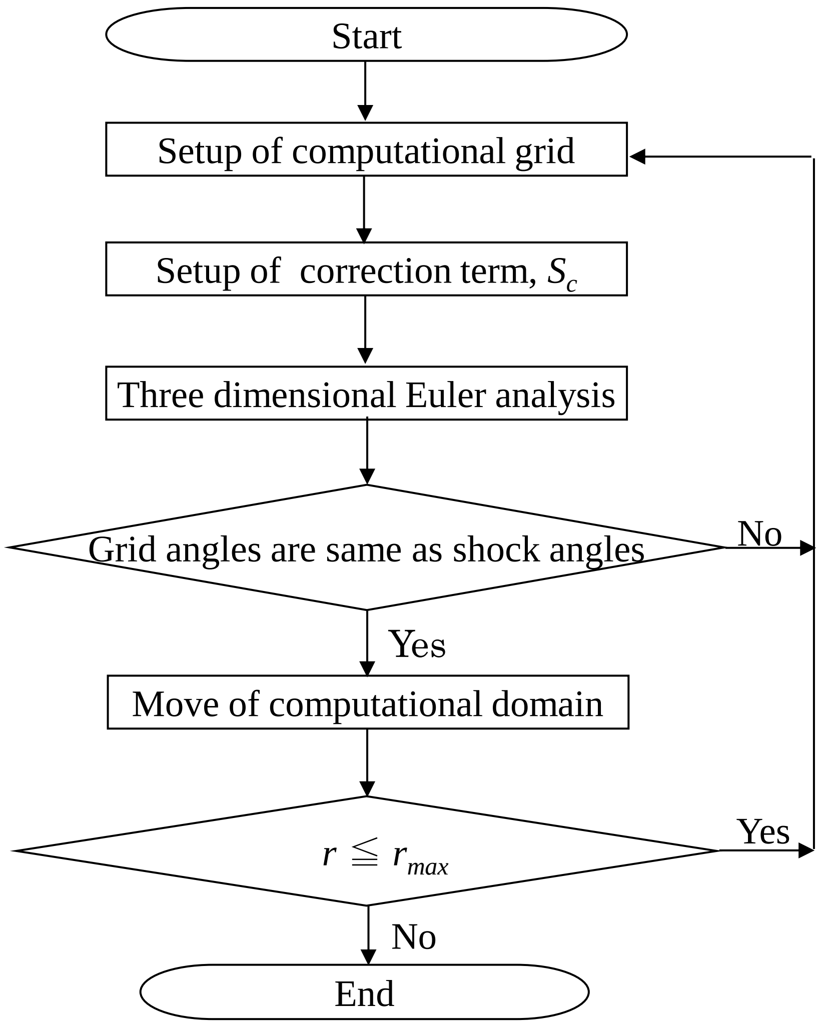
Axi-symmetric grid at near field

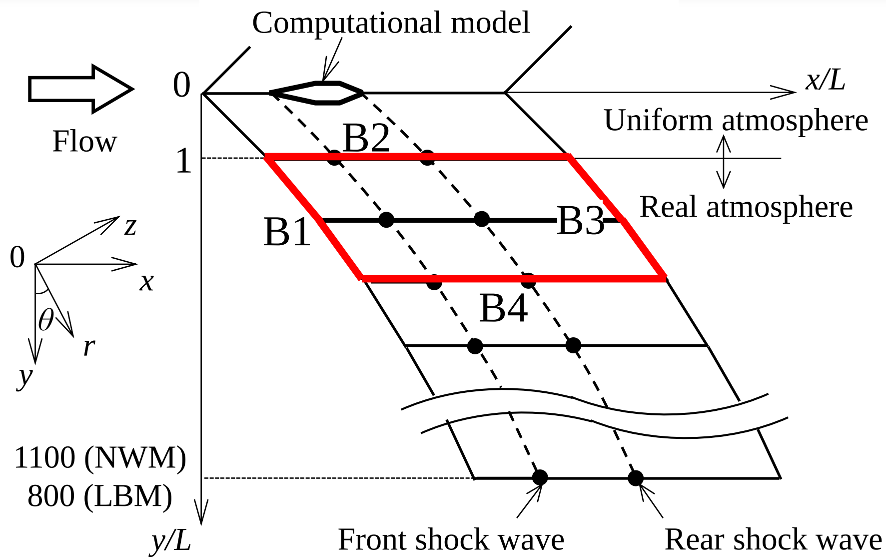


- Boundary condition in r direction
  Special treatment is necessary
  ⇒ r/L = 0-1 : uniform atmosphere

