Experimental and Numerical Studies of Shock Wave Interaction with Gas-Liquid Interfaces(衝撃波と気液界面との干渉に関する実験的・数値的研究)

著者	Dan Igra
号	2549
発行年	2000
URL	http://hdl.handle.net/10097/7822

	Dan Igra
氏　　　　　　名	ダン　イグラ
授　与　学　位	博士（工学）
学位授与年月日	平成12年9月13日
学位授与の根拠法規	学位規則第4条第1項
研究科、専攻の名称	東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
学位論文題目	Experimental and Numerical Studies of Shock Wave Interaction with Gas - Liquid Interfaces （衝撃波と気液界面との干渉に関する実験的・数値的研究）
指　導　教　官	東北大学教授　高山　和喜
論文審査委員	主査　東北大学教授　高山　和喜　東北大学教授　澤田　恵介 東北大学教授　升谷　五郎　東北大学教授　井小萩　利明 東北大学助教授　齋藤　務

論文内容要旨

Droplet breakup induced by high speed gas flows has many applications such as damage of rain droplets impinging on aircrafts in supersonic flight, ablation of space vehicles during atmosphere re-entry, combustion and detonation in two-phase mixtures, etc. As a result, it has been extensively studied by many researchers. Of the various breakup modes of liquid droplets impinged by shock waves, the so-called stripping type breakup takes place over a wide range of the Weber numbers of approximately from 100 to 20,000, where the Weber number We is defined as $We=\rho U^2 d/\sigma$, where ρ is the gas density, U is the velocity difference between the gas and the droplet, d is the droplet diameter and σ is the surface tension.

Previously, schlieren method or shadowgraph was implemented to visualize this process, in which the shape of disintegrating spherical droplets appeared to be fireballs. On these photographs the internal structure of the disintegrating spherical droplets such as shattering mist clouds and wakes were hardly distinguished. However, on holographic interferometry it can be extracted, although not as complete 3D images, so that the structure of the mist clouds and wakes look different from that seen in schlieren photographs and shadowgrams. Object beams of holographic interferometry carried phase information scattered from micro-mist particles were recorded on a holofilm. Through the process of reconstruction, the phase information were partially recovered, whereas in the schlieren method or shadowgraph, these could never be stored on the film.

Advantages of double exposure holographic interferometry, applied to droplet breakup process, were well demonstrated by comparing images on reconstructed and unreconstructed holographic interferograms. Images on unreconstructed image holograms are equivalent to shadowgraphs, so that the shape of disintegrating droplets observable on them appears to be fireballs and is significantly different from those seen in interferograms. This trend is especially noticeable at later stages of the breakup process.

In all the experiments mentioned so far spherical water droplets were employed to result in a three-dimensional interaction pattern. In three-dimensional interactions their visualization is difficult. In particular, wave interactions inside the droplet and the wake structure have never been correctly visualized. However these could be observable when a planar shock wave collides with a cylindrical liquid column, which is a two-dimensional droplet. In order to account for the process of disintegration and particularly to clarify the effect of wave motions inside the droplets the visualization of the interaction of a shock wave with a liquid column in a shock tube would be important. The visualization could correctly illuminate the complex process of three-dimensional droplet disintegrations; it would also provide a straightforward comparison with a numerical scheme simulating the shock wave interaction with a liquid droplet.

In this thesis water columns of various initial diameters were impinged by shock waves and their deformation and breakup were visualized using finite and infinite fringe interferometry.

To interpret the experimental results, numerical simulations were also carried out. Two different types of numerical schemes were developed. The first one is based on the CIP scheme and the second one is based on an upwind TVD scheme. In the past few numerical simulations were applied to droplet breakup they studied droplet deformation in convective flows, in which the flow was assumed to be incompressible at low speed range. The CIP method was employed for simulating the shock wave/liquid droplet interaction. However, the density ratio between the liquid and gas phases was selected to be 10, which is in two orders of magnitude smaller than the value of real water/air phases. Several modifications were implemented in the present work to the CIP scheme in order to apply it to handle water/air interface without causing any density diffusion or oscillations at the interface.

