南京航空航天大学

论文集

（二〇〇九年） 第2册

航空宇航学院

（第2分册）

南京航空航天大学科技部编

二〇一〇年五月

航空宇航学院

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航空宇航学院2009年学术论文清单（0121）

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
1	刘剑明 赵宁 胡偶	博士 教授 博士	0121 0121 0121	GHOST-CELL METHOD FOR INVISCID THREE-DIMENSIONAL FLOWS WITH MOVING BODY ON CARTESIAN GRIDS	Modern Physics Letters B	2009.23.03
2	刘剑明 赵宁 胡偶	博士 教授 博士	0121 0121 0121	The Ghost Cell Method and its Applications for Inviscid Compressible Flow on Adaptive Tree Cartesian Grids	Advances in Applied Mathematics and Mechanics	2009.01.05
3	史志伟 明晓	副研究员 教授	0121 0121	Experimental investigation on a pitching motion delta wing in usteady free stream	Modern physics letters B	2009.23.03
4	史志伟 张传鸿 刘志强	副研究员 研究生 研究生	0121 0121 0121	齐莫曼翼与反齐莫曼翼空间流场测量对比分析	实验流体力学	2009.23.03
5	史志伟 明晓	副研究员 教授	0121 0121	非定常自由来流对静态三角翼气动特性的影响	空气动力学学报	2009.27.04
6	史志伟 范本根 吴根兴	副研究员 硕士 教授	0121 0121 0121	飞机大迎角俯仰运动下的横侧向气动特性及被动控制	实验力学	2009.24.05
7	史志伟	副研究员	0121	振荡来流对静态和俯仰运动三角翼气动特性的影响	第二届近代实验空气动力学会议论文	
8	史志伟 刘志强 昂海松	副研究员 硕士 教授	0121 0121 0112	双翼微型飞行器水平阵风响应特性实验研究	中国力学学会学术大会2009	
9	刘志强 史志伟 白鹏	硕士 副研究员	0121 0121 外单位	双翼微型飞行器水平阵风响应实验研究	实验流体力学	2009.23.03
10	郭同庆 陆志良 吴永健	副教授 教授 副教授	0121 0121 0121	a time-domain method for transonic flutter analysis with multidirectional coupled vibrations	MODERN PHYSICS LETTERS B	2009.23.03
11	高宜胜 伍贻兆 王江峰	硕士生 教授 教授	0121 0121 0121	先进飞行器气动隐身一体化设计方法研究现状与趋势	江苏航空	2009.01
12	周春华 舒昌	教授 教授	0121 0121	A local domain-free discretization method to simulate three-dimensional compressible inviscid flows	International Journal for Numerical Methods in Fluids	2009.61
13	郭欣 唐登斌	博士生 教授	0121 0121	Boundary Layer Stability with multiple Modes in Hypersonic Flows	Modern Physics Letters B	2009.23.04
14	陈林 唐登斌 刘小兵	博士生 教授	0121 0121 外单位	边界层掀过程中环状涡和尖峰结构的演化	中国科学 G辑	2009.39.10
15	王江峰 伍贻兆 程克明	教授 教授 教授	0121 0121 0122	Numerical Simulation of Hypersonic MHD Flow with Nonequilibrium Chemical reacitons on Unstructured Meshes	Modern Physics Letters B	2009.32.03
16	王江峰 夏健 田书玲	教授 教授 讲师	0121 0121 0121	基于非结构动态网格的翼型积冰过程数值模拟	航空学报	2009.30.12
17	刘晨 王江峰 伍贻兆	博士 教授 教授	0121 0121 0121	低马赫数流动中的预处理Euler方程的收敛特性	航空学报	2009.30.05
18	秦波	副研究员	0121	Nonlinear property of slightly compressible media permeated with air-filled bubbles	Frontiers of Physics in China	2009.04.01
19	唐智礼 J.Periaux G.Bugeda E.Onate	副教授	0121 外单位 外单位	Lift maximization with uncertainties for the optimization of high-Lift devices	International Journal For Numerical Methods in Fluids	2009 DOI:10.1002/fld.2130
20	唐智礼 董军	副教授	0121 外单位	Couplings in multi-criterion aerodynamic optimization problems Using Adjoint Methods and Game Strategies	Chinese Journal of Aeronautics	2009.22.01
21	唐智礼	副教授	0121	Uncertainty based robust optimization in aerodynamics	Modern Physics Letters B	2009.23.03

