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A numerical study on automatic mesh refinement for the simulation of Edney shock-shock interactions

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Abstract. The growing interest in hypersonic flight has motivated several research efforts devoted to the study of shock-shock interactions which can dramatically influence the heat load on different components of hypersonic aircraft. In the present work the use of an adaptive numerical scheme for the study of Edney type IV and type VI interactions is investigated. The numerical approach is based on a discontinuous Galerkin finite element method in which an h-adaptive algorithm is used to automatically refine the mesh in the regions where the most interesting flow structures are present. Several adaptation criteria are investigated. Furthermore, it is shown that the gradients obtained by the internal element reconstruction are not suitable for the computation of indicators because they are strongly affected by the shock capturing stabilisation. An alternative approach, based on the use of gradients obtained from a least-squared reconstruction which involves the neighbouring elements, is proposed.

INTRODUCTION

Hypersonic aircraft powered by air-breathing propulsion systems have been the subject of several research efforts in the last years. There is a growing interest in this topic since these technologies can lead to breakthroughs in both civil applications (long-range civil transport, hybrid scramjet/rocket systems for LEO space transportation) and military applications (long-distance fast strike capabilities for defence systems) [1].
Among of the several issues which are related to hypersonic flight, particular attention should be paid to the development of shock-shock interactions which can dramatically increase the heat load on several components of hypersonic aircraft. A significant example is represented by an experimental flight of the X-15 test aircraft in 1967. During that flight, a dummy ramjet was connected to the fuselage of the aircraft by a pylon: the interaction between the bow shock wave in front of the pylon with the shock wave coming from the leading edge of the ramjet nacelle lead to high heat fluxes on the pylon which experienced significant damages. This kind of interaction was classified as type IV interaction by Edney [2]. The same phenomenon can be observed in the inlet of ramjet or scramjet engines. Usually, the design condition for these engines is based on a configuration in which the shock wave generated by the forebody impinges onto the leading edge of the engine cowl. This can lead to the development of significant heat loads on the engine cowl. A study on the minimisation of these effects by geometry optimisation was proposed by Rodi [3].

In this work the Edney type IV and type VI shock-shock interactions are numerically investigated in a Discontinuous Galerkin (DG) finite element framework. The focus of the work is on the use of adaptive algorithms which can automatically refine the mesh in the most interesting regions. These approaches can be easily implemented in a DG scheme since the discretisation can automatically deal with non-conforming meshes and hanging nodes. In particular, DG schemes allow to locally adapt the mesh size (h-adaptivity), the reconstruction order (p-adaptivity) or to change completely the basis functions depending on the region of the flow [4, 5].
Several sensors to drive the adaptation are tested (density gradient, pressure gradient, equation residuals). All these sensors require the computation of gradients. The results show that the gradient obtained by the internal element reconstruction is not suitable for driving the adaptation since the shock capturing reduces significantly the gradient

magnitude across strong shock waves. An alternative approach based on the reconstruction of the gradient from the neighbours elements is proposed.

NUMERICAL SETUP

The problems studied in this work are described by the compressible Navier-Stokes equations for an ideal fluid with constant specific heat ratio ($\gamma = 1.4$) and constant viscosity. The spatial discretisation is carried out by means of the DG method with a second order accurate reconstruction. Convective fluxes are computed by means of the local Lax-Friedrichs (or Rusanov) flux [6]. Diffusive fluxes are computed by means of a recovery based approach [7]. Shock capturing is performed by a feedback filtering approach [8]. The integration in time is performed by means of an explicit Euler scheme with first order accuracy. The algorithms are implemented in a parallel Fortran 90 code that has been tested on both inviscid and viscous flow fields [7, 8, 9, 10]. The unstructured meshes used for the initialisation of the adaptation process are generated by Gmsh [11].

