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Reflection and Penetration of a Shock Wave Interacting with a Starting Vortex

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Experimental and numerical studies are conducted to investigate the interaction of a weak shock wave ($M_s = 1.22$) and a strong vortex ($M_{v,\max} > 1$). In terms of shock dynamics, two meaningful physics are observed from the experiment: reflected wave from the vortex edge and transmitted wave penetrating the vortex core. These weak waves are shown in the numerical interpretation to contribute to the emission of acoustic waves in shock–vortex interaction.

Nomenclature

A	=	accelerated wave
C	=	circumference centered on the vortex at the far field
C_+, C_-	=	characteristics
I	=	incident shock wave
K_+, K_-	=	invariant along characteristics
M	=	Mach stem in the shock reflection
M_s	=	moving shock Mach number
M_v	=	tangential Mach number around a vortex base on ambient speed of sound
$M_{v,\max}$	=	maximum rotational Mach number of the vortex, maximum M_v
U	=	faster or upper shock wave
$U_{\max}$	=	maximum tangential velocity in the shock–vortex interaction
p	=	pressure
R	=	reflected wave
r	=	radius distance from the vortex center
r_c	=	radius of the vortex core
S	=	slip line or slip layer
T	=	transmitted wave
V	=	main vortex
V_θ	=	tangential velocity
θ	=	azimuth angle or flow direction
ρ	=	density
Φ	=	angle of the incident shock wave

Subscripts

free	=	without disturbance
m	=	mean value along a circumference
s	=	ambient value behind the incident shock wave
u, l	=	upper (faster), lower (slower)
Δ	=	difference between two adjacent contours

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Introduction

THE problem of shock–vortex interaction was first introduced in the 1950s by some researchers of fluid dynamics and acoustics.[1–4] Quadrupole noise has been known to be a key sound source of the screech tone in supersonic jets. The investigation of shock–vortex interaction also are a building block to understand more complex problems such as shock–boundary-layer interaction. In the 1960s, Dosanjh and Weeks approached this problem with a shock tube experiment and acoustic analogy.[5,6] Ribner's theoretical work[7] is also remarkable because it has succeeded to predict qualitatively the acoustic wave of the Dosanjh and Weeks[5] experiment, but his theory is only limited to the moderate range far from shock waves. More recently, many computational papers of the model study of shock–vortex interaction have been published thanks to the advances of numerical techniques.[8–10]

Ellzey et al.[9] pointed out that the shock–vortex interaction consists of two main categories: The shock wave is severely distorted by the surrounding flow, and the quadrupole sound is generated and propagated. The shock distortion effect is dominant at the earlier stage (or near field), whereas the sound is radiated at the later stage (or far field). This interpretation is supported and strengthened by other researchers in the series of papers.[11,12] The shock distortion and the quadrupole sound are the primary physics, but do not describe the interaction of a shock wave with a strong vortex entirely. Our question is what is the linkage between the two stages, and the objective of this study is to understand the mechanism how the shock wave produces acoustic waves. It is strange that no previous researchers took into account the strong vortex case where the maximum rotating vortex Mach number becomes supersonic ($M_{v,\max} > 1$): See the parameter domain in Fig. 1. That is, there may be some locally supersonic region in the strong vortex even though the ambient flow field is subsonic. In a recent paper,[13] some weak waves emitted in the interaction of a shock wave with a strong vortex are precisely traced without being neglected as noise. Reflection and penetration of the incident shock wave on a vortex was observed in both the experiment and computation. Our primary interest should be focused to the meaning of the weak waves.

In this study, the author proposes a simple experimental model of the interaction case of a weak shock wave ($M_s = 1.22$) and a strong vortex ($M_{v,\max} = 1.22$). The numerical solutions of Navier–Stokes equations are counterchecked with holographic interferograms and shadowgraphs. The emitted weak waves are precisely detected and traced to interpret the delicate flow physics.