Shock refractions at an air-water interface in weak and strong incident shock regimes

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ABSTRACT The current numerical study employs BlastFoam solver to simulate inviscid 2D pseudosteady shock refraction at an air-water interface. Water is modelled as a stiffened gas with $\gamma = 2.8$ and $p_\infty = 850$ MPa, while air is modelled as an ideal gas. Simulations are second-order accurate in space and fourth-order accurate in time. Weak and strong incident shock regimes identified based on predicted refraction sequences in the previous study are of emphasis. Two shock Mach numbers, 3.4 and 4.4 are chosen, one for each regime where the refraction patterns at various interface inclination angles (β) are identified to verify the expected sequence of refraction with increasing β. The existence of a new irregular refraction transition pattern termed BPMR is verified in the Weak shock strength regime.

1 INTRODUCTION

Pseudosteady shock refraction in gas-liquid multiphase interfaces has not garnered much attention compared to gas-gas interfaces. Takayama and Ben-Dor (1989) conducted an experimental analysis on water wedges, contrasting Regular to Mach reflection transitions with solid wedges. Subsequently, Nourgaliev et al. (2005) performed numerical simulations on air-water interfaces and identified the refraction sequence with increasing interface inclination angle, β (90 - θ_w, where θ_w is the wedge angle), for a shock Mach number of 1.46. This shock Mach number was presented to be in the Very weak incident shock regime. Anbu Serene Raj et al. (2024) recently conducted a comprehensive experimental and numerical study on shock refraction in air-water interfaces in the very weak incident shock regime. The authors supported the results with analytical shock polars drawn from the shock relations derived for a stiffened gas used to model water. They also verified the refraction sequence in this regime to be RRR → *BPR* → FPR → FMR, where RRR, BPR, FPR and FMR are Regular Refraction with Reflected shock wave, Bound Precursor refraction with a Regular reflection, Free Precursor refraction with a Regular reflection and Free Precursor refraction with a Mach reflection, respectively. The study also included identifying the analytical transition criteria (shown in Figure 1) for the refraction patterns, using which the refraction sequences for weak and strong incident shock regimes were predicted. Figure 1 shows these transition lines drawn in the (M_S, θ_w^c) plane, where M_S, θ_w^c are the shock Mach number and complementary wedge angle. The blue line indicates the detachment criterion (θ_D) where an RR transitions to an MR (Ben-Dor 1992). The red line (M_b = 1) corresponds to the sonic condition of the induced flow Mach number (in the shock stationary frame of reference) inside water. It demarcates the inclination angles for which the refraction pattern exhibits a transmitted shock wave and those that exhibit an evanescent free precursor wave.

