博士論文（要約）

Full-Field Simulation for Sonic Boom Propagation through Real Atmosphere

（実在大気中のソニックブーム伝播に関する全空間解析）

山下　礼

Doctoral Thesis

Full-Field Simulation for Sonic Boom Propagation through Real Atmosphere

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Contents

Nomenclature

Roman Symbols

a_n	:	velocity normal to wave front
A	:	Jacobian matrix or ray tube area
c	:	speed of sound
D	:	maximum diameter
e	:	total energy per unit volume
e_{vO_2}, e_{vN_2}	:	vibrational energy of O_2 and N_2 per unit volume
E, F, G	:	inviscid flux vectors
E_v, F_v, G_v	:	viscous flux vectors
$\widetilde{F}$	:	inviscid flux vector at cell interface
g	:	acceleration of gravity
h	:	altitude
h_a	:	absolute humidity
h_r	:	relative humidity
H	:	axi-symmetric inviscid term
H_v	:	axi-symmetric viscous term
I	:	unit matrix
J	:	Jacobian
$\dot{m}$	:	mass flux
m_i	:	pressure gradient of segment i (Appendix)
M	:	Mach number
n_s	:	number of molecular species
L	:	length of body
p	:	pressure
$\widetilde{p}$	:	pressure flux
Pr	:	Prandtl number
q	:	primitive variables

Q	:	conservative variables
R	:	gas constant
Re	:	Reynolds number
s	:	flux limiter function
S	:	source term
$S(x)$	:	cross-sectional area at x coordinate
S_C	:	correction term for gravity term
S_G	:	gravity term
S_W	:	translational-vibrational relaxation term
t	:	time
$\vec{t}$	:	unit vector tangential to surface of body
T	:	temperature
T_{01}	:	triple point temperature
T_{vO_2}, T_{vN_2}	:	vibrational temperature of O_2 and N_2
u, v, w	:	velocity components
$\vec{U}$	:	velocity vector
V_n	:	velocity component normal to cell interface
w_{vO_2}, w_{vN_2}	:	translational-vibrational relaxation term of O_2 and N_2
$w_{v,\,max}$	:	maximum value of translational-vibrational relaxation term
x_n, y_n, z_n	:	unit vector components normal to cell interface
x, y, z	:	Cartesian coordinates
x, r, θ	:	cylindrical coordinates

Greek Symbols

α	:	angle of flow velocity from x direction
β	:	temperature lapse rate
β_r	:	relaxation coefficient
γ	:	ratio of specific heat
$\Delta e_{tr,\,\mathrm{max}}$	:	maximum increase in translational energy per unit volume
Δp	:	pressure fluctuation from atmospheric pressure
Δp_i	:	pressure rise at the boundary of segments i and i–1 (Appendix)
Δp_{max}	:	pressure rise
Δt_{ex}	:	exchange time of translational-vibrational energy

Δt_{rt}	:	rise time
$\varepsilon_{O_2}, \varepsilon_{N_2}$	:	mole ratio of air of O_2 and N_2
$\theta_{O_2}, \theta_{N_2}$	:	characteristic vibrational temperature of O_2 and N_2
κ	:	thermal conductivity
λ	:	spectral radius
λ_{Di}	:	time duration of segment i (Appendix)
μ	:	viscous coefficient
μ_M	:	Mach angle
$\mu_{M\,\mathrm{mod}}$	:	modified Mach angle
ρ	:	density
τ	:	viscous shear stress
τ_{O_2}, τ_{N_2}	:	relaxation time of O_2 and N_2
ϕ	:	scalar quantity
ξ, η, ζ	:	generalized coordinates

Subscript

0	:	ground
1	:	value just before shock wave
a	:	atmosphere
L, R	:	left-side and right-side values at cell interface
∞	:	freestream value at flight altitude

Superscript

eq	:	thermal equilibrium
*	:	nondimensional variable

Chapter 1

Introduction

1.1 Sonic Boom

Shock waves generated from a supersonic or hypersonic flight object propagate through the atmosphere down to the ground. Consequently, the rapid pressure rises caused by the shock waves generate significant impacts including explosive sounds on the ground. This phenomenon is known as sonic boom [1], which occurs primarily due to an aircraft flying faster than the speed of sound [2] and a meteorite falling to the earth [3, 4].

Figure 1.1 shows a schematic of sonic boom propagation from the near field around a supersonic aircraft to the far field reaching the ground. Multiple shock waves generated from a fuselage and wings are consolidated into an N-shaped waveform (N-wave) in the far field, and as a result the explosive sound occurs twice on the ground [5]. For the sonic boom problem, the overland civil supersonic flight has been restricted, and there has been no civil supersonic aircraft after the Concorde was retired in 2003 [6]. The International Civil Aviation Organization (ICAO) [7] presently deliberates an international standard in which the allowable level of sonic boom is determined to realize an overland supersonic flight. To formulate the clear international standard, sonic boom intensity in various flight and atmospheric conditions must be precisely predicted. Therefore, research activities of sonic boom including not only the sonic boom minimization [8, 9] but also the development of accurate prediction methods for sonic boom [10, 11] are accelerated. Moreover, to validate the accuracy of sonic boom predictions, several flight tests for sonic boom were recently conducted by NASA [12, 13] and the Japan Aerospace Exploration Agency (JAXA) [14, 15].