22	唐智礼 J.Periaux G.Bugeda E.Onate	副教授	0121 外单位 外单位	Lift maximization with uncertainties for the optimization of high lift devices using Multi-Criterion Evolutionary Algorithms	2009 IEEE Congress on Evolutionary Computation (CEC 2009)	18-21, May, 2009 PP: 2324-2331
23	闫再友	副教授	0121	Expression for the Gradient of the First Normal Derivative of the Velocity Potential	CMES: Computer Modeling in Engineering & Sciences	2009.46.01
24	闫再友 才漪	副教授 助理工程师	0121 0121	Multi-Domain Direct BEM and Its Application to the Simulation of Helmholtz Resonator	中国科学技术大学学报	2008.38.04
25	陈永亮 沈宏良	讲师 教授	0121 0121	过失速下俯敏捷性及纵向控制效能需求研究	飞行力学	2009.27.6
26	夏健 田书玲 伍贻兆	教授 讲师 教授	0121 0121 0121	Numerical simulation of parachute inflation process using an ovrset deforming grids method	Modern Physics Letters B	2009.23.03
27	田书玲 伍贻兆 夏健	讲师 教授 教授	0121 0121 0121	NUMERICAL SIMULATION OF UNSTEADY FLOW FIELD AROUND HELICOPTER IN FORWARD FLIGHT USING A PARALLEL DYNAMIC OVERSET UNSTRUCTURED GRIDS METHOD	Modern Physics Letters B	2009.23.03
28	季晨振 舒昌 赵宁	硕士 教授 教授	0121 0121 0121	A LATTICE BOLTZMANN METHOD-BASED FLUX SOLVER AND ITS APPLICATION TO SOLVE SHOCK TUBE PROBLEM	Modern Physics Letters B	2009.23.03
29	丁玲 舒昌 赵宁	硕士 教授 教授	0121 0121 0121	NUMERICAL SIMULATION OF DAM BREAK BY ADAPTIVE STENCIL DIFFUSE INTERFACE METHOD	Modern Physics Letters B	2009.23.03
30	李秋 舒昌 陈红全	硕士 教授 教授	0121 0121 0121	SIMULATION OF INCOMPRESSIBLE VISCOUS FLOWS BY BOUNDARY CONDITION-IMPLEMENTED IMMERSED BOUNDARY METHOD	Modern Physics Letters B	2009.23.03
31	陈红全 饶 玲	教授	0121 0121	THE TECHNIQUE OF THE IMMERSED BOUNDARY METHOD: APPLICATION TO THE NUMERICAL SOLUTION OF IMCOMPRESSIBLE FLOWS AND WAVE SCATTERING	Modern Physics Letter B	2009.23.03
32	陈红全 Glowinski R. Périaux J.	教授	0121	A Domain Decomposition/Nash Equilibrium Methodology for the Solution of Direct and Inverse Problems in Fluid Dynamics with Evolutionary Algorithms	Lecture Notes in Computational Science and Engineering	2008.6
33	王红 陈红全 马志华 蒲赛虎	硕士 教授 博士 硕士	0121 0121 0121 0121	动边界问题无网格算法及其动态点云	南京航空航天大学学报	2009.41.03
34	吴晓军 陈红全 邓有奇 马自华	博士 教授 研究院 博士	0121 0121 外单位 0121	栅格绕流数值模拟研究	空气动力学学报	2009.27.01
35	龚正 沈宏良 吴根兴	博士 教授	0121 0121 0121	非定常气动力对飞行动力学特性影响分析	南京航空航天大学学报	2009.41.03

航空宇航学院2009年学术论文清单（0122）

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
1	李斌斌 程克明 顾蕴松	博士 教授 教授	0122 0122 0121	基于斜出口合成射流激励器的边界层分离控制	南京航空航天大学学报	2009.41.03
2	王成鹏 田旭昂 程克明	副教授 硕士 教授	0121 0121 0122	NUMERICAL INVESTIGTIONS OF PSEDUO-SHOCK WAVES IN VARIABLE CROSS-SECTION DUCTS	Modern Physics Letters B	2009.23.03
3	王成鹏 杨永阳 刘晨 王江峰 程克明 伍贻兆	副教授 硕士 博士 教授 教授 教授	0122 0122 0122 0121 0122 0121	超燃燃烧室 流场计算方法比较分析	航空动力学报	2009.24.05
4	董昊 王成鹏 程克明	博士 副教授 教授	0122 0122 0122	咽式高超进气道流动特性及性能分析	航空动力学报	2009.24.11
5	张军 任登峰 谭俊杰	副研究员	0122 外单位 外单位	Multi-material numerical simulation of moving shock interacing with consecutive bubbles	南京航空航天大学学报英文版	2009.26.03
6	张红英 程克明 伍贻兆	助理研究员 研究员 教授	0122 0122 0121	某高超飞行器流倒冷流特征及气动力特性研究	空气动力学学报	2009.27.01
7	张红英 刘卫华 童明波 孙为民	助理研究员 教授 教授 工程师	0122 014 0112 外单位	降落伞初始充气阶段数值模拟	南京航空航天大学学报	2009.41.02
8	张红英 程克明 伍贻兆	助理研究员 研究员 教授	0122 0122 0121	高超声速飞行器内流道流态及其对全机气动力特性的影响的实验研究	空气动力学学报	2009.27.02

