Unsteady shock reflections over an oscillating ramp using the Meshless method

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ABSTRACT A gridless method to study the unsteady flow problems involving moving discrete points is attempted in this work. An in-house solver is developed in Cartesian coordinates to solve 2D, unsteady, Euler equations for the shock moving over a pivoting (combination of rotating and oscillating motion) compression ramp. An algorithm for solving Arbitrary Lagrangian-Eulerian (ALE) equations based on clouds of points is used in the computational domain. The spatial derivatives are approximated by local least-square curve fits. Harten, Lax, van Leer, Contact (HLLC) scheme is extended to a gridless method to calculate the numerical fluxes. Temporal discretization using the fourth-order classical Runge-Kutta method with local time stepping is implemented. The code is validated against a test case of a supersonic freestream M = 2.98 flowing past a compression ramp rotating at a constant rate, starting from an initial ramp angle of 19º, until an MR is obtained. The accurate prediction of the transition angle and the Mach stem height comparison with the shock wave angle demonstrates the capability of the solver in capturing shock reflections and transitions. This solver will be subsequently used to simulate and study a moving shock over an oscillating ramp and the various flow characteristics, such as the height of the unsteady Mach stem, the position of the reflection point, and the shock angle at the reflection or triple point, for a fixed shock Mach number will be studied at different frequencies of oscillation.

1 INTRODUCTION

Shock reflections have been widely studied using analytical, experimental, and numerical methods for the steady, unsteady, and pseudo-steady flows to develop a better understanding of the reflection patterns and their transitions. For steady flows, a supersonic flow having a constant free stream Mach number is established over stationary bodies such as wedges. This results in shock waves emanating from the bodies and their reflections from reflecting surfaces. In pseudo-steady flows, a shock wave moves at constant speeds over bodies with non-curved surfaces, which causes reflections over the body surface. These kinds of pseudo-steady flows usually exhibit self-similarity. However, unsteady flows can include a mix of the above kinds of interactions, with curved waves moving over planar/curved surfaces (Reshma, 2021). Furthermore, the reflection surfaces may be stationary or moving. Typically, such flows are encountered in contoured wind tunnels during starting phenomena or rapidly flapping surfaces in supersonic air intakes acting as control surfaces or used for thrust vectoring. A detailed review of steady-state and pseudo-steady RR↔MR shock structures and their transitions has been discussed well by (Ben-Dor, 2007) for both strong and weak reflections. Abundant literature is available for steady shock reflections and RR↔MR transitions (Roy, 2019; Mölder, 1979; Hornung, 1979); however, for unsteady shock reflections, very limited research has been carried out and remains vastly unexplored (Goyal 2021).

This study uses the Meshless method to examine the impact on the shock structure of a planar shockwave moving over a rapidly oscillating planar ramp. This is an unsteady shock reflection phenomenon wherein the shock reflection may transform into a different type of reflection altogether depending on the shock Mach number, the instantaneous slope of the ramp, and the ramp rotation/oscillation rate. Traditional Finite Volume Methods (FVM) for Computational Fluid Dynamics (CFD) often require significant pre-processing time to model the motion and distortion of grid cells, using techniques such as overlapping grid-based, grid deformation-based, and grid re-meshing approaches (Batina, 1993; Zhang, 2004). In contrast, gridless/meshless methods are a newer alternative approach to FVM for CFD problems, which avoids mesh-related issues (Duan, 2015) which can be detrimental to the convergence and accuracy of the solution. In gridless methods, the computational domain is discretized using clouds of points, with each point having its cloud of immediate neighboring points within a desirable critical radius. Unlike the traditional grid-based method, gridless methods are free from skewness and stretching/distortion of mesh, making them advantageous when solving flow with complex configurations and moving boundaries.

This study uses an in-house code developed to solve 2D, unsteady Euler equations in Cartesian coordinates to simulate the flow over a rotating/oscillating compression ramp. The solver operates on a gridless method to solve steady and unsteady flow problems using discrete points for stationary grid cases and moving discrete points for moving grid problems. The Arbitrary Lagrangian-Eulerian (ALE) algorithm is used in the Governing equations based on clouds of points in the computational domain, where spatial derivatives are approximated by local least-square curve fits. The solver uses the Harten, Lax, van Leer, Contact (HLLC) scheme extended to the gridless method to calculate the numerical fluxes (Ma, 2014), and temporal discretisation is done using the fourth-order classical Runge-Kutta method. This work uses the developed gridless solver to study the effect of ramp rotational motion and the oscillation rate on the shock structures and shock transition criteria from RR↔MR and vice versa. Further, various flow characteristics, such as the height of the unsteady Mach stem, the position of the reflection point, and the shock angle at the reflection or triple point, for a fixed shock Mach number at different frequencies of oscillation/rotation, will also be investigated in this work.