Sonic boom researches on supersonic aircrafts have been significantly advanced, whereas those on hypersonic aircrafts have been hardly conducted. However, the development of hypersonic aircrafts is recently accelerated [16, 17], and the sonic boom problem must be addressed not only in supersonic aircrafts but also in hypersonic aircrafts [18]. Sonic boom intensity of a hypersonic aircraft may be weaker than that of a supersonic aircraft because of the following reason: The cruising altitude of the hypersonic

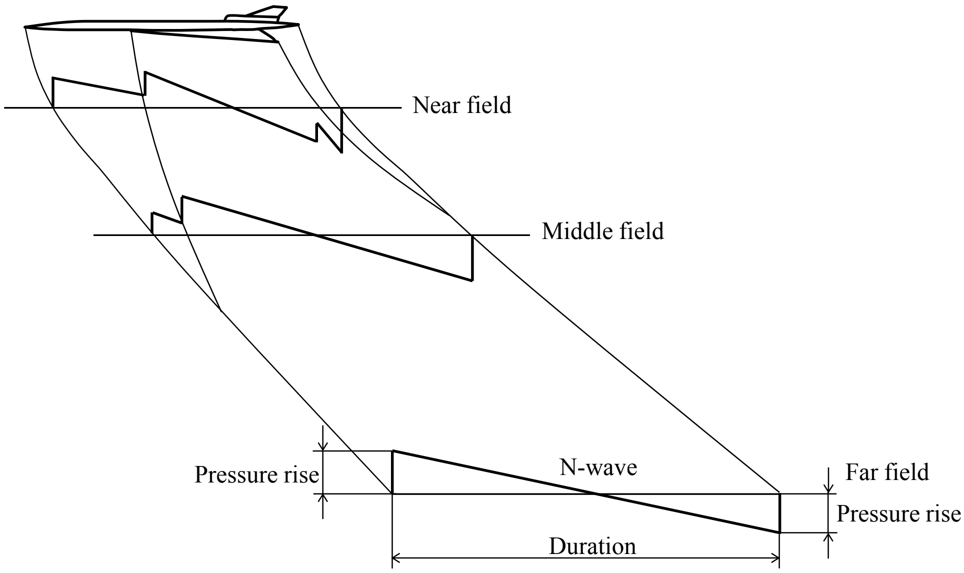

Fig. 1.1 Schematic of sonic boom propagation generated from supersonic aircraft.

aircraft is assumed to be higher than that of the supersonic aircraft, and the distance of sonic boom propagation to the ground increases with increasing the flight altitude. However, sonic boom propagation from hypersonic aircrafts cannot be precisely predicted because the existing prediction methods for sonic boom based on the weak shock theory [19] do not consider the strong nonlinearity and thermochemical nonequilibrium in hypersonic flow regimes [20]. Therefore, the accurate prediction method considering these effects must be constructed to evaluate sonic boom intensity generated from hypersonic aircrafts.

Sonic boom is generated from not only an aircraft flying faster than the speed of sound but also a meteorite falling to the earth. Ten-thousand near-earth asteroids are presently observed [21], and there is always the possibility of a meteorite falling. In fact, the big meteorite events were observed near the Marshall Islands in 1994 [22], Indonesia in 2009 [23], and Chelyabinsk, Russia in 2013 [24–27]. In particular, the Chelyabinsk event was well known because the significant damage was caused by the meteorite falling. The Chelyabinsk meteorites exploded several times, and small fragments generated by the explosions fell to the ground. At that time, strong shock waves were generated from not only the meteorites exploding but also their hypersonic flights, and they propagated toward the ground. Consequently, the sonic boom rather than the direct impact of the fragments caused the significant damage including not only the destruction of the building but also the human damage. Extrapolated from the measurement of the window breakage in Chelyabinsk, the pressure rise caused by the shock wave was estimated to be 3.2 ± 0.6 kPa [24]. Hence, it can be seen that the sonic boom intensity in the Chelyabinsk meteorite was much stronger than that in a supersonic aircraft (e.g., the pressure rise generated by the Concorde flying at the cruising speed was approximately 95 Pa [6]). Because the proportion of the population area on the earth is low, a natural disaster, as well as the Chelyabinsk event, was not observed in the past century. However, it is thought that the meteorite of the same size as that of Chelyabinsk falls to the earth once in a decade [27, 28]; thus, there is always the possibility of a natural disaster caused by a meteorite falling. From these facts, it is important to evaluate the influence of meteorite impacts including sonic boom and to anticipate hazard meteorites. However, the sonic boom prediction of a hypersonic meteorite has been mainly predicted by the self-similar solution [29, 30], without consideration of the atmospheric effects such as atmospheric stratification, viscosity, and thermochemical nonequilibrium. In addition, the existing prediction methods based on the weak shock theory [19] cannot be applied to the sonic boom prediction of the hypersonic meteorite because of the strong nonlinearity and thermochemical nonequilibrium in a hypersonic flow regime [20]. Therefore, the accurate prediction method must be constructed to precisely predict sonic boom propagation generated from hypersonic meteorites as well as that generated from hypersonic aircrafts.