航空宇航学院2009年学术论文清单（0131）

序号	姓名	职称	单位	论文题目	刊物、会议名称	年、卷、期
1	胡海岩 王在华	教授 教授	0131 0131	Singular perturbation methods for nonlinear dynamic systems with time delays	Chaos, Solitons and Fractals	2009.4
2	江湘青 胡海岩	博士 教授	0131 0131	Reconstruction of Distributed Dynamic Loads on a Thin Plate via Mode-Selection and Consistent Spatial Expression	Journal of Sound and Vibration	2009.323.3—5
3	靳艳飞 胡海岩	博士 教授	0131 0131	一类线性阻尼振子的随机共振研究	物理学报	2009.58.05
4	刘博 胡海岩	博士 教授	0131 0131	群时延引起的受控小车二级摆失稳及其抑制	Acta Mechanica Sinica	2009.22.05
5	刘博 原口正和 胡海岩	博士 博士 教授	0131 0131 0131	A New Reduction-Based LQ Control for Dynamic Systems with a Slowly Time-Varying Delay	Acta Mechanica Sinica	2009.25.04
6	茅晓晨	博士	0131 0131 0131 0131	Singular Perturbation Methods for Nonlinear Dynamic Systems with Time Delays	Chaos, Solitons and Fractals	2009.30.02
7	茅晓晨 胡海岩	博士 教授	0131 0131	Hopf Bifurcation Analysis of a Four-Neuron Network with Multiple Time Delays	Nonlinear Dynamics	2009.55.1—2
8	茅晓晨 胡海岩	博士 教授	0131 0131	Dynamics of a Delayed Four-Neuron Network with a Short-Cut Connection: Analytical, Numerical and Experimental Studies	International Journal of Nonlinear Sciences and Numerical Simulation	2009.10.04
9	茅晓晨 胡海岩	博士 教授	0131 0131	Stability and Hopf bifurcations of a delayed network of four neurons with a short-cut connecttin	International Journal of Bifurcation and Chaos	2008.18.10
10	茅晓晨 胡海岩	博士 教授	0131 0131	四神经元时滞网络的稳定性与分叉	力学季刊	2009.30.01
11	原口正和 胡海岩	博士 教授	0131 0131	Stability Analysis of a Noise Control System in a Duct by Using Delay Differential Equation	Acta Mechanica Sinica	2009.25.01
12	陈辉 文浩 金栋平 胡海岩	博士 博士 教授 教授	0131	用弹性绳系系统进行空间捕捉的最优控制	宇航学报	2009.30.02
13	刘丽丽 文浩 金栋平 胡海岩	博士 博士 教授 教授	0131 0131 0131 0131	绳系卫星轨道转移的最优控制	航空学报	2009.30.02
14	刘丽丽 文浩 金栋平 胡海岩	博士 博士 教授 教授	0131 0131 0131 0131	空间碎片队绳系卫星冲击的影响分析	振动与冲击	2009.28.07
15	王晓宇 金栋平	博士 教授	0131 0131	飞行时间不受约束的绳系卫星最优控制	应用力学学报	2009.26.01
16	文浩 金栋平 胡海岩	讲师 教授 教授	0131 0131 0131	Costate Estimation for Dynamic Systems of the Second Order	Science in China, *Series E*	2009.52.03
17	游伟倩 陈怀海 崔旭利	博士生 教授 博士生	0131 0131 0131	Research on LQR Optimal control and the H-infinity Mixed-Sensitivity Method in Vibration Control of High Order Flexible Structures	Proceedings of The Second International Conference on Modelling and Simulation	2009.04

18	姜双燕 陈怀海 贺旭东	博士生 教授 副教授	0131 0131 0131	基于IMC的多输入多输出高阶系统PID控制器设计	航空学报	2009.30.02
19	王亮 陈怀海 贺旭东 游伟倩	博士 教授 副教授 博士生	0131 0131 0131 0131	轴向运动边长度悬臂梁的振动控制	振动工程学报	2009.22.06
20	段勇 陈前 林莎	博士 教授 硕士	0131 0131 0131	颗粒阻尼对直升机旋翼桨叶减振效果的试验	航空学报	2009.30.11
21	段勇 陈前 周宏伟	博士 教授 博士	0131 0131 0131	垂直简谐激励下颗粒阻尼耗能特性的仿真研究	振动与冲击	2009.28.02
22	鲁帆 陈前	博士 教授	0131 0131	Investigation of condition monitoring of a flap system	Key Engineering Materials	2009.413－414
23	滕汉东 陈前	博士 教授	0131 0131	液固混合介质的隔振性能分析	振动工程学报	2009.22.03
24	滕汉东 陈前	博士 教授	0131 0131	Study on vibration isolation properties of solid and liquid mixture	Journal of Sound and Vibration	2009.326.1－2
25	滕汉东 陈前	博士 教授	0131 0131	Performance Characteristics of SALiM Isolator	World Congress on Engineering	2009.1－2
26	滕汉东 陈前 张翠霞	博士 教授 硕士	0131 0131 0131	一类液固混合介质隔振器的动力学特性研究	力学学报	2009.41.02
27	邵敏强 陈卫东 陈前	博士 教授 教授	0131 0131 0131	基于随机游走和输入估计方法的振动主动控制研究	振动与冲击	2009.28.07
28	崔鹏 韩景龙	博士 教授	0131 0131	一种局部形式的流固耦合界面插值方法	振动与冲击	2009.28.10
29	王云海 韩景龙	博士 教授	0131 0131	Symbolic Computation for a Class Vector Field with Double Resonance Hopf Bifurcation	2009 International Conference on Electronic Computer Technology	
30	黄丽丽 韩景龙 员海玮	硕士 教授 讲师	0131 0131 0131	考虑气动不确定性的气动弹性系统模型确认	航空学报	2009年30卷11期
31	王在华 郑远广	教授 博士	0131 0131	The optimal form of the fractional-order difference feedbacks in enhancing the stability of a sdof vibration system	Journal of Sound and Vibration	2009.326
32	王在华 胡海岩	教授 教授	0131 0131	含分数阶导数阻尼的线性振动系统的稳定性	中国科学 G 辑	2009.39.10
33	李俊余	博士	0131	Hopf bifurcation of the sunflower equation	Nonlinear Analysis: Real World Applications	2009.1
34	李俊余 王在华	博士 教授	0131 0131	Local Hopf bifurcation of complex nonlinear system with time delay	International Journal of Bifurcation and Chaos	2009.19.03
35	李俊余 王在华	博士 教授	0131 0131	一类时滞系统Hurwitz稳定的简单判据	动力学与控制学报	2009..07.02
36	郑远广 王在华	博士 教授	0131 0131	Stability and Hopf bifurcations of an optoelectronic time-delay feedback system	Nonlinear Dynamics	2009.57
37	赵永辉	副教授	013	Flutter suppression of a high aspect-ratio wing with multiplecontrol surfaces	Journal of Sound and Vibration	2009.324
38	赵永辉	副教授	013	Stability of a two-dimensional airfoil with time-delayed feedback control	Journal of Fluids and Structures	2009.25
39	赵永辉 胡海岩	副教授 教授	0131 0131	Active control of vertical tail buffeting by piezoelectric actuators	Journal of Aircraft	2009.46.04

