Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Optics and Lasers in Engineering 44 (2006) 170–189
OPTICS and LASERS in ENGINEERING

Simultaneous Shadow, Schlieren and Interferometric Visualization of Compressible Flows

Harald Kleine[a,*], Hans Grönig[b], Kazuyoshi Takayama[c]

[a]*School of Aerospace, Civil and Mechanical Engineering, University of New South Wales/Australian Defence Force Academy, Northcott Drive, Canberra, ACT 2600, Australia*
[b]*Stoßwellenlabor, RWTH Aachen, Templergraben 55, 52056 Aachen, Germany*
[c]*Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-2-1 Katahira, Aoba-ku, Sendai 980–8577, Japan*

Available online 8 June 2005

Abstract

For detailed investigations of processes and phenomena in the flow of compressible fluids, it is sometimes necessary to apply more than just one flow visualization technique as each method has its own characteristic strengths and weaknesses. In the case of flows with a low degree of repeatability, it may become mandatory to perform these multiple visualizations within the same experiment at identical or at least almost identical instants. This paper describes how two or more density-sensitive visualization techniques can be coupled in order to obtain simultaneously the distribution of density and its gradient and/or its second derivative in a flow field. The resulting optical systems are more complex than a conventional single visualization apparatus, but they can provide an unprecedented wealth of information about the flow field. By applying multiple visualization techniques, the inherent shortcomings of each individual method can be overcome and the risk of overlooking or misinterpreting certain flow features is reduced.

Keywords: Density-sensitive flow visualization; Shadowgraph; Color schlieren; Holographic interferometry; Mach–Zehnder interferometry; Compressible flows

*Corresponding author. Tel.: +61 2 6268 8047; fax: +61 2 6268 8276.
E-mail address: h.kleine@adfa.edu.au (H. Kleine).

0143-8166/$ - see front matter
doi:10.1016/j.optlaseng.2005.04.009

1. Introduction

The nature of compressible flows requires the use of non-intrusive measurement techniques, as gauges and probes would alter the flow to a generally unacceptable degree unless they are integrated in the confining walls of the test section or a model immersed in the flow. Density-sensitive flow visualization — in the form of shadow, schlieren and interferometry techniques — has long been established as a staple diagnostic tool set to obtain both qualitative and quantitative information about these flows. The records delivered by each of these principal experimental methods can usually be used directly (i.e., without further processing) for a qualitative/phenomenological description of the flow structure and the mechanisms that establish it. By further refinement of these techniques one can also, to some extent, obtain detailed quantitative information about the flow field, particularly if the visualization results are combined and compared with those generated by CFD (Computational Fluid Dynamics). Provided that the level of resolvable details is comparable for the numerical and the experimental approach, the combination of results allows one not only to perform a simple verification of main flow patterns, but also the investigation of embedded small-scale structures [1].

As a general rule, the technique for visual investigation of a compressible flow should be adequately chosen with respect to sensitivity, resolution, dynamic range, and, of course, financial viability. Some of the demands that have to be met are, however, contradictory: whilst a large amount of quantitative data should be made available through the visualization, the same photograph should still be useful for a phenomenological description of the problem, which means that it should not be overloaded with information. The resolution of the visualization method has to be good enough so that one can identify small-scale flow patterns, but the overall structure should still be recognizable and not be obscured by too much detail. Given these different requirements and the individual positive and negative characteristics of the commonly used methods (which will be outlined in the next section) the application of multiple visualization techniques for a comprehensive investigation of a flow field is the most obvious approach. This can be done in different experiments when flow structures are reproducible, but for flows characterized by a certain degree of randomness only a simultaneous visualization with different methods can yield the desired result. Such a multiple-method visualization provides, literally and figuratively, the most comprehensive image of a compressible flow.

2. Density-Sensitive Visualization Techniques

Density-sensitive methods can be applied to generate an image of refractive index variations within a compressible flow. In the following discussion it will be assumed that the refractive index n and the gas density ρ are linearly related and may therefore be used synonymously:

$$n = 1 + K\rho, \tag{1}$$