1.2 Existing prediction methods for sonic boom

Sonic boom intensity depends on the configuration of flight object, the flight and atmospheric conditions, and the ground geometry [2]. In particular, the atmospheric effects such as atmospheric stratification [31], molecular relaxation [32, 33], and atmospheric turbulence [34–36] significantly affect the sonic boom intensity because the sonic boom propagates for quite a long distance until it reaches the ground. Therefore, the accurate prediction of sonic boom with consideration of all such effects is challenging but essential for evaluating the perceived loudness of sonic boom. Thus far, the prediction methods for sonic boom have been mainly developed to realize a low-boom supersonic aircraft [8, 9], and the predictions have been conducted in three different fields: the near field around a supersonic aircraft, the far field reaching the ground, and the caustic-vicinity field [37] where the shock waves are focused due to accelerations, maneuvers, and low-supersonic flights. In this section, the representative prediction methods in each field and the limitation of the application are described.

1.2.1 Near field

As a three-dimensional aircraft configuration and strong nonlinearity must be considered in the near field, near-field pressure waveforms have been obtained by experiments or Computational Fluid Dynamics (CFD). The experiments are categorized into two types: wind tunnel [38, 39] and ballistic range [40] experiments. The experimental techniques using wind tunnels have been already established, and the experimental results have been used to validate the accuracy of computation [41]. However, the influence of a sting to which the experimental model is attached cannot be ignored in the wind tunnel experiments. In contrast, such a sting is unnecessary in ballistic range experiments because the free flight of the model is conducted. For this reason, the ballistic range experiments have been conducted, although the experimental technique should be further improved because the flight control including the angle of attack is difficult. In addition, CFD analysis [42] is often performed not only to obtain near-field waveforms but also to evaluate the flow field around the body. However, the computational results may be somewhat different from the experimental results because of the complexity of the flow fields around three-dimensional aircraft configurations. Thus, the CFD methods for precisely predicting sonic boom intensity have been studied [43, 44].

1.2.2 Far field

It is difficult to precisely predict sonic boom propagation for quite a long distance in the real atmosphere because sonic boom intensity depends on various effects such as geometrical spreading, nonlinearity, and atmospheric effects [33]. Hence, far-field waveforms have been obtained by simplified prediction methods based on the weak shock theory formulated by Whitham [19], in which a shock wave is treated as a sound wave, and the propagation speed at any point is modified by the isentropic wave theory to consider the nonlinear effect; i.e., the propagation speed is assumed to be a sum of the local speed of sound and the change of velocity. In addition, a shock wave is determined by the area-balancing technique: if two Mach lines intersect with each other, the bisector is treated as a shock wave. According to the Whitham's theory, the pressure rise of weak shock wave in the far field decreases as the power –3/4 of radial distance from the body axis (according to the Lin's self-similar solution, the pressure rise of strong shock wave decreases as the power –2 of radial distance [29]). Although sonic boom intensity can be roughly predicted by the Whitham's solution, the accuracy is inadequate for evaluating the perceived loudness of sonic boom because of the following two reasons: First, the strong nonlinearity in the near field around a flight object cannot be considered by the solution. Second, the atmospheric effects such as atmospheric stratification, molecular relaxation, and viscosity cannot be considered. Thus, several prediction methods, in which the weak shock theory is extended to the more practical use, have been proposed.

The waveform parameter method invented by Thomas [45] is a representative prediction method for sonic boom. In this method, far-field waveforms can be predicted by extrapolating the near-field waveform that is obtained by the experiment or CFD [46], and the wave propagation is computed in consideration of several effects including geometrical spreading, nonlinearity, and atmospheric stratification (see Appendix for details). However, the rise time of sonic boom, which is one of the most important parameters for evaluating sonic boom intensity, cannot be predicted by the waveform parameter method because the shock wave is treated as a discontinuity; i.e., the shock wave has no thickness. Although the formation mechanism of rise time has not been well clarified, it is thought that the molecular relaxation and thermoviscous dissipation including the fluid friction and thermal conduction have significant effects on the formation of rise time [32]. Hence, several prediction methods of rise time, in which the molecular relaxation and thermoviscous dissipation are considered, have been proposed. These methods are categorized into two approaches. One is the frequency domain approach [47], wherein the relaxation effects are considered in the frequency domain while the wave propagation is computed in the time domain. The other is the time domain approach based on the augmented Burgers equation [48], wherein the wave propagation with the relaxation effects is computed in the time domain. Recently, the method of solving the augmented Burgers equation is often used to predict far-field waveforms, including not only the pressure rise but also the rise time.