40	员海玮 韩景龙	讲师 教授	0131 0131	Robust flutter analysis of a nonlinear aeroelastic system with parametric uncertainties	AEROSPACE SCIENCE AND TECHNOLOGY	2009.13.2-3
41	员海玮 韩景龙	讲师 教授	0131 0131	气动弹性系统的模型确认与鲁棒颤振分析	振动工程学报	2009.22.05
42	林贤坤 张令弥 郭勤涛 张宇峰	博士生 教授 副教授 高工	0131 0131 外单位 外单位	Dynamic Finite Element Model Updating of Prestressed Concrete Continuous Box-Girder bridge	Earthquake Engineering and Engineering Vibration	2009.08.03
43	林贤坤 张令弥 郭勤涛 赵晓平	博士生 教授 副教授 副教授	0131 0131 外单位 外单位	协同进化遗传算法在传感器优化配置中的应用	振动与冲击	2009.28.03
44	林贤坤 张令弥 郭勤涛 张宇峰	博士 教授 副教授 高工	0131 0131 外单位 外单位	预应力连续箱梁桥的基准动力有限元模型研究	振动与冲击	2009.28.11
45	孙鑫晖 张令弥 王彤	博士 教授 副教授	0131 0131 0131	基于左矩阵分式模型的短记录数据模态参数识别	振动与冲击	2009.28.12
46	孙鑫晖 张令弥 王彤	博士 教授 副教授	0131 0131 0131	基于奇异值分解的频响函数降噪方法	振动、测试与诊断	2009.29.03

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GHOST-CELL METHOD FOR INVISCID THREE-DIMENSIONAL FLOWS WITH MOVING BODY ON CARTESIAN GRIDS

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This paper depicts a ghost cell method to solve the three dimensional compressible time-dependent Euler equations using Cartesian grids for static or moving bodies. In this method, there is no need for special treatment corresponding to cut cells, which complicate other Cartesian mesh methods, and the method avoids the small cell problem. As an application, we present some numerical results for a special moving body using this method, which demonstrates the efficiency of the proposed method.

Keywords: Cartesian grids; moving boundary; ghost cell method.

1. Introduction

This work considers a numerical simulation of three-dimensional flow with moving boundaries. As we all know, there are three main methods[1] of moving geometry during a time step: overset (overlapping) meshes, deforming meshes, and Cartesian approach. Essentially, with an overlapping mesh technique,[2–4] individual components are meshed separately using local structured meshes that overlay a background structured mesh. As any boundary body moves its associated mesh moves with it, with the other meshes remaining unchanged. Since information must be transferred between meshes, the identification of mesh intersection points and interpolation of data on all overlapping meshes is necessary. With deforming meshes[5–7] the volume mesh deforms in response to the surface motion, and after large deformations a time remeshing and (often non-conservative) interpolation to the new mesh is performed. Deforming-mesh approaches can be conservative over a time step, making them attractive for small deformations. However, for gross boundary motions associated with large time steps the quality of the difference stencil can degrade rapidly due to this distortion. A third alternative regaining popularity is the use of completely Cartesian mesh. Conceptually, this approach is quite simple. Solid bodies are cut out of a single static background mesh and their boundaries represented by different types of cut cell, or solid bodies are equipped with ghost cells using the immersed boundary. In practice, cut cells may be arbitrarily small and in cases involving body motion, the cut cell data changes in one of the following four ways: cut cell becomes solid cell, cut cell becomes an uncut flow cell, cut cell remains unchanged, uncut flow cell becomes cut cell. Some technique must be employed to overcome those problems and time step stability restrictions. Several authors use a merging technique,[8–10] where small irregular cut cells are merged together with a neighboring regular grid cell. Using this merging technique, then the conservation is automatically maintained. But this method increases the amount of geometry processing. Recently, Murman et al[1] present an implicit approaches for 3d moving boundaries, and give a detailed space-time analysis is used to present and discuss the moving-boundary scheme, with particular attention given to complexities arising in multiple dimensions. In their article, a conservation correction is added to obtain conservation in 2d, but the correction for 3d is very hard. Furthermore, Forrer and Berge[11] put forward an interesting immersed boundary method to solve a 2d moving geometries. Practice has shown this immersed boundary method to be very simple and effective. Though the method is not conservable, but the error can obtain a second order accuracy at the boundary by special treatment for moving wall pressure. Furthermore, the method avoid the small cell problem. In our article, we combine a ghost cell method as the one of Forrer et al[11] with the isentropic strategy to calculate a 3d magazine with moving doors, which is embedded in the fuselage of the fighter plane.