2 NUMERICAL METHODOLOGY – ALE FORMULATION

The compressible Euler governing equations in ALE differential form for the 2D inviscid cartesian coordinate system can be expressed as follows,

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F_i}}{\partial z} + \frac{\partial \boldsymbol{G_i}}{\partial r} = \boldsymbol{S}, \tag{1}$$

where **F** and **G** are the flux vectors in the 'x' and 'y' directions, respectively, **S** is the source vector and **U** is the vector of conserved quantities and can be defined as:

$$\boldsymbol{U} = [\rho,\ \rho u, \rho v, E]^T, \tag{2}$$

$$\boldsymbol{F_i} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ (E+p)u \end{bmatrix},\ \boldsymbol{G_i} = \begin{bmatrix} \rho v \\ \rho v u \\ \rho v^2 + p \\ (E+p)v \end{bmatrix}, \boldsymbol{S} = w_z \frac{\partial \boldsymbol{U}}{\partial z} + w_r \frac{\partial \boldsymbol{U}}{\partial r}, \tag{3}$$

where ρ, p and E represent the density, pressure, and total energy per unit volume, respectively, u and v are the velocity components of gas in x and y directions, w_x and w_y are the velocity components of the discrete points. With the perfect gas assumption, the pressure p is calculated using the equation of state:

$$p = \rho R T \tag{4}$$

$$E = \frac{p}{\gamma - 1} + \frac{1}{2}\rho(u^2 + v^2) \tag{5}$$

Where γ is the ratio of the specific heats. If the discrete points are fixed, and, w_x and w_y are both zero, then eqs., (1) – (3) corresponds to the Eulerian description of conservation equations. If the discrete points move with the moving boundaries, eqs., (1) – (3) correspond to the Lagrangian conservation equations.

3 CODE VALIDATION

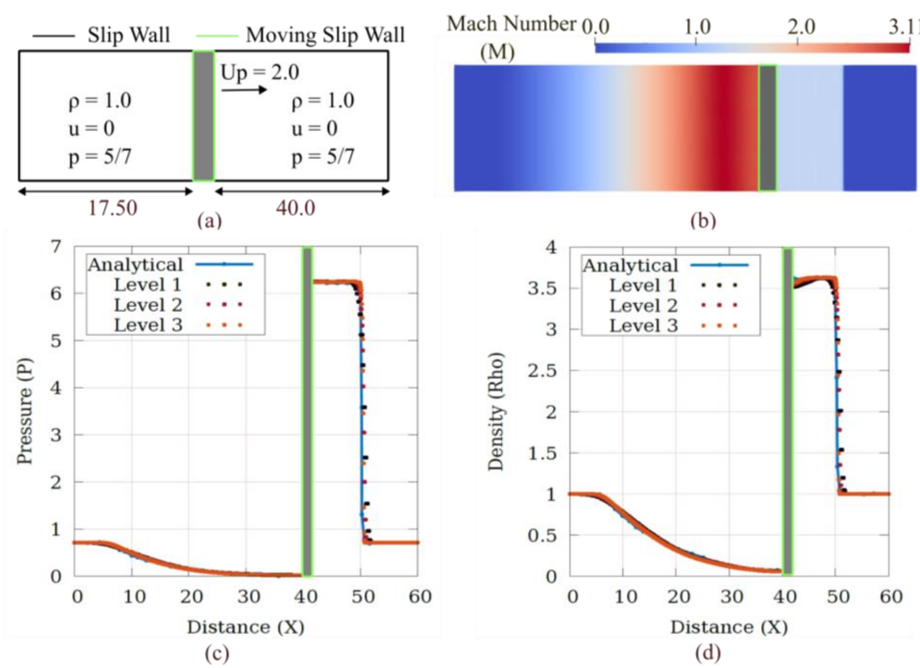

Figure 1. (a) Initial Computational Domain along with Boundary conditions, (b) Mach number contour for HLLC flux scheme, (c) Pressure plot along the centre line with grid convergence at t = 11, (d) Density plot along the centre line with grid convergence.

The computational programs are implemented in Fortran and compiled using the GNU Fortran Compiler. The accuracy of the developed solver is validated against a moving piston test case (Tan, 2011). The moving piston case is a one-dimensional (1D) problem involving shocks and rarefaction waves. This test case aims to showcase the code's capability to capture the moving shock location and strength accurately. The computational domain for the moving piston test case, along with the boundary conditions, is shown in Figure 1(a). Three grid refinement levels have been used with a uniform grid point spacing of 0.25, 0.125, and 0.0625, respectively, for levels 1, 2, and 3 refinements. During this process, a shock wave forms in front of the moving piston, and a rarefaction wave is generated in the rear. At t = 0, the piston of width 2.5 is centred at x = 18.75. At the final state t = 11, chosen the same as (Tan, 2011), the piston moved in the direction 'X' at x = 40.75. Figure 1(c-d) compares the density and pressure with the reference data obtained from (Leipmann, 1957). It is evident from the results that pressure and density calculated from the developed gridless solver align well with the reference data. The accurate prediction of the shock location demonstrates the conservation of mass, momentum, and energy through the moving piston. Nonetheless, the density plot indicates a slight undershoot immediately ahead of the piston, a phenomenon often observed in various earlier publications (Murman, 2003).

Multiple test cases have been simulated to validate the code's capability in accurately capturing 2D shocks and other flow structures in steady-state and unsteady scenarios. These cases will be presented in the full paper, along with the 2D moving grid validation case (Naidoo, 2011), wherein, a free stream Mach number (M = 2.98) flow over an initial ramp angle $\theta_i = 19^o$ is established. Subsequently, the ramp is rotated at a constant rate until the Mach stem is obtained, the transition angle is noted, and further Mach stem growth is plotted against the shock wave angle.

4 OBJECTIVE

The validated code will then be used to simulate a moving planar shock wave with a fixed shock Mach number over a pivoting ramp. The pivoting motion is initiated when the shock wave arrives at the ramp pivot point. Various combinations of amplitudes (maximum rotation angle) and oscillation frequencies will be considered for the study. The results will be included in the full paper, along with the 2D moving grid code validation.

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