Accuracy of the prediction methods was recently evaluated by comparison with the Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom #1 (D-SEND#1) [14] conducted by JAXA. As a result, the latest prediction method of solving the augmented Burgers equation [48] was the best possible way to predict the sonic boom intensity, including not only the pressure rise but also the rise time. However, the discrepancies between predictions and flight test measurements were significantly changed according to the flight and atmospheric conditions [49], because of the following two reasons: First, the effects of molecular relaxation and thermoviscous dissipation were treated as simplified models, and the treatments might not be adequate for analyzing sonic boom propagation in various flight and atmospheric conditions because these effects have not been fully clarified, although they have been investigated by one-dimensional numerical and asymptotic analyses [50]. Second, the effect of atmospheric turbulence [34–36], which causes the ragged distortion of the waveform behind the shock wave, was not considered because it cannot be well modeled. Therefore, the effects of molecular relaxation, thermoviscous dissipation, and atmospheric turbulence should be further investigated, and the prediction method considering the detailed models of these effects must be constructed to precisely predict sonic boom propagation through the real atmosphere.

1.2.3 Caustic-vicinity field

Acoustic rays that indicate the propagation paths of shock waves converge in accelerations [51], maneuvers [52], and low-supersonic flights [53]. Consequently, the envelop surface of the rays forms a caustic cusp, at which the sonic boom intensity becomes approximately three times larger than that without the focusing of the rays. This phenomenon is known as focused sonic boom [54]. In order to predict focused sonic boom, the diffraction effect caused by atmospheric stratification with altitude must be considered. Because the far-field prediction methods such as the waveform parameter method cannot consider the diffraction effect, focused sonic boom has been analyzed by other prediction methods of solving the progressive wave equation [55], Khokhlov–Zabolotskaya (KZ) equation [56], nonlinear Tricomi equation [57] and so on. The accuracies of these methods were evaluated by comparison with the flight test, known as the Superboom Caustic Analysis and Measurement Project (SCAMP) [12] at NASA. As a result, the latest prediction method of solving the lossy nonlinear Tricomi equation [58] was the best possible way to evaluate the focused sonic boom, and the focusing strength was in good agreement with the flight test results. However, because the lossy nonlinear Tricomi equation does not incorporate the important effects of geometrical spreading and atmospheric stratification, the accuracy of the prediction may significantly differ in the flight and atmospheric conditions. In addition, the attenuation characteristics of the evanescent wave [57, 58] under the caustic region have not been fully clarified, although this wave is assumed to decay exponentially toward the ground. Therefore, the flight test, known as the Farfield Investigation of No boom Threshold (FaINT) [13] at NASA, was conducted to evaluate sonic boom cutoff phenomena [53] in the caustic-vicinity field, where the shock waves do not reach the ground because of an increase in atmospheric temperature toward the ground.

1.2.4 Limitation of application

Sonic boom waveforms generated from supersonic aircrafts in several flight and atmospheric conditions can be predicted by the existing prediction methods. However, these methods are based on the weak shock theory, and even complex phenomena are treated as simplified models. Thus, the applications of these methods are limited, and there are four big issues as follows. First, the accuracy of the rise time prediction is not necessarily adequate because the molecular relaxation and thermoviscous dissipation are evaluated as simplified models, and the effect of atmospheric turbulence cannot be well considered, as described in section 1.2.2. Second, the prediction of focused sonic boom in the caustic-vicinity field is conducted without consideration of the important effects such as geometrical spreading and atmospheric stratification, and the prediction accuracy of the evanescent wave is not adequate, as described in section 1.2.3. Third, the prediction methods based on the weak shock theory cannot be applied to sonic boom propagation generated from hypersonic flight objects because of the following reason: The area-balancing technique [19] for determining the weak shock waves cannot be applied to the strong shock waves with strong nonlinearity. In addition, the formation process of rise time significantly differs in supersonic and hypersonic flow regimes because the effects of molecular relaxation and chemical nonequilibrium in the hypersonic flow regime are much stronger than those in the supersonic flow regime. Forth, the variation in the circumferential direction around the body axis cannot be considered, and the ground effects [59, 60], including the ground reflection and ground topography, are treated as simplified models in the exciting prediction methods. For these reasons, the applications of the existing prediction methods are limited, and they must be further improved to precisely predict sonic boom intensity in various flight, atmospheric, and ground conditions. Moreover, considering the fact that the several flight tests for sonic boom measurements were recently conducted, high-precision numerical flight experiments should be conducted in concert with the flight tests. Therefore, instead of the simplified prediction methods using the weak shock theory, the rigorous prediction method based on the CFD, i.e., the full-field simulation method [61, 62] seems to be a valid approach not only for analyzing sonic boom propagation through the real atmosphere but also for realizing numerical flight experiments (see next section for details).