Water/air two phase flows are difficult to simulate, it is one of the most challenging topics of computational fluid dynamics. The main problem lies in modeling the interface between the gas and the liquid phases. Shock capturing schemes such as TVD or ENO schemes are usually useful in simulating accurately single component gas flows. However, in the case of multi-components flows, consisting of two foreign gas interfaces or two-phase flows, usually non realistic pressure fluctuations appear across the interfaces. These pressure fluctuations are generated as a result of calculation of pressures from the equation of state based on the total energy of the gas. In multi-component flows, even when densities and velocities of the various components are initially identical, the internal energy of each fluid component will be different due to the difference in their specific heats ratios γ, and hence after one time step energy diffusion starts to exist across the interface. When using γ which changes discontinuously across the interface, incorrect pressures values will be obtained at the interface. In the next time step, a false velocity will be derived since its derivation was based on incorrect pressure values.

Many researchers proposed possible methods to overcome this problem. These schemes were usually quasi conservative schemes, in which the density variation at the interface was not sharp due to its diffusive nature. In most schemes, the shock wave were typically stretched over 2 - 3 grid points while the interface was smeared over 5 - 7 grid points. This could be acceptable in dealing only with a pure gas phase. However, in the case a two-phase flow such as a mixture of gas and liquid phases accompanying very large density difference between the two phases, density diffusion at the interface is strictly unacceptable. Physically interfacial mixing hardly takes place at gas/liquid interfaces except in very special cases. Numerical diffusion might result in unphysical densities at the interfaces. Therefore, a different method should be used in order to overcome this numerical mixing. This method can eliminate pressure fluctuations at the interface and keep a discontinuous density profile at the interface. Here the results derived from an exact Riemann solver at the interface will be applied for correcting the density diffusion and pressure fluctuations at the interface by interpolating the results of the exact Riemann solver with grid points that were not affected by diffusion near the interface. As a result the pressure and density are corrected at the grid points across the interface. Therefore, the numerical density diffusion and pressure oscillations are eliminated. Thus a discontinuous interface is retained for the next iteration.

The second numerical scheme developed here is an upwind TVD scheme with the correction step described above. The interface is captured using the level set approach. The level set approach is an interface capturing scheme based on level set functions. It can capture the interface between two grid points. The level set function ψ is defined as the distance between a grid point and the interface so that $\psi=0$ designates the material interface.

The present thesis consists of 6 chapters:

In Chapter 1, an introduction and background of the current research is presented.

In Chapter 2, the development of the modified CIP scheme is presented. The modification to the CIP scheme to simulate a gas/liquid interface sharply are highlighted. This new modified scheme has the following advantages compared with the original CIP scheme.

(a) The modified CIP scheme can handle physical gas liquid interfaces with a liquid gas density ratio of about 800 and speed of sound ratio of about 5;

(b) The modified CIP scheme does not diffuse the density at the gas/liquid interface;

(c) The modified CIP scheme has better interface tracking.

A shock wave interaction with a water column is successfully simulated. The obtained results are compared with experimental ones good agreement between the two results is achieved. In the experiment, double exposure holographic interferometry was used to visualize the gas and liquid phases. The density variation inside the droplet was studied and its effect on the breakup process was evaluated. For the first time wave motion inside the water column were visualized. It has been shown both numerically and experimentally that these waves propagate inside the water column at the initial stages of the breakup process. It was found that the pressure distribution inside the water column mainly affects the deformation in the early stages of the breakup process. However, at later stages it is insignificant since the flow field is dominated by the boundary layer stripping.

In Chapter 3, the development of an upwind TVD scheme coupled with the level set approach and an interface correction step is presented. The numerical scheme is extended for solving multi dimensional flows using directional splitting. As is clearly evident from the numerical examples, the proposed scheme is suitable for handling gas/liquid interfaces. It does not create pressure oscillation nor density diffusion at the interface.

In Chapter 4, the numerical scheme developed in Chapter 3 is applied to the shock wave interaction with a liquid column. These numerical results are compared with experimental results obtain from finite fringe interferometry and with numerical results of shock wave interaction with a solid cylinder. The shock wave motions existed inside the water column, which was found to be similar to that of a shock wave inside a circular reflector. The flow field is initially similar to that of shock wave interaction with a solid cylinder. Their similarity terminates when the interfacial instability appears. Based on the numerical results the onset of the interfacial instability was found that for the Mach numbers studied in the current thesis the instability of the water column interface remains in quasi-steady state with the aid of experimental results the various stages of the water column breakup were determined.

Liquid column deformation for various shock wave