H-adaptive algorithm

The h-adaptive algorithm adopted for the mesh refinement works by splitting isotropically each cell in four sub-cells. The resulting mesh has hanging nodes. In order to drive the adaptation process an indicator is required. The procedure requires to obtain a preliminary steady solution on a coarse mesh. After this, the indicator field is evaluated and the algorithm refines the elements with the largest values of the indicator in the domain. In particular, a given fraction of the mesh is refined at each adaptation step (typically 10% of the elements). The following indicators are considered in this work: pressure gradient magnitude, density gradient magnitude and equation residuals. The equation residuals are evaluated in the volume quadrature points of the elements by computing the divergence of the fluxes and by taking the norm-2 of this value on each element.

NUMERICAL RESULTS

Edney type IV interaction

The problem setup is inspired to the experimental tests carried out at ONERA [12]. The configuration is characterised by a shock generator followed by a cylinder. The flow field is characterised by a supersonic inlet at $M_\infty = 10$ with a static temperature T_∞=52 K. A temperature of 300 K is imposed on the cylinder surface. The Reynolds number based on the cylinder radius is $Re_\infty = 1329$. The temperature field (normalised with respect to the freestream total temperature) is reported in Figure 1.

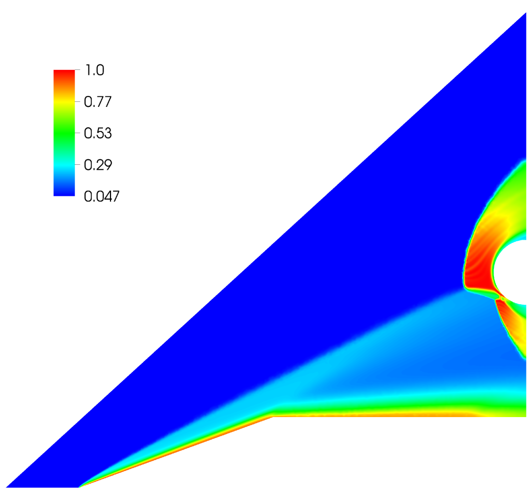
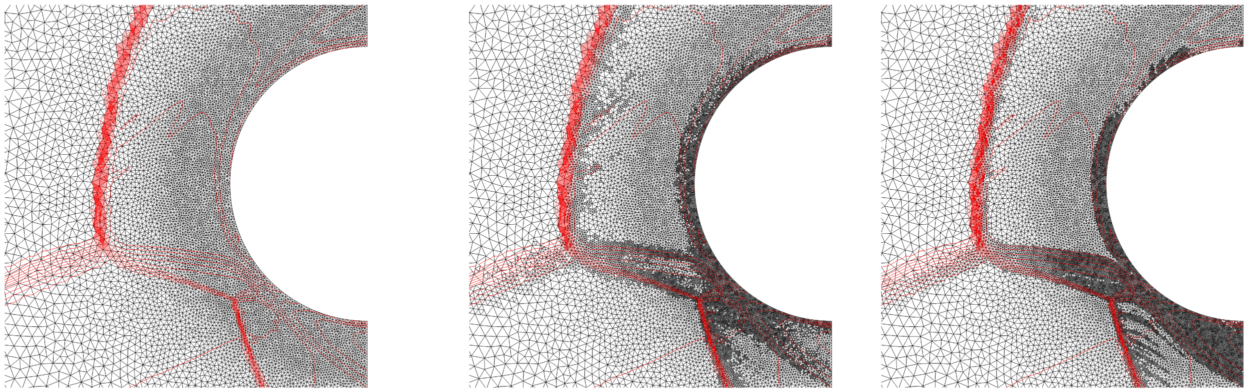


FIGURE 1. Temperature field in the presence of Edney type IV interaction at $M_\infty = 10$ (results normalised with T^0_∞)



(a) (b) (c)

FIGURE 2. Edney type IV interaction: original (a) and adapted meshes with residual-based indicator computed from gradients of internal reconstruction (b) and gradients reconstructed from neighbours (c)