1.3 Full-field simulation

1.3.1 Introduction of full-field simulation method

Full-field simulation [61, 62] represents CFD analysis for sonic boom predictions, wherein the entire flow field including the near, far, and caustic-vicinity fields is solved as a single computational domain. This simulation has the potential for considering various flight, atmospheric, and ground conditions because of the following three reasons: First, even complex effects such as molecular relaxation, viscosity, chemical nonequlibrium, and turbulence can be incorporated by modifying the governing equations [63–65], although the rigorous physics-based models of these effects must be constructed as needed. Second, the three-dimensional structure of a shock wave can be clarified because this method can consider the variation in the circumferential direction around the body axis. Third, the ground effects, including not only the ground reflection but also the ground topography, are precisely predicted because even a complex geometry, as well as an aircraft configuration, can be analyzed by the CFD methods [66, 67]. For these reasons, the full-field simulation method seems to be a powerful tool for precisely predicting sonic boom propagation in the realistic environmental conditions and for clarifying the complex sonic boom phenomena that have not been well clarified. Moreover, this simulation holds promise for conducting numerical flight experiments, wherein flight tests for sonic boom measurements are precisely reproduced.

CFD analysis for sonic boom propagation in the far field has been conducted by solving the one-dimensional, spherical-symmetric, and axi-symmetric equations [68–70]. However, the resolution of the shock wave was not necessarily adequate, and the computational load was very high. In addition, there is no precedent for three-dimensional CFD analysis considering atmospheric stratification. Therefore, the following three problems must be improved to perform full-field simulation in the real atmosphere. First, the computational approach for considering atmospheric stratification must be constructed. In the case of compressible CFD analysis, the flow field is generally discretized by the computational grid and is solved by the Riemann solver [71]. Consequently, the change caused by atmospheric stratification with altitude is treated as a discontinuity in the Riemann solver, and nonphysical waves are generated. Thus, a computational approach for avoiding this change must be constructed because such an approach has not yet been proposed. Second, the solution-adapted grid over the entire flow field must be constructed to precisely capture shock waves [72]. Because the shock-wave angles change with the atmospheric temperature, the grid angles must be changed according to the propagation directions of the shock waves in the stratified atmosphere; thus, the three-dimensional solution-adapted grid must be constructed. Third, the computational load must be reduced as much as possible because the computational domain ranges over quite a long distance, and the thermal nonequilibrium flow analysis [68, 69] with high computational load is essential for predicting the rise time. With those in mind, the framework of the full-field simulation method is developed to analyze sonic boom propagation through the real atmosphere in this study.

1.3.2 Roadmap for formulation of full-field simulation method

Figure 1.2 shows the roadmap for constructing the framework of the full-field simulation method. The roadmap is composed of three phases. The first phase is the formulation of the full-field simulation method including the computational approach, the method of constructing the solution-adapted grid, and the segmentation method of a computational domain. The computational approach is formulated to simulate sonic boom propagation including five important effects as follows:

- **Geometrical spreading**: the attenuation effect due to the geometrical spreading of a wave with increasing distance from a generation source.
- **Nonlinearity**: the effect of wave steepening that is caused by the difference in the propagation speed of waves.
- **Atmospheric stratification**: the atmospheric effect due to variation in atmospheric properties with altitude.
- **Molecular relaxation (thermal nonequilibrium)**: the relaxation effect due to translational-vibrational energy exchange.
- **Viscosity**: the dissipation effect due to the fluid friction and thermal conduction.

If the computational approach considering these five effects is formulated, the extension of this approach is assumed to be relatively easy because the full-field simulation is based on the CFD. The method of constructing the solution-adapted grid is formulated so as to meet the following three requirements. First, shock waves must not intersect with the grid lines; thus, the grid lines in the entire computational domain must align with the shock waves. Second, the grid resolution near the shock waves must be adequately high. Third, the number of grid points must be reduced as much as possible because the computational domain ranges over quite a long distance. The segmentation method of a computational domain is constructed to