- 3D grid : rotating 2D grid about x axis (0−180 deg)
- Each sector : Δ r/L≧4 (8 points overlapping)
- Change of grid angle : every 5 points
- Total grid number : 14 million(NWM), 8 million(LBM) points

2. Numerical method



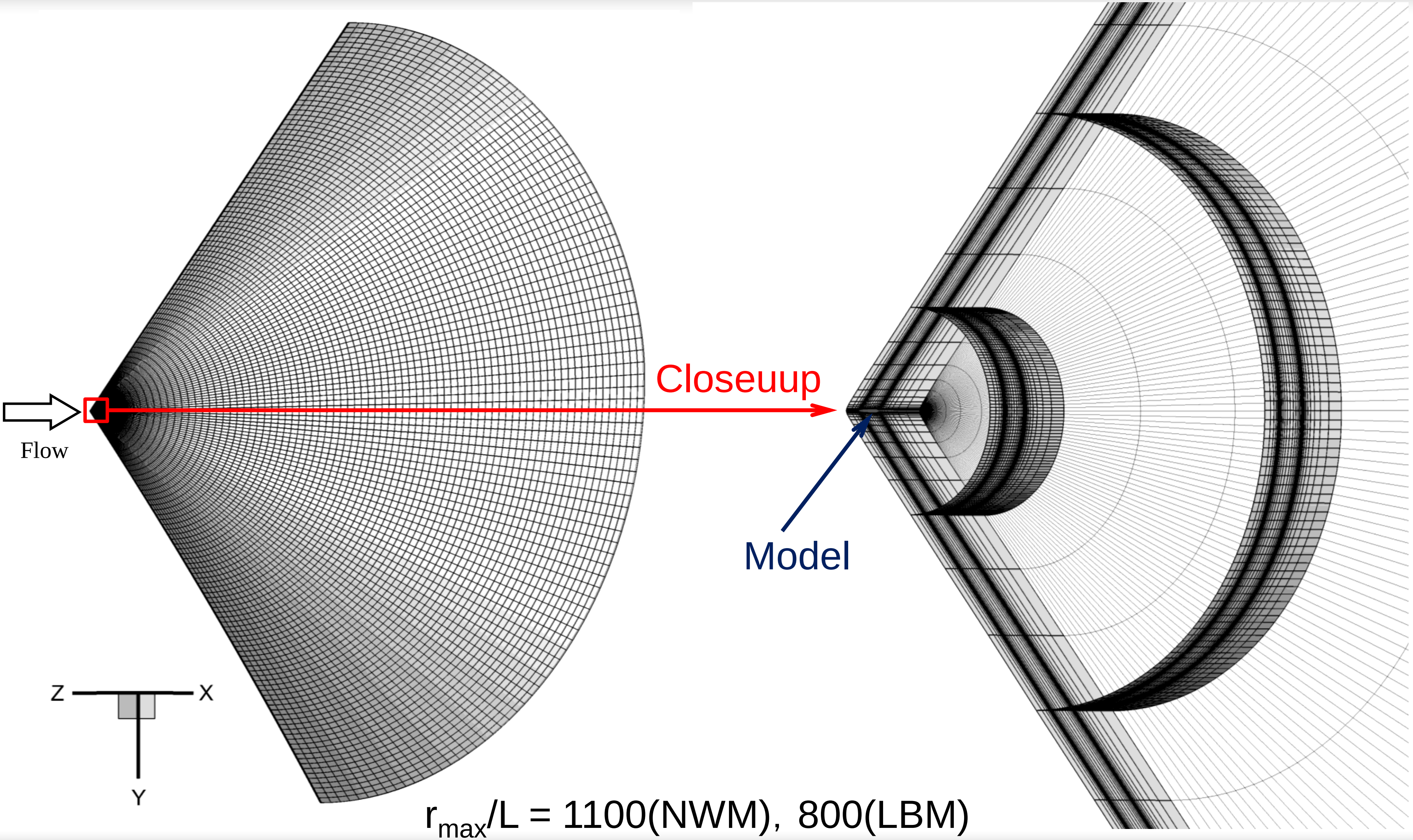


How to calculate S_C

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = S_G + S_C$$

① Uniform flow conditions are set in sector including B1 to B4
② Numerical Fluxes are calculated
③ S_C is derived as $\partial Q / \partial t = 0$
④ S_C = const. in normal calculation

2. Numerical method



r_{max}/L = 1100(NWM), 800(LBM)

3. Numerical results

Parameter

Pressure rise	:	Δp [Pa]
Altitude	:	h [km]