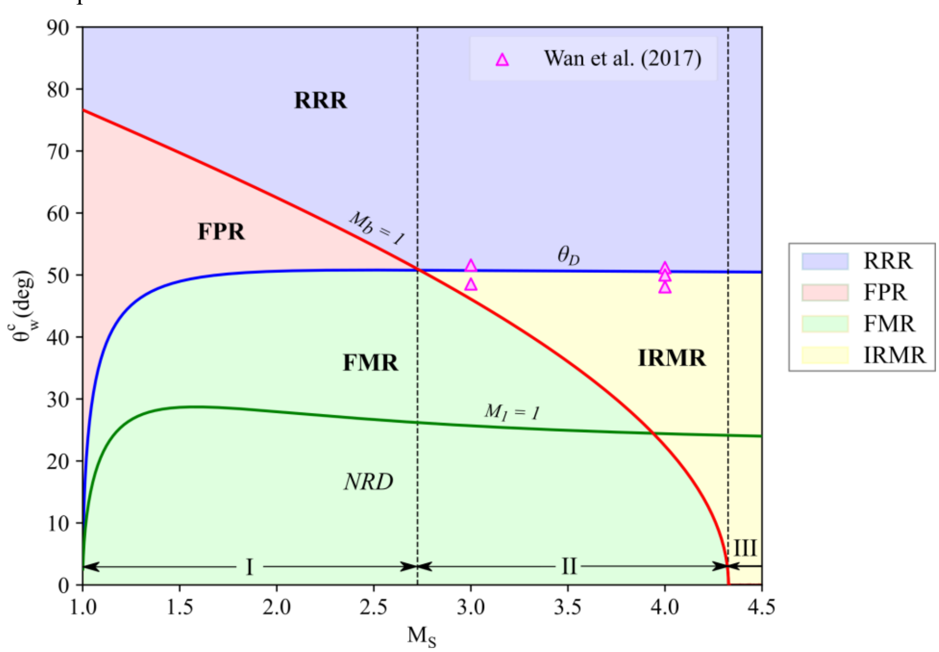

Figure 1. Transition lines of the refraction patterns on an air-water interface in the (M_S, θ_w^c) plane: I – Very weak incident shock regime, II – Weak incident shock regime, III – Strong incident shock regime; RRR - Regular Refraction with a Reflected shock wave, FPR - Free Precursor refraction with a Regular reflection, FMR - Free precursor Mach Refraction, IRMR - Irregular Refraction with a Mach Reflection.

The numerical study by Wan et al. (2017) included pseudosteady shock refraction analysis on the air-water interface for shock Mach numbers 3 and 4 (marked in figure 1). However, it did not cover the entire interface inclination angle range. They identified an RRR and an IRMR for both shock Mach numbers, where IRMR is an Irregular Refraction with a Mach Reflection. The current study aims to numerically verify the refraction sequence predicted by the shock polar analysis for weak and strong incident shock regimes (I, II in figure 1) in our previous study using the BlastFoam solver on the OpenFOAM software.

2 METHODOLOGY

The BlastFoam solver of the OpenFOAM software is used to numerically study the shock refraction patterns arising in an air-water interface. Water is modelled as a Stiffened gas, given by

$$p = \rho(\gamma - 1)c_v T - p_\infty, \tag{1}$$

where p, ρ, c_v, T, γ and p_∞ are the pressure, density, specific heat capacity at constant volume, gamma and stiffening pressure, respectively. To accurately model water at low pressures, γ, c_v, and p_∞ are taken to be 2.8, 1495 J/kgK, and 850 MPa (Yeom and Chang 2013). These stiffened gas parameters maintain the physical properties of water, such as density (1053 kg/m^3), c_p (4186 J/kgK) and speed of sound (1503 m/s). Air is modelled as an ideal gas. 2D inviscid simulations are carried out in a rectangular domain (60 mm × 38.1 mm) with a structured cartesian grid size of 0.025 mm. The shock is initiated with the pre- and post-shock conditions of the required shock Mach number, while the interface is maintained at a particular inclination angle (β) with respect to the moving shock wave.

Simulations are carried out using a second-order accurate Harten, Lax and van Leer Contact (HLLC) approximate Riemann solver, based on the work of Toro, Spruce, and Speares (1994) for flux evaluation. For temporal discretization, an explicit strong stability-preserving four-stage fourth-order Runge-Kutta approach with adjustable time-stepping is employed (Spiteri and Ruuth 2002). The gradients are calculated using the least square discretization scheme and vanLeer flux limiters (van Leer 1974). The volume of fluids (VOF) method is used to capture the interface.

3 RESULTS & DISCUSSION

Figure 1 shows that the weak incident shock regime for an air-water interface occurs for $2.72 < M_S < 4.32$; beyond that is the strong shock regime. The refraction sequences predicted in the previous study for weak and strong incident shock regimes are RRR → IRMR → FMR and RRR → IRMR, respectively.