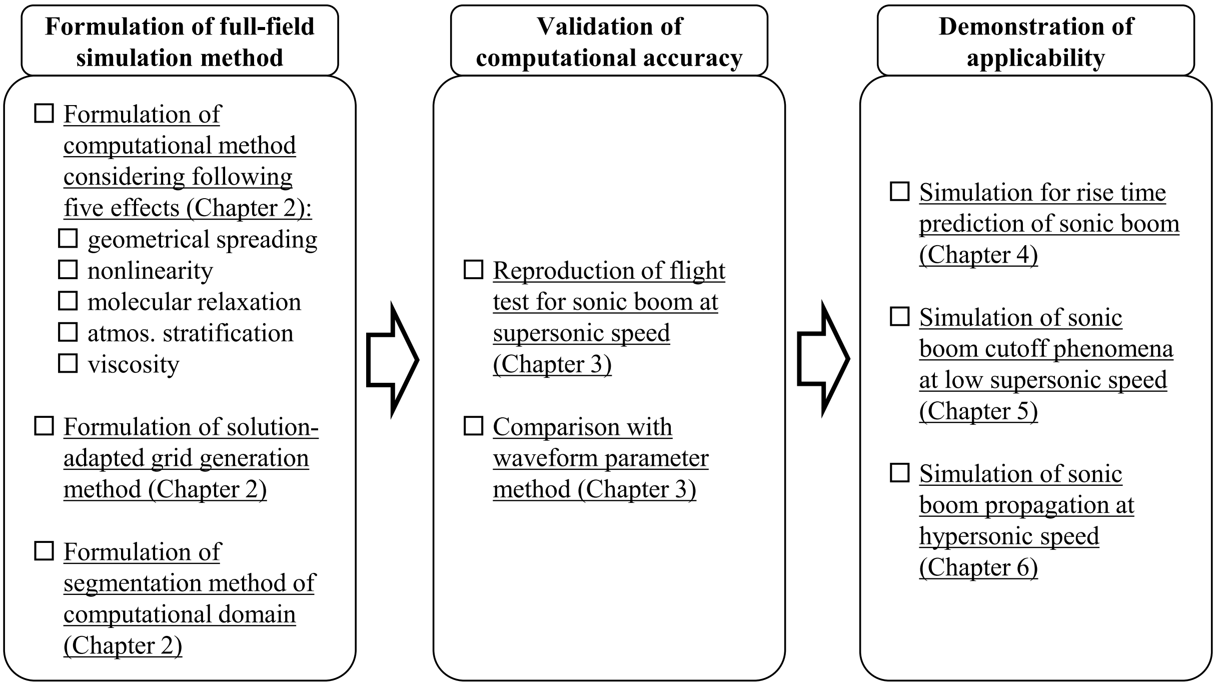

Fig. 1.2 Roadmap for constructing framework of full-field simulation method.

reduce the computational load and to improve the efficiency of computation.

The second phase is the validation of computational accuracy. Full-field simulation is performed to reproduce the flight test, and the simulation results are validated by comparison with the results of the waveform parameter method, which is a representative prediction method for sonic boom, and the flight test data. Consequently, the reproducibility of the flight test for sonic boom in the real atmosphere is investigated.

The third phase is the demonstration of the applicability to the analysis of complex sonic boom phenomena that have not been well clarified. First, full-field simulation with the thermal nonequilibrium is performed to investigate the formation mechanism of rise time as described in section 1.2.2. Second, full-field simulation is performed to analyze sonic boom cutoff phenomena [53] generated from a low supersonic flight object, including focused sonic boom in the caustic-vicinity field as described in section 1.2.3. Third, full-field simulation is performed to investigate sonic boom characteristics in hypersonic flow regimes as described in section 1.1. Consequently, the usefulness of full-field simulation method is investigated as a valid approach for analyzing sonic boom characteristics at all speeds including nonequilibrium characteristics and for clarifying sonic boom phenomena that cannot be investigated in the existing prediction methods.

When all three phases shown in Fig. 1.2 are accomplished, it can be said that the framework of the full-field simulation method is constructed. For the practical use of the framework, the appropriate computational method including the governing equations is selected according to the application and is extended as needed. Consequently, the full-field simulation can precisely reproduce sonic boom propagation in various flight, atmospheric, and ground conditions; thus, numerical flight experiments can be conducted by the full-field simulation.

1.4 Objectives

Based on the above discussion, the objectives of this study are to formulate the framework of the full-field simulation method for sonic boom, according to the roadmap shown in Fig. 1.2, and to clarify sonic boom phenomena as follows:

- Formation mechanism of rise time due to molecular relaxation in uniform and stratified atmospheres.
- Sonic boom characteristics at low supersonic speeds, including cutoff phenomena in the caustic-vicinity field.
- Sonic boom characteristics at hypersonic speeds, including waveform transition of sonic boom according to flight Mach number.

Consequently, sonic boom phenomena that have not been well clarified become better understood, and the full-field simulation method becomes a powerful tool for precisely predicting sonic boom propagation through the real atmosphere and for realizing numerical flight experiments.

1.5 Outline of this thesis

An outline of this thesis is as follows. In chapter 2, the full-field simulation method is described. In chapter 3, the accuracy of full-field simulation is validated by comparison with the results of the waveform parameter method and the D-SEND#1 [14] flight test conducted by JAXA. In chapters 4 to 6, full-field simulation is performed to demonstrate the applicability of the full-field simulation method and to clarify sonic boom phenomena that cannot be investigated in the existing prediction methods. In chapter 4, full-field simulation is performed to investigate the effect of molecular relaxation on the sonic boom waveform and the formation mechanism of rise time in the uniform and stratified atmospheres. In chapter 5, full-field simulation is performed to analyze sonic boom propagation at low supersonic speeds, including sonic boom cutoff phenomena, and to investigate the applicability of this simulation to the analysis of focused sonic boom in the caustic-vicinity field. In chapter 6, full-field simulation is performed to clarify the waveform transition in a hypersonic flow regime and to investigate the applicability to sonic boom propagation from a hypersonic flight object. In chapter 7, the conclusion is described.