3.1　Pressure rise

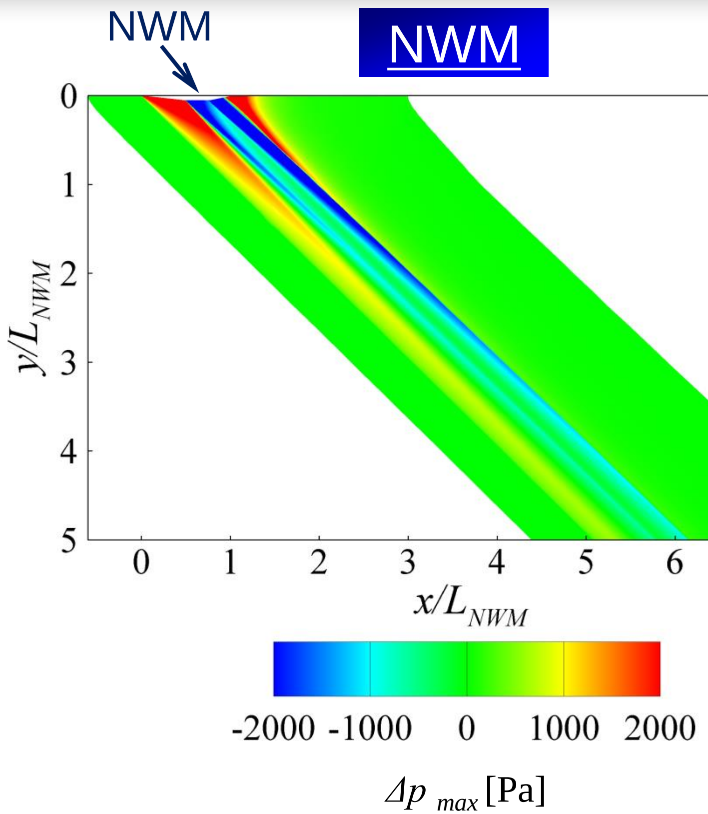
3.2　Pressure waveform（r/L = 1）

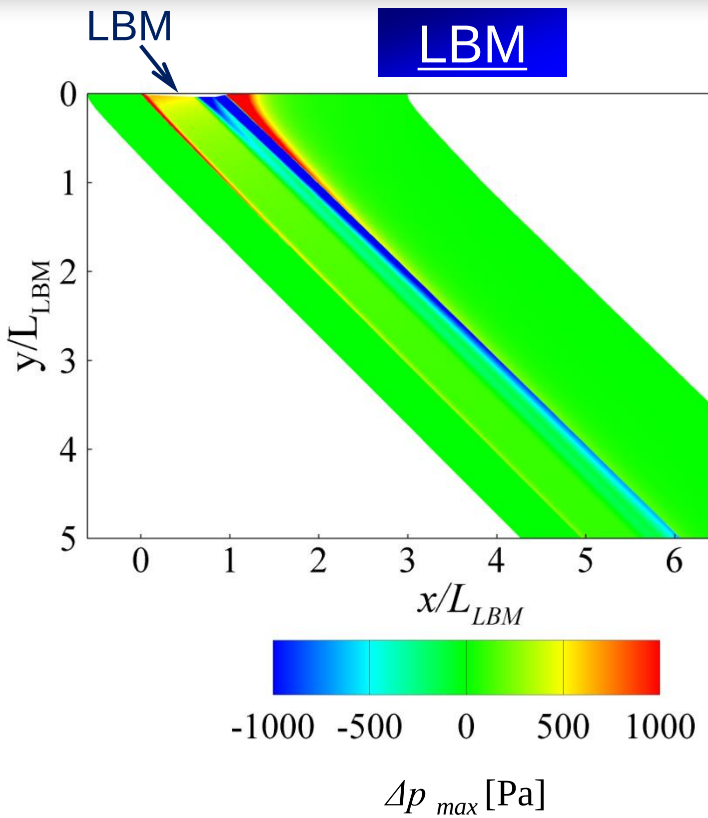
3.3　Pressure waveform（h = 0.5 km）

3.4　Closeup of front shock wave

3.5　Maximum pressure rise

3. Numerical results