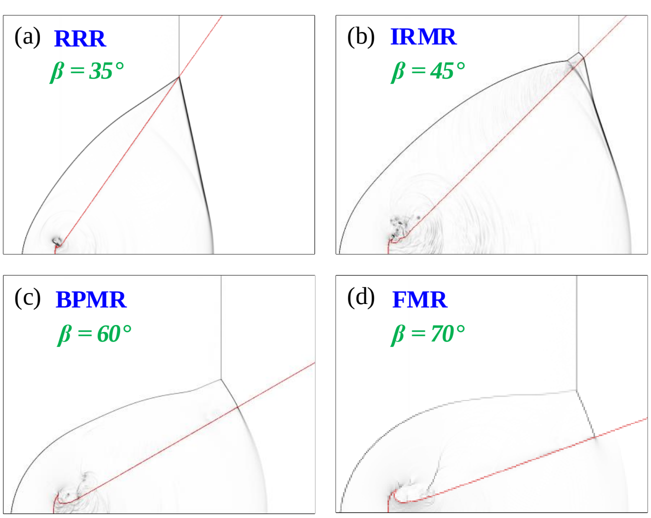

Figure 2. $M_S = 3.4$

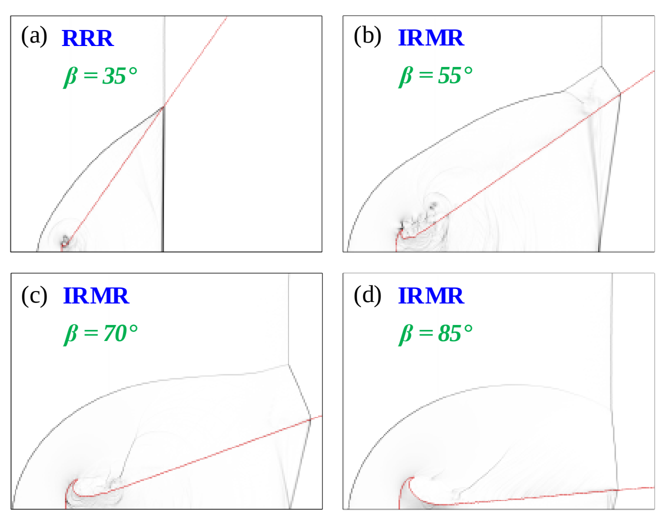

Figure 3. $M_S = 4.4$

Figure 2. Numerical pressure gradient contours showing different refraction patterns for various interface inclination angles in the Weak incident shock regime.

Figure 3. Numerical pressure gradient contours showing different refraction patterns for various interface inclination angles in the Strong incident shock regime.

3.1 Weak incident shock regime

Figure 2 shows the numerical pressure gradient contours of shock refraction patterns obtained for various inclination angles (β) at a shock Mach number, M_S = 3.4. It can be seen that for β = 35°, there exists an RRR (figure 2(a)), whereas for β = 45° an IRMR (figure 2(b)) occurs, with a Double Mach Reflection (DMR) in air with transmitted shock inside water. As the inclination angle increases, the RRR transitions into an FMR through a bound precursor transition pattern characterized by the perpendicularity of the transmitted shock to the interface. Such a transition pattern occurs at 60° inclination angle (figure 2(c)). It is distinct from the BPR pattern in the very weak incident shock regime as the reflection pattern in air is an MR in contrast to that of an RR. Therefore, such refraction patterns will be referred to as Bound Precursor Mach Refraction (BPMR). In this particular shock strength, the reflection pattern of the BPMR corresponds to that of a Transitional Mach Reflection (TMR). With further increase in β, M_b becomes subsonic. Hence, the refraction pattern will be a free precursor refraction with a Mach reflection (FMR), as shown in figure 2(d) at β = 70°.

3.2 Strong incident shock regime

To study the refraction sequence of the strong incident shock regime, a shock Mach number of 4.4 is chosen. From the numerical pressure gradient contours shown in figure 3 for various inclination angles, it can be seen that the refraction sequence consists of only two patterns as predicted: RRR (figure 3(a)) and IRMR (figure 3(b-d)). An inclination angle of 35° produces an RRR, whereas higher β produces an IRMR with various Mach reflections such as DMR (β = 55°), TMR (β = 70°) and SMR (β = 85°). Therefore, the numerical simulations corroborate the prediction of the earlier study that in the strong incident shock regime, a transmitted shock wave is produced irrespective of the inclination angle.

4 CONCLUSION

The current numerical study investigates the shock refraction patterns in an air-water interface at various interface inclination angles (β). The shock refraction sequence with increasing β is identified from the numerical pressure gradient contours for shock Mach numbers 3.4 and 4.4 corresponding to weak and strong incident shock regimes, respectively. For M_S = 3.4, the refraction sequence is verified as RRR → IRMR → *BPMR* → FMR. The bound precursor transition pattern with a Mach reflection in the weak incident shock regime is named BPMR, to differentiate it from BPR in the very weak incident shock regime. Also, for M_S = 4.4 in the strong incident shock regime, the refraction sequence is substantiated as RRR → IRMR.

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