Chapter 2

Full-Field Simulation Method

The contents of this chapter are not open to the public because they will be published in journal articles.

Chapter 3

Validation of Computational Accuracy

The contents of this chapter are not open to the public because they will be published in journal articles. Parts of this chapter were already published as follows:

- Yamashita, R., and Suzuki, K.: Full-Field Sonic Boom Simulation in Real Atmosphere, AIAA Paper 2014-2269, June 2014.
- Yamashita, R., and Suzuki, K.: Rise Time Prediction of Sonic Boom by Full-Field Simulation with Thermal Nonequilibrium, AIAA Paper 2015-2583, June 2015.

Chapter 4

Full-Field Simulation for Rise Time Prediction

The contents of this chapter are not open to the public because they will be published in journal articles.

Chapter 5

Full-Field Simulation at Low Supersonic Speed

The contents of this chapter are not open to the public because they will be published in journal articles. Part of the contents was already published as follows:

- Yamashita, R. and Suzuki, K.: Full-Field Simulation for Sonic Boom Cutoff Phenomena, Transactions of the Japan Society for Aeronautical and Space Sciences, Vol.58, No.6, 2015, pp. 327-336.

Chapter 6

Full-Field Simulation at Hypersonic Speed

The contents of this chapter are not open to the public because they will be published in journal articles. Part of the contents was already published as follows:

- Yamashita, R. and Suzuki, K.: Waveform Transition of Sonic Boom from N-wave to Caret-wave generated from a Sphere at Hypersonic Speed, AIAA Journal, 2015 (published online).

Chapter 7

Conclusions

A framework of the full-field simulation method was formulated to reproduce sonic boom propagation through the real atmosphere and was used to clarify formation mechanism of rise time, sonic boom cutoff phenomena, and the waveform transition in hypersonic flow regimes. The results are summarized as follows.

Formulation of full-field simulation method (Chapters 2 and 3)

(Not open to the public because the contents of this chapter will be published in journal articles.)

Full-field simulation for rise time prediction (Chapter 4)

(Not open to the public because the contents of this chapter will be published in journal articles.)

Full-field simulation at low supersonic speed (Chapter 5)

(Not open to the public because the contents of this chapter will be published in journal articles.)

Full-field simulation at hypersonic speed (Chapter 6)

(Not open to the public because the contents of this chapter will be published in journal articles.)

As mentioned above, the framework of the full-field simulation method was completely constructed because all three phases were completed, as shown in Fig. 7.1. Moreover, the formation mechanism of rise time, the sonic boom cutoff phenomena, and the waveform transition in hypersonic flow regimes were well clarified by the full-field simulation. Therefore, the objectives of this thesis were completed. Because the full-field simulation based on the CFD has the potential for considering various flight, atmospheric, and ground conditions, it seems promising for realizing high-accuracy numerical flight experiments for sonic boom.