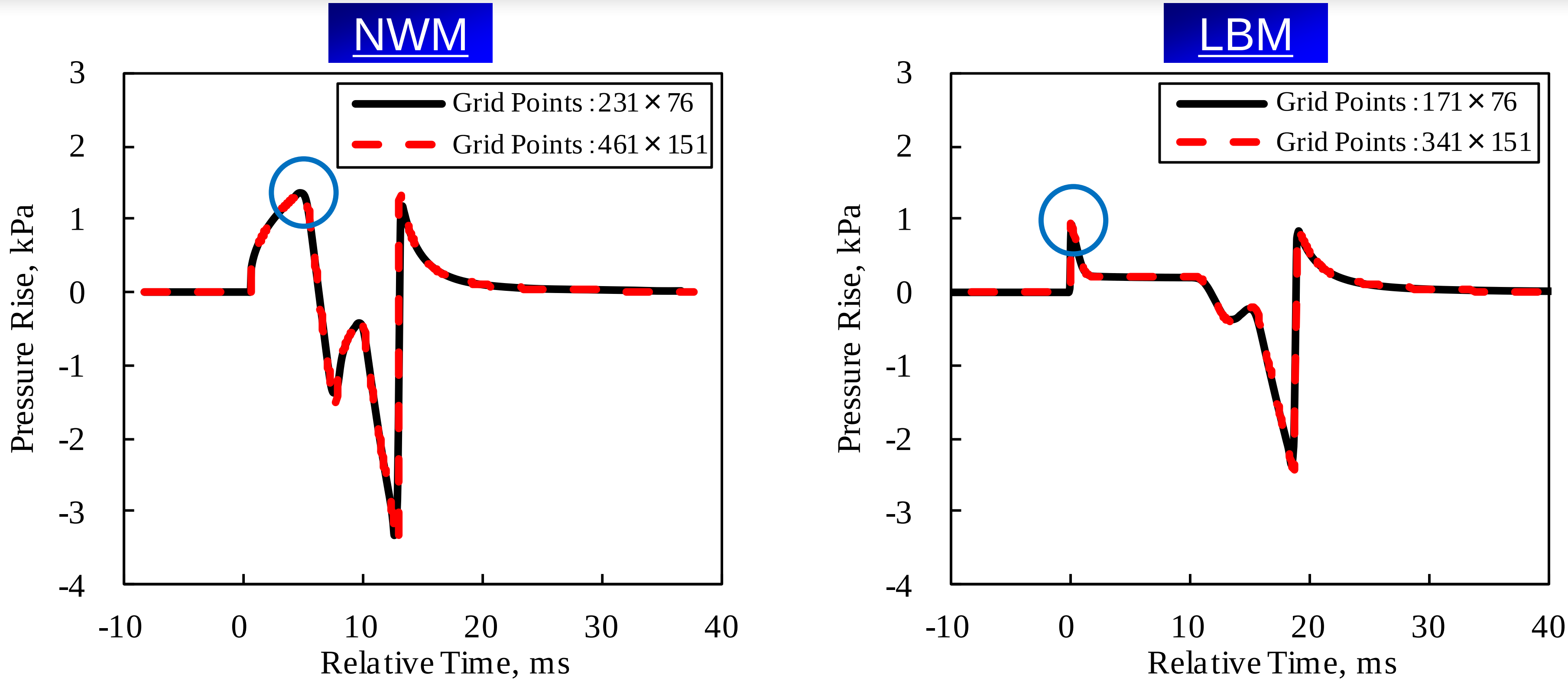




Pressure rise distribution

- NWM : Compression waves arise behind front shock wave
- LBM : Fluctuations are suppressed behind front shock wave
- The other configuration of flow field is same in both cases

