INVISCID QUASISTATIC MODELLING FOR UNSTEADY SHOCK REFLECTIONS WITH SEPARATION

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Shock-boundary layer interactions have been extensively studied during the past half-century due to the fact that such flows exhibit low frequency unsteadiness that can be detrimental to devices such as air intakes or nozzles. In the past few years, experimental data have been complemented by high fidelity simulations (Garnier *et al.* *AIAA J.* 2002; Wu and Martin *JFM* 2008; Touber and Sandham *JFM* 2011) making possible to collect over the whole flowfield data with high time and space resolutions.

Recently, Agostini *et al.* (*AIAA J.* to appear) have analyzed Large Eddy Simulations of shock reflections performed at IUSTI using filtered cross-correlations and the theory of characteristics. They have found that the kinematics of the whole region downstream of the reflected shock, including the shock itself, is fully governed by the phenomena located within the separated region. Interestingly, data from the outer flow are easier to interpret than signals in the separated region from which they originate since they are mostly free from non-coherent small-scale turbulent fluctuations. The present work aims at taking advantage of the denoised informations located outside of the interaction region to derive a simple inviscid scheme describing the main features of the interaction.

The standard approach in modelling a shock reflection with separation is to consider typical longitudinal evolutions of the wall pressure in the interaction, such as the one plotted in Fig. 1a. It suggests a modelling by a shock induced by the separation followed by an isobaric region (plateau) and then by another shock associated with the recompression shock. The model is then built by replacing the separated region with a non-permeable wall shaped as a triangle, as described for instance in Délery and Marvin (AGARDograph 1986): such a model is sketched in Fig. 1b.

The model is satisfactory as far as the wall pressure is concerned. It has, however, been found from the LES data that longitudinal pressure profiles at altitude higher than the elevation y_c of the crossing point between the incident and separation shock show an additional compression region, as seen in Fig. 1c for $X^* \simeq 0.15$. It can be explained using the hodograph method: the incident shock entering the boundary layer results in a small compression region upstream of the expansion fan. The inviscid modelling of Fig. 1b has been consequently modified to take into account this extra compression by adding a second ramp, resulting in the new refined model in Fig. 1d.

The angle of the first ramp is set constant according to the free interaction theory. However both the relative lengthes of the first and second ramps and the angle of the second ramp can vary, either with the intensity of the incident shock or, under a quasi–static assumption with constant intensity, in time due to the unsteadiness of the interaction region. The later possibility is explored by looking at conditionally–averaged pressure profiles. Samples from the LES have been sorted according to the extension of the separated region and data have been averaged over the 15% samples respectively associated with the smallest and largest recirculation bubbles. It is worth noting that the averaged data are satisfactory converged despite the small percentage of the total data associated with each sets since the LES data encompass more than 150 periods of the low-frequency unsteadiness.

The evolution of the conditionally–averaged pressure profiles are plot in Fig. 2 in the reference frame of the separation shock. It is seen in Fig. 2a that a decrease in the size of the bubble results in the disappearance of the pressure plateau. It implies that the length of the first ramp, associated with the isobaric region, has to be reduced when the bubble shrinks. The pressure profile above the shock intersection of Fig. 2b also shows that the extra pressure increase downstream of the reflected shock is higher for small bubbles. This is taken into account in the model by an increase of the deviation angle of the second ramp. Lastly, a zoom on the region of Fig. 2b associated with the expansion fan is plotted in Fig. 3a. It demonstrates that the pressure drop induced by the expansion waves is constant whatever the size of the separated region. This is translated into the model by setting constant the angle of the downstream segment of the solid boundary. Taking the model of Fig. 1d as a reference for large bubbles, its counterpart for small bubble sizes is then summarized by the sketch of Fig. 3b.

The ability of the new model to describe and interpret several unsteady features of the interaction will be discussed in the presentation. Validations based on LES of a transitional interaction will also be described.