2. Numerical Method and the Treatment of Moving Wall Boundary

In the work presented here we only consider inviscid Euler equation, and a hexahedral, cell-centered finite volume dimensional splitting method with Lax-Friedrichs numerical flux has been implemented as the flow solver. A MUSCL-type extrapolation using minmod slope limiter, with a formal second order accuracy in space, has been applied to extrapolate the conserved variables onto the left- and right-hand sides of each cell face. Following, we will introduce ghost cell method (GCM) for three dimensional flows with static or moving body.

Recently, Forrer and Berger[11] described the concept of a mirror flow extrapolation of a given solution over a reflecting wall which may be curved or moving at a fixed or varying speed, and developed a Cartesian grid method to treat the cells along a reflecting boundary. In their paper,[11] the values of the ghost cell are obtained from the corresponding extrapolated values from the nearest boundary point x_w. As an example, we described only for pressure here. Then the corresponding ghost cell values are obtained by

$$p_{ghost} = p(x_w) + |x_w - x_{ghost}| \frac{p(x_w) - p(x_w^h)}{h}, \qquad (1)$$

where $x_w^h = x_w + h\mathbf{n}$, the value of $p(x_w^h)$ at the wall obtained by a bilinear interpolation. The equation (1) show the solution has a non-zero pressure gradient at the wall, which satisfy the theorem that particles moving along the wall change their speed due to this pressure gradient. Using this Ghost cell method, it can yield a second order accurate boundary treatment from the results,[11] and avoid the small cut cell problem.

In our simulation, for the simplicity of the code, the reduction of the complexity of the moving door structure and the improvement of accuracy, we use the second order boundary treatment,[11] and the isentropic strategy[12,13] to give the ghost boundary conditions as follows

$$p_{ghost} = p(x_w) + |x_w - x_{ghost}| \frac{p(x_w) - p(x_w^h)}{h},$$

$$\rho_{ghost} = \rho_A \left(\frac{p_{ghost}}{p_A} \right)^{1/\gamma},$$

$$V_{ghost} = V_A - 2(V_A \cdot \mathbf{n})\mathbf{n} + 2(V_s \cdot \mathbf{n})\mathbf{n},$$

$$E_{ghost} = \frac{p_{ghost}}{\gamma - 1} + \frac{1}{2}\rho_{ghost}|V_{ghost}|^2, \tag{2}$$

where V_A and V_s are flow velocity, moving solid boundary velocity and γ is the constant ratio of specific heats, respectively. For two dimensional static or moving boundary, we can see Fig. 1 . For each of the ghost cell centers (e.g. cell ghost), his corresponding symmetric point (e.g. point A) is determined at a location exterior to the body and reflected symmetrically with respect to the body surface. The cell centers surrounding each symmetric point are determined. As an example, points a, b, c and d are the cell centers surrounding point A in Fig. 1. The value of the conserved variables U at the point A can been determined by a bilinear interpolation or a linear interpolation corresponding to distance:

$$U_A = \frac{e^{-|Aa|}U_a + e^{-|Ab|}U_b + e^{-|Ac|}U_c + e^{-|Ad|}U_d}{e^{-|Aa|} + e^{-|Ab|} + e^{-|Ac|} + e^{-|Ad|}}, \tag{3}$$

where $|Aa|, |Ab|, |Ac|, |Ad|$ are the distances between A and a, b, c, d respectively. Furthermore, the extension to three dimensional flow problem can achieved by the same formula as (3).

3. Numerical Results

Here, we present the results for magazine with moving door. The shape of magazine with moving doors is shown in Fig. 1. In our simulation, we consider a flow with freestream Mach number of 0.8, and the angle speed of door is $150^o/s$. Because of the flow symmetry, only one half of the results of the flow field has been shown. Figure 2 present the results at time t = 5/150s, 30/150s, 60/150s, 90/150s, 120/150s.