3. Numerical results

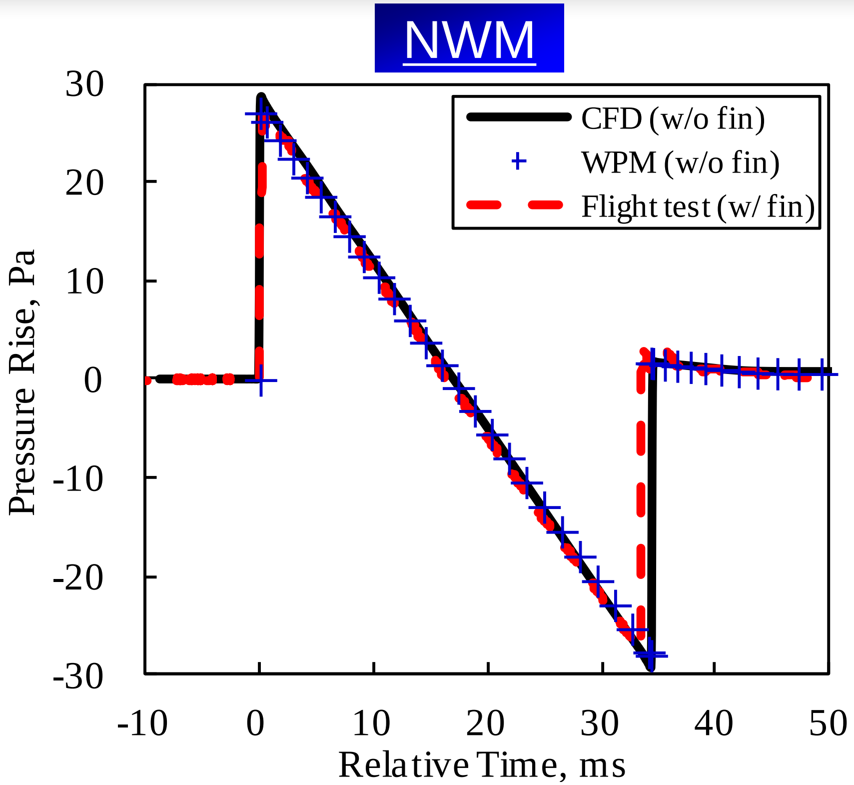


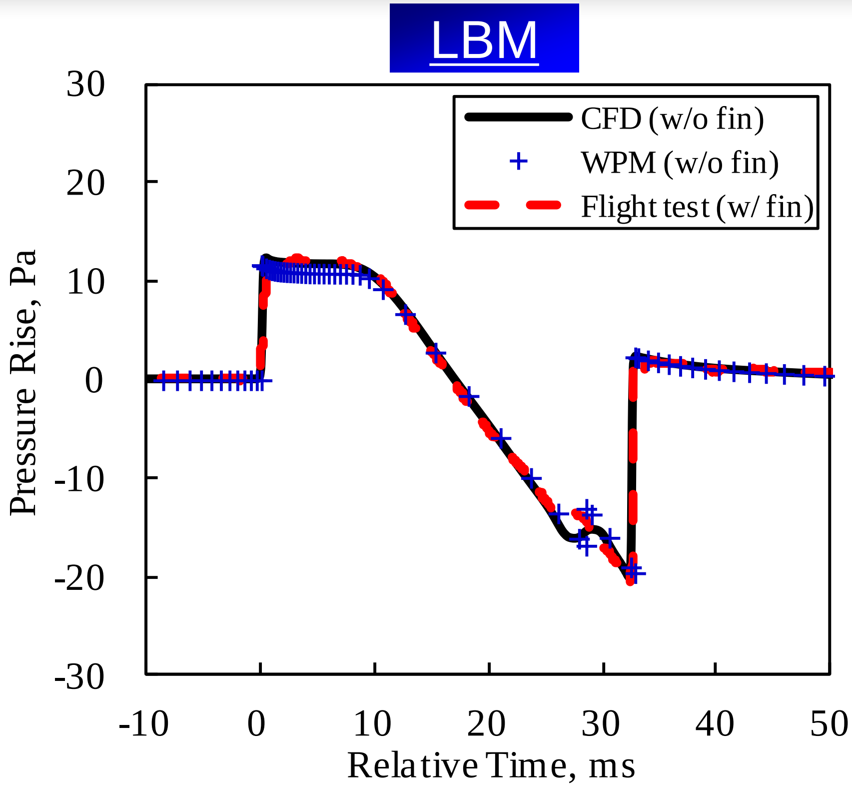
Pressure waveform（*r/L* = 1）

- Difference of waveform behind front shock wave
- Max. pressure rise ： 2.5 %（NWM）、0.005 %（LBM）