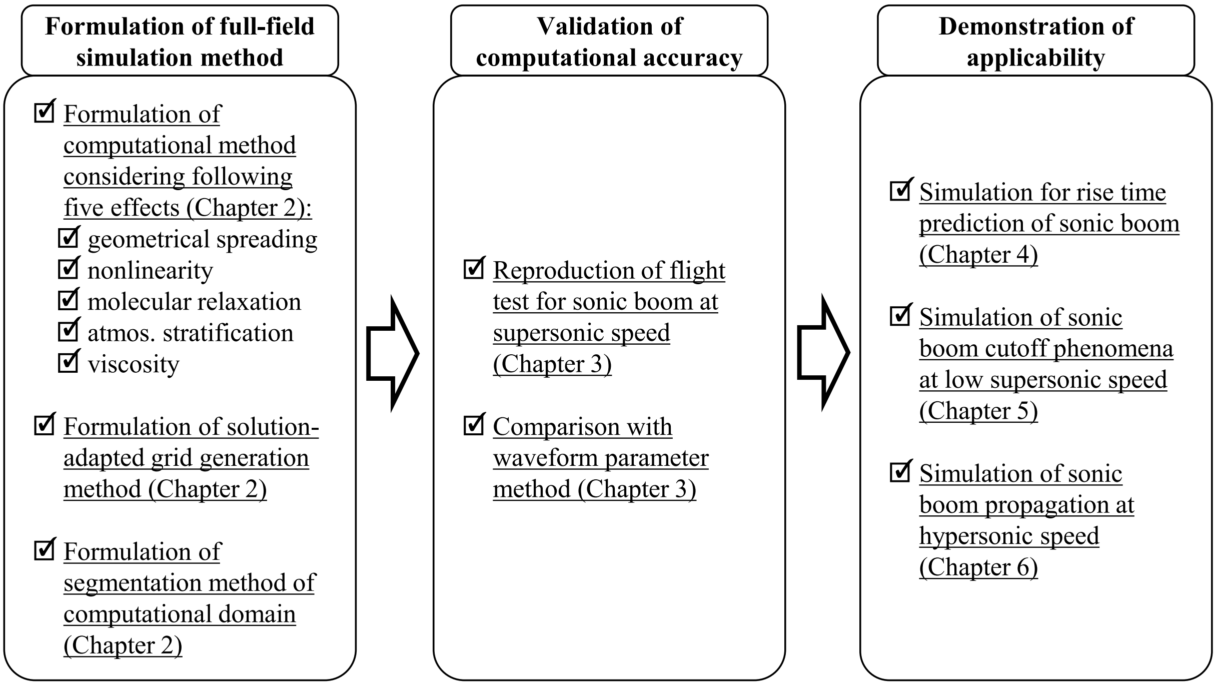

Fig. 7.1 Roadmap for constructing framework of full-field simulation method.

Appendix

Waveform Parameter Method

The waveform parameter method [45] invented by Thomas is the representative prediction method for sonic boom in the far field reaching the ground. In this method, the pressure fluctuation is derived from the conservation of the Blokhintsev energy invariant in the geometric acoustics, and the nonlinear effect on the waveform distortion is considered by the isentropic wave theory, in which the propagation speed is assumed to be a sum of the local speed of sound and the change of velocity. The entire pressure waveform is split into a sequence of segments, and the segmented waveform is described by the following three parameters. The first parameter m_i is the pressure gradient of segment i. The second parameter Δp_i is the pressure rise of the shock wave at the boundary of segments i and i–1. The third parameter λ_{Di} is the time duration of segment i. Figure A.1 shows the schematic of these parameters. These parameters along the ray path are computed by the three ordinary differential equations as

$$\frac{dm_i}{dt} = C_1 m_i^2 + C_2 m_i \tag{A.1}$$

$$\frac{d\Delta p_i}{dt} = \frac{1}{2} C_1 \Delta p_i \left(m_i + m_{i-1}\right) + C_2 \Delta p_i \tag{A.2}$$

$$\frac{d\lambda_{Di}}{dt} = -\frac{1}{2} C_1 \left(\Delta p_i + \Delta p_{i+1}\right) - C_1 m_i \lambda_{Di} \tag{A.3}$$

$$C_1 = \frac{\gamma + 1}{2\gamma} \frac{c_a}{p_a a_n} \tag{A.4}$$

$$C_2 = \left(\frac{1}{2\rho_a} \frac{d\rho_a}{dt} + \frac{3}{2c_a} \frac{dc_a}{dt} - \frac{1}{a_n} \frac{da_n}{dt} - \frac{1}{2A} \frac{dA}{dt} \right) \tag{A.5}$$

where p, ρ and c are the pressure, density, and speed of sound, respectively. a_n is the velocity normal to the wave front, and A is a ray tube area [73] as cut by the wave front. Subscript a means the atmospheric value. The derivation of the equations above is left out here (see reference 45 for details). The variables C_1 and C_2 in the nonuniform atmosphere change along the ray path. However, if these variables are assumed to

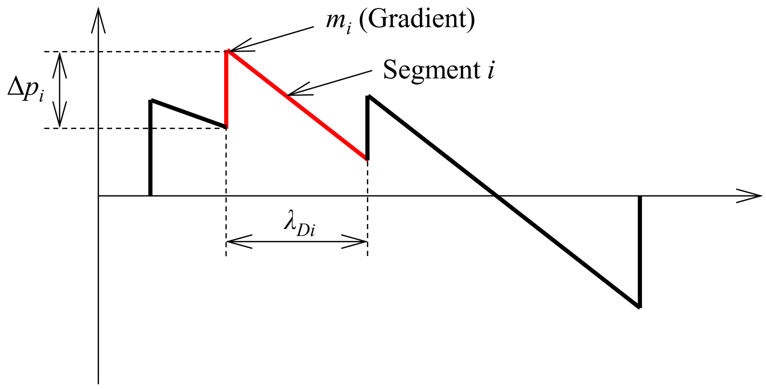

Fig. A.1 Three waveform parameters where red line indicates waveform of segment *i*.

be constant during the sufficiently small time, the equations above can be solved by the finite difference method. As the acoustic waves propagate along the ray paths, they are distorted by the nonlinear effect, resulting in the coalescence of the waves. In the waveform parameter method, λ_{Di} becomes zero when two waves coalesce into a single wave. In such a case, the coalescence point is computed, and the waveform parameters are redefined at this point.

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