The results obtained on the original mesh (57915 triangles) are used to evaluate the indicator field and to adapt the mesh. In particular, the residual based indicator is used for this test case. The contours of the Mach field (red lines) obtained on the original mesh are reported in Figure 2. It is possible to compare the original mesh in Figure 2a with the adapted mesh (Figure 2b) obtained by using the residual based indicator computed with the internal element reconstruction. The Figure shows clearly that the algorithm refines the mesh behind the bow shock but it fails in the identification of the elements which are crossed by the shock. This is due to the fact that the shock capturing approach (modal filtering) used for the stabilisation of the DG scheme reduces the linear modes amplitude in the shock region. For this reason, the gradients and so the residuals (which are obtained by the divergence of the fluxes) are underestimated in these cells. A similar behaviour was observed by substituting the filter stabilisation with a slope limiter approach. In order to solve this problem, an alternative approach to compute the gradients required by the indicator is introduced. In particular, a least-square fitting procedure is applied on the neighbours elements in order to estimate the gradients from the average value inside each element and inside its neighbours. The results obtained by this alternative approach are reported in Figure 2c which shows clearly that the algorithm correctly identifies the shock region.

Edney type VI interaction

A double wedge configuration invested by a supersonic inviscid flow at $M_\infty = 9$ is considered for this test case. The flow is characterised by the interaction of two oblique shock waves generated at the beginning of each wedge: the interaction generates a single shock, a contact surface and an expansion fan. The fan is reflected by the wall and is responsible for the weakening of the final shock [13]. The predicted Mach number field is reported in Figure 3.

The solution obtained on the original uniform mesh with 19899 triangular elements is used to compute several indicators for the adaptive algorithm. The gradients required for the computation of the indicators are here evaluated from the least-square procedure introduced in the previous test case. The results in Figure 4 allow to compare the original mesh with the adapted meshes obtained by the pressure gradient indicator, the density gradient indicator and the residual-based indicator, respectively. The plot shows clearly that, as expected, the pressure gradient indicator does not capture properly the contact surface.

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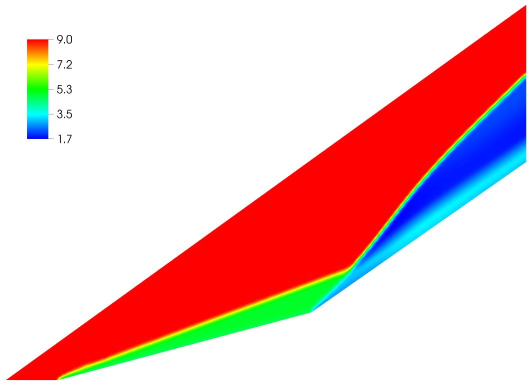

FIGURE 3. Mach field in the presence of Edney type VI interaction at $M_\infty = 9$

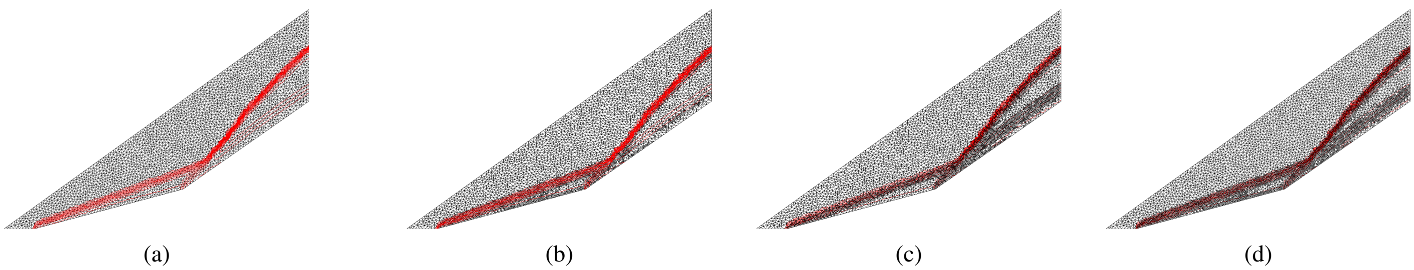

FIGURE 4. Edney type VI interaction: original (a) and adapted meshes with indicators based on pressure gradient (b), density gradient (c) and equation residuals (d)

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