Grid convergence is adequate to validate sonic boom intensity

3. Numerical results



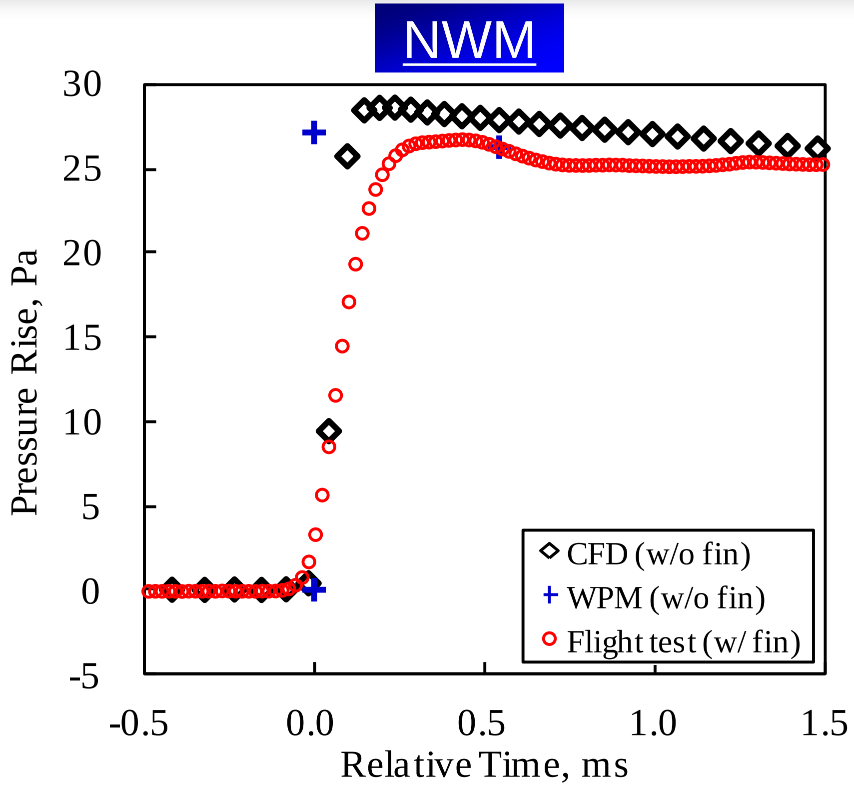


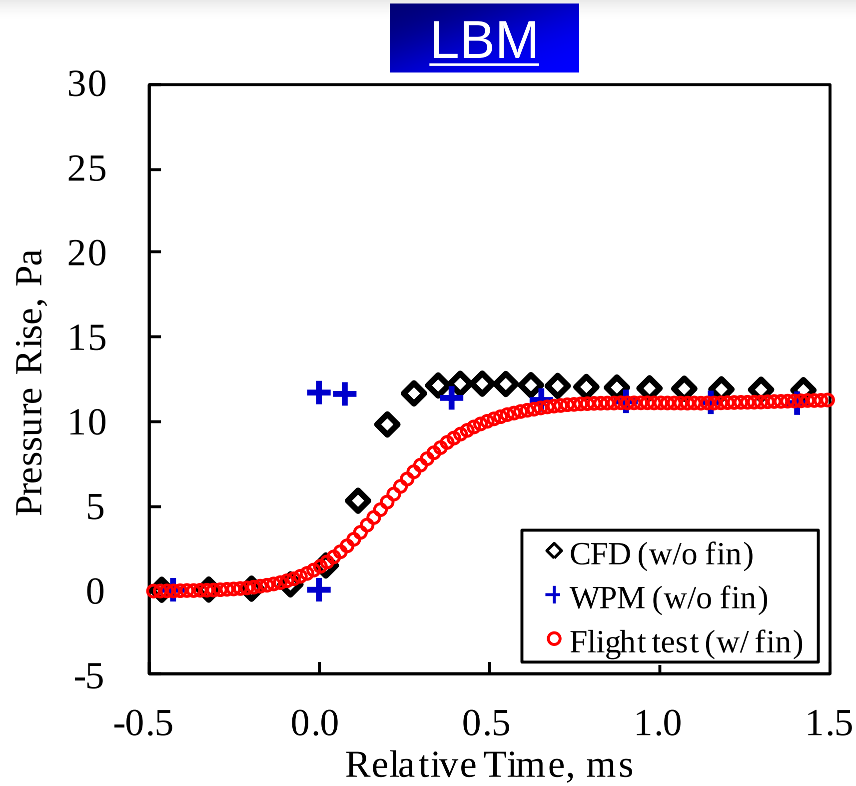
Pressure waveform（h = 0.5 km, θ = 0 deg）

- NWM : Shape of waveform is almost same in all results