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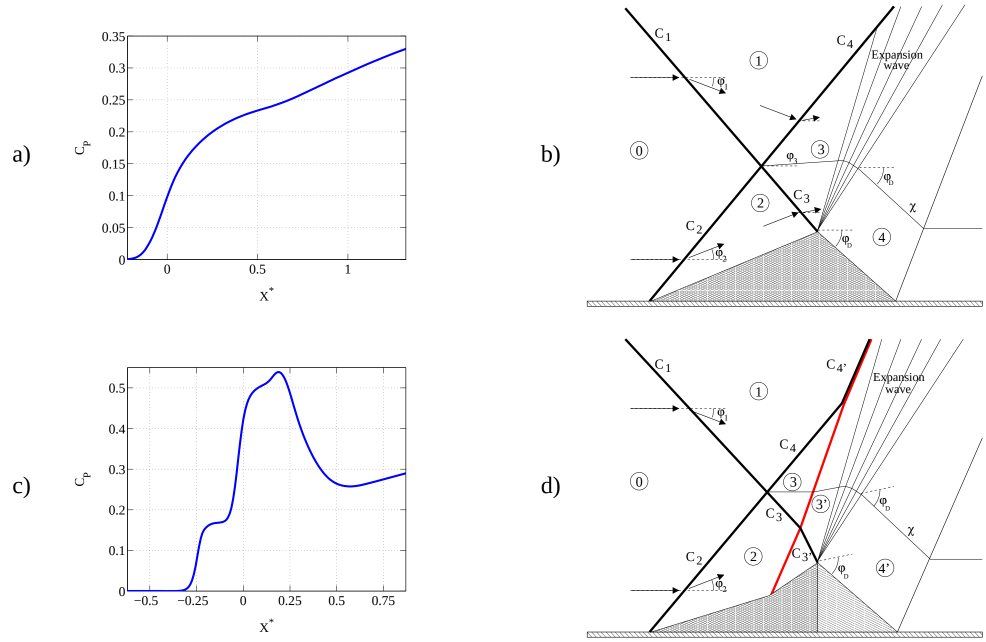

Figure 1. Longitudinal evolution of the mean pressure coefficient at wall (a) and at altitude $y = 1.3\ y_c$ (c) with standard (b) and refined (d) inviscid modellings for shock–boundary layer interaction through shock reflection.

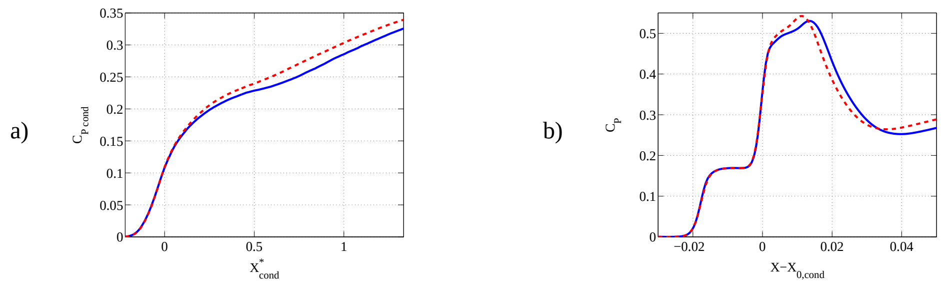

Figure 2. Longitudinal evolution of conditionally–averaged pressure coefficient at wall (a) and at altitude $y = 1.3\ y_c$ (b) in the reference frame of the separation shock: average over sets of samples of 15% size having the smallest (dashed red) and largest (solid blue) separated regions.

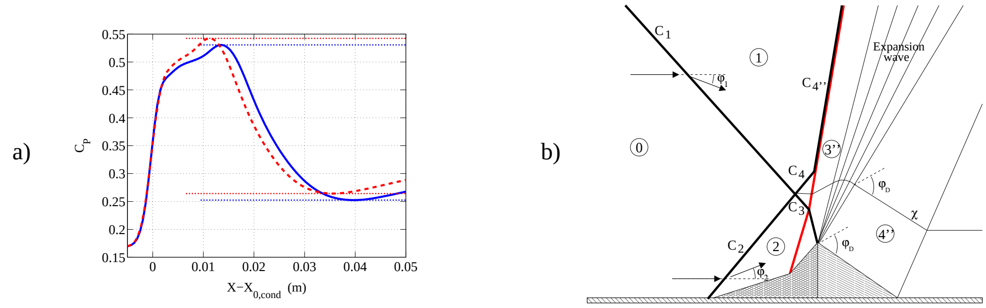

Figure 3. Zoom on the longitudinal evolution of conditionally–averaged pressure coefficient at altitude $y = 1.3\ y_c$ (a, same color scheme as in Fig. 2) and refined inviscid modellings associated with small separation regions (b).