Acknowledgments

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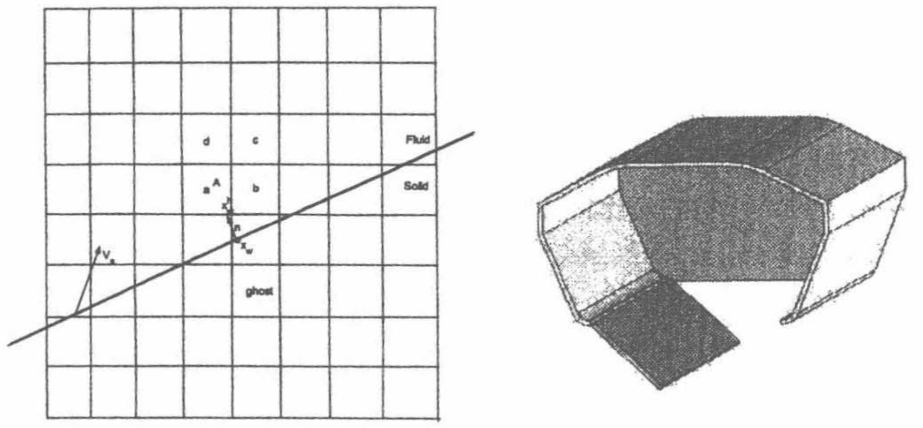

Fig. 1. Ghost moving boundary conditions and the shape of magazine.

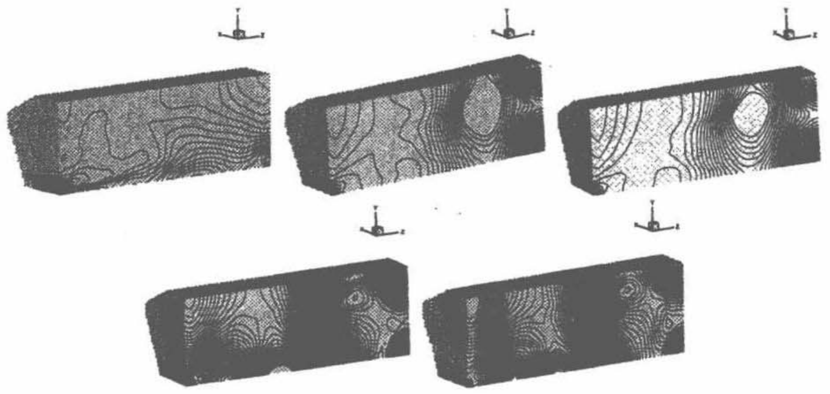

Fig. 2. 70 fluid pressure contours, when time t = 1/30s, t = 1/5s, t = 2/5s, t = 3/5s, t = 4/5s, respectively.

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The Ghost Cell Method and its Applications for Inviscid Compressible Flow on Adaptive Tree Cartesian Grids

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Abstract. In this paper, an immersed boundary algorithm is developed by combining the ghost cell method with adaptive tree Cartesian grid method. Furthermore, the proposed method is successfully used to evaluate various inviscid compressible flow with immersed boundary. The extension to three dimensional cases is also achieved. Numerical examples demonstrate the proposed method is effective.

AMS subject classifications: 65M06, 65M50, 76J20

Key words: Ghost cell method, Cartesian grid, adaptive tree method, inviscid compressible flow.

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1 Introduction

This paper focuses on the Ghost Cell method (GCM) and its applications for inviscid compressible flow on adaptive tree Cartesian grids. As we all know, a continuous obstacle of computational fluid dynamics (CFD) for configurations with complex geometry is the problem of mesh generation. Although a variety of grid generation techniques are now available, the generation of a suitable grid for a complicated, multi-element geometry is still a tedious, difficult and time-consuming task.

At present, the spatial discretization methods mainly have three approaches [1,2] for dealing with complicated geometry: unstructured grids, body-fitted curvilinear grids, and Cartesian grids. Unstructured grids mainly use triangles in two dimensional flow, tetrahedrons or prisms in three dimension. The advantages lie in the facility of mesh generation for complicated geometry. But the generation is not toilless,

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and still hard to get a good quality grid. Also the memory requirements and computational time are in general high. The main advantage of structured grids follows from the property that the indices i, j, k represent a linear address space (computational space), since it directly corresponds to how the flow variables are stored in the computer memory. Furthermore, more importantly in CFD applications, it gives more accurate results due to the discretisation methods used in most flow solvers. But there are also disadvantages. These are the generation of single structured grids for complex geometries, also time-consuming, and it can produce highly skewed grids too. In order to deal with complicated configurations, multiblock structured grids must be used. However, very long times are still required for the grid generation in the case of complex configurations.

A third alternative is the Cartesian grid approach. Conceptually, this approach is quite simple. Solid bodies are cut out of a single static background mesh and their boundaries represented by different types of cut cell, or solid bodies are equipped with ghost cells using the immersed boundary. Most previous work on Cartesian grids for the compressible Euler equations are based on Cartesian finite volume method [3]. But these methodologies may suffer stability problems when an explicit time step is used, cut cells become very small, and degenerate cells will be encountered. Generally, in two dimensions, a degenerate cell is defined as a cut-cell where the irregularly shaped (embedded) boundary (i) intersects the cell at more than two points or (ii) interacts any cell face at more than 1 point [4]. Some technique must be employed to overcome those problems and time step stability restrictions [4,5]. Jia et al. [4] present a robust and efficient hybrid cut-cell/ghost-cell method to overcome the degenerate cell, and the heat equations are considered. Several authors [2,6] use a merging technique, where small irregular cut cell is merged together with a neighboring regular grid cell. By using this merging technique, the conservation is automatically maintained. But this method increases the amount of geometry processing. Other methods include Berger et al. [7,8] use rotated boxes (h-box method) to enhance stability and, Colella and coworkers [9,10] use flux-redistribution procedures. Furthermore, embedded or immersed boundary ghost cell methods may be also a good choice, and Cartesian grid finite difference schemes for CFD problems have proven to be quite efficient.

Recently, Sjögreen and Petersson [3] develop an embedded boundary finite difference technique for solving the compressible two- or three-dimensional Euler equations in complex geometries on a Cartesian grid, and slope limiters are used on the embedded boundary to avoid non-physical oscillations near shock waves. Dadone and Grossman [11,12] provide a novel finite difference ghost cell method on a Cartesian grid, which considers the effect of curvature, and enforces symmetry conditions for entropy and total enthalpy along a normal to the body surface. The results on Cartesian grids indicate that the ghost cell method of [11,12] is remarkably convergent in grid and presents dramatic advantages with respect to the widely used first- and second-order pressure extrapolation techniques on body-fitted polar grids. In above mentioned papers of embedded or immersed boundary ghost cell methods, uniform grid or any grid clustering near the body are used, which must be maintained to the far-field boundary. In [13], Dadone and Grossman give a far-field coarsening and mesh adaptation method for Cartesian grids. Cartesian grids in conjunction with tree data structure are a natural choice for solution-adaptive grids. In this paper, the ghost cell methods with the adaptive tree Cartesian grids, we make a further study for the ghost cell immersed boundary method in inviscid compressible flows, and give some applications of the proposed method. Moreover, the conservation of the method is studied. The extension to three-dimensional flow is also presented.

The remainder of the paper is arranged as follows. In section 2, the high order numerical scheme for Euler equation is described. The boundary treatment is shown in section 3. In section 4, we give the tree data structure and the treatment based grid adaptation. The numerical results obtained using the ghost cell method on the adaptive Cartesian grid are presented in section 5. Concluding remarks are made in the final section.

2 Governing equations and numerical methods

2.1 Governing equations

The inviscid compressible Euler equations can be given in vector form explicitly expressing the conservation laws of mass, momentum and energy. The equations in a Cartesian coordinate system can be written as

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}+\frac{\partial G(U)}{\partial y}+\frac{\partial H(U)}{\partial z}=0, \tag{2.1}$$

where

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho E\end{bmatrix},\quad F=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ u(\rho E+p)\end{bmatrix},\quad G=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ v(\rho E+p)\end{bmatrix},\quad H=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ w(\rho E+p)\end{bmatrix}.$$

The variables p,ρ,u,v,w are the pressure, the density, and the three Cartesian components of the velocity vector, respectively, and E represents the total energy per unit mass. The pressure p is obtained using an equation of state for ideal gases

$$p=(\gamma-1)\Big(\rho E-\frac{1}{2}(u^2+v^2+w^2)\Big). \tag{2.2}$$

2.2 Numerical methods

In order to solve the multi-dimensional Euler equations, dimensional splitting is applied. We use one-dimensional Godunov's method in each coordinate direction, respectively. A MUSCL-type extrapolation using a *minmod* slope limiter, with a formal second order accuracy in space, has been applied to extrapolate the conserved variables onto the left- and right-hand sides of each cell face. An approximate Riemann solver is used to get face flux. For every one-dimensional problem, time discretization use the optimal second TVD Runge-Kutta method [15].

A particularly simple and robust approximate Riemann solver, called HLL, was proposed by Harten, Lax and van Leer in [14]. But it has the serious flaw of diffusing contact surfaces. This is mainly because the HLL solver reduces the exact Riemann problem to two pressure waves and therefore neglects the contact surface. An improved version of the HLL Riemann solver, named HLLC, is proposed by Toro [16], which is a modified three waves solver. This HLLC scheme is found to have the following properties [17]: (1) exact preservation of isolated contact and shear waves, (2) positivity preserving of scalar quantity, and (3) enforcement of entropy condition. The HLLC solver is versatile, and has been successfully used in various inviscid or viscous compressible flow on multifarious grids. Due to the significant advantages, in this work, HLLC solver is adopted as the approximate Riemann solver to discrete the convection flux on adaptive tree Cartesian grids.

The HLLC flux is defined by [16, 18]

$$F_{HLLC}=\begin{cases} F_l, & \text{if } S_L>0,\\ F(U_l^*), & \text{if } S_L\le 0<S_M,\\ F(U_r^*), & \text{if } S_M\le 0\le S_R,\\ F_r, & \text{if } S_R<0, \end{cases} \tag{2.3}$$

where

$$U_l^*=\begin{bmatrix}\rho_l^*\\(\rho u)_l^*\\(\rho v)_l^*\\(\rho w)_l^*\\(\rho E)_l^*\end{bmatrix}=\Omega_l\begin{bmatrix}\rho_l(S_L-q_l)\\(S_L-q_l)(\rho u)_l+(p^*-p_l)n_x\\(S_L-q_l)(\rho v)_l+(p^*-p_l)n_y\\(S_L-q_l)(\rho w)_l+(p^*-p_l)n_z\\(S_L-q_l)(\rho E)_l-p_lq_l+p^*S_M\end{bmatrix},$$

$$U_r^*=\begin{bmatrix}\rho_r^*\\(\rho u)_r^*\\(\rho v)_r^*\\(\rho w)_r^*\\(\rho E)_r^*\end{bmatrix}=\Omega_r\begin{bmatrix}\rho_r(S_R-q_r)\\(S_R-q_r)(\rho u)_r+(p^*-p_r)n_x\\(S_R-q_r)(\rho v)_r+(p^*-p_r)n_y\\(S_R-q_r)(\rho w)_r+(p^*-p_r)n_z\\(S_R-q_r)(\rho E)_r-p_rq_r+p^*S_M\end{bmatrix},$$

$$F_l^*\equiv F(U_l^*)=\begin{bmatrix}\rho_l^*S_M\\(\rho u)_l^*S_M+p^*n_x\\(\rho v)_l^*S_M+p^*n_y\\(\rho w)_l^*S_M+p^*n_z\\((\rho E)_l^*+p^*)S_M\end{bmatrix},\quad F_r^*\equiv F(U_r^*)=\begin{bmatrix}\rho_r^*S_M\\(\rho u)_r^*S_M+p^*n_x\\(\rho v)_r^*S_M+p^*n_y\\(\rho w)_r^*S_M+p^*n_z\\((\rho E)_r^*+p^*)S_M\end{bmatrix},$$

$$\Omega_l\equiv(S_L-S_M)^{-1},\qquad \Omega_r\equiv(S_R-S_M)^{-1},$$
$$p^*=\rho_l(q_l-S_L)(q_l-S_M)+p_l=\rho_r(q_r-S_R)(q_r-S_M)+p_r,$$

and

$$q \equiv un_x + vn_y + wn_z,$$

with $\vec{n}=[n_x, n_y, n_z]^T$ being the unit normal vector to the interface. Intermediate wave velocity S_M is taken from Batten et al. [19]

$$S_M = \frac{\rho_r q_r (S_R - q_r) - \rho_l q_l (S_L - q_l) + p_l - p_r}{\rho_r (S_R - q_r) - \rho_l (S_L - q_l)}.$$

Signal velocities S_L and S_R are defined as

$$S_L = \min\left(\lambda_1(U_l), \lambda_1(U^{Roe})\right),$$
$$S_R = \max\left(\lambda_m(U_r), \lambda_m(U^{Roe})\right),$$

with $\lambda_1(U^{Roe})$ and $\lambda_m(U^{Roe})$ being the smallest and largest eigenvalues of the Roe matrix.

In the approximate Riemann solvers, a higher-order approximation must be interpreted in terms of flux values to achieve second order accuracy at control-volume boundaries. This paper use van Leer's monotone upstream-centred scheme for conservation laws (MUSCL) approach to get second-order accuracy, and *minmod* limiter to damp spurious oscillation, which are shown as follows [20]

$$\begin{aligned} u^R_{j+\frac{1}{2}} &= u_{j+1} - \frac{1}{4}\left[(1-k)\widetilde{\Delta}_{j+\frac{3}{2}} u + (1+k)\widetilde{\widetilde{\Delta}}_{j+\frac{1}{2}} u\right], \\ u^L_{j+\frac{1}{2}} &= u_j + \frac{1}{4}\left[(1-k)\widetilde{\widetilde{\Delta}}_{j-\frac{1}{2}} u + (1+k)\widetilde{\Delta}_{j+\frac{1}{2}} u\right], \end{aligned} \tag{2.4}$$

where

$$\begin{aligned} &\widetilde{\Delta}_{j+\frac{1}{2}} u = \text{minmod}(\Delta_{j+\frac{1}{2}} u, \omega \Delta_{j-\frac{1}{2}} u), \\ &\widetilde{\widetilde{\Delta}}_{j+\frac{1}{2}} u = \text{minmod}(\Delta_{j+\frac{1}{2}} u, \omega \Delta_{j+\frac{3}{2}} u), \\ &\text{minmod}(x, \omega y) = \text{sgn}(x) \max\{0, \min[|x|, \omega y \text{sgn}(x)]\}, \end{aligned}$$

and k is a coefficient of MUSCL scheme. When set $k=1/3$, we can get a third order upwind scheme for uniform grid. ω is a constant specified by user, generally, $\omega=1$.

3 Ghost cell methods on Cartesian grids

Recently, Dadone and Grossman [11,12] present some systemic results about a novel ghost cell method for static body on Cartesian grids. In their papers, the ghost cell values are developed from an assumed flow field model in vicinity of the wall consisting of a vortex flow with locally symmetric distribution of entropy S and total enthalpy H per unit mass along a surface normal, and take into account the effect of curvature. If we make R the signed local radius of curvature of the wall, V_t the velocity component