- LBM : Not N-wave but trapezoid at front shock wave

S-G-D method is effective to reduce sonic boom intensity

3. Numerical results





Closeup of front shock wave (h = 0.5 km)

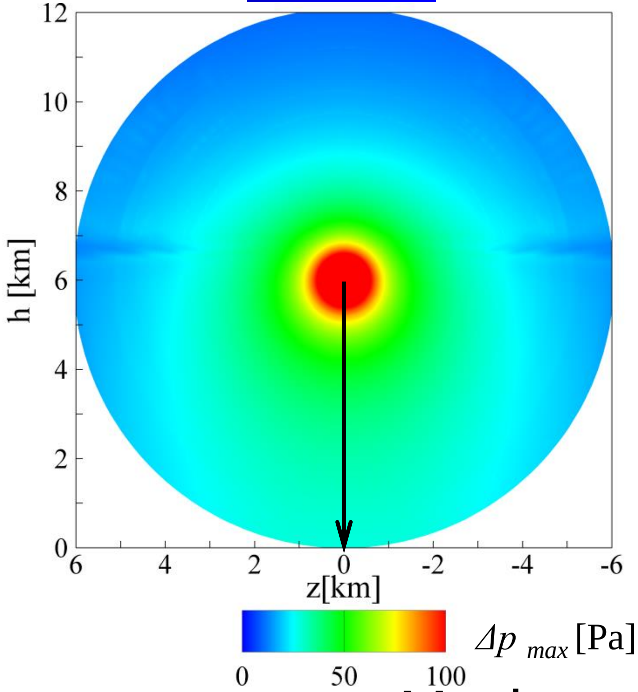
- Difference of Δp_{max} in CFD and WPM : Less than 5 % in both cases

  Full-field simulation is feasible to evaluate sonic boom

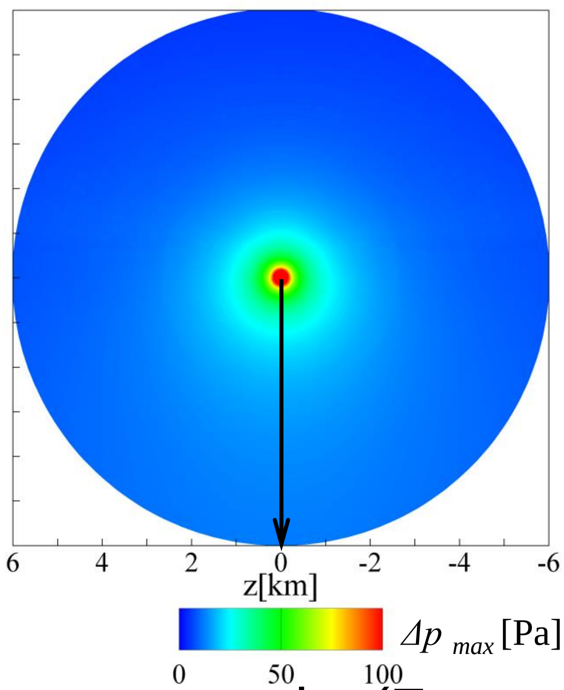
- Difference of Δp_{max} in CFD and Flight test : 6.3 %(NWM),0.03 %(LBM)

3. Numerical results

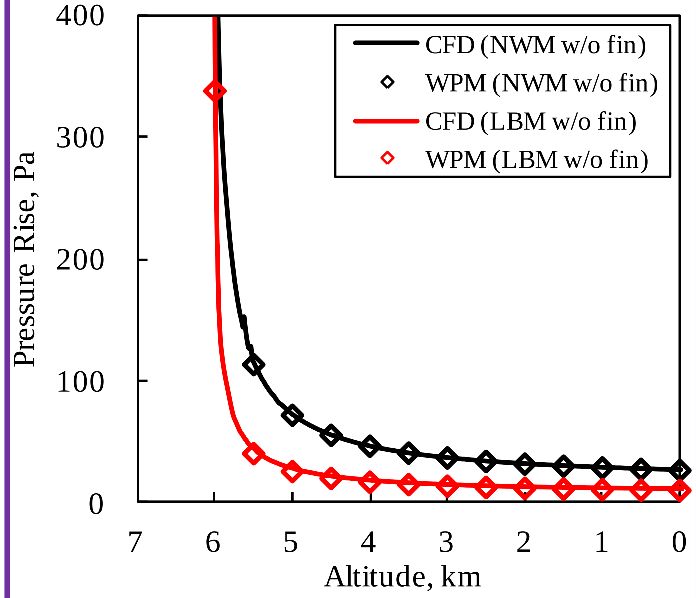
NWM



LBM



$\theta = 0$ deg



Maximum pressure rise(Front shock wave)

- Attenuation ： Different according to direction of propagation

  Effect of atmos. pressure、Convergence effect (by temperature)
- Max. pressure in LBM is lower than that in NWM all over region
- Nature of sonic boom propagation is the same in CFD and WPM

4. Conclusions

1. Nature of sonic boom propagation obtained by full-field simulation is in good agreement with that by waveform parameter method

2. Accuracy of full-field simulation is same level of waveform parameter method

3. Sonic boom intensities at front shock wave obtained by full-field simulation conform to flight test results

5. Future plan

- Full-field simulation is effective to predict sonic boom
- Full-field simulation can be conducted by rigorous model based on real physical phenomena
  - Unsteady nature
  - Ground effect
  - Molecular relaxation
  - Thermochemical nonequilibrium and etc.

Full-field sonic boom simulation becomes powerful tool as accurate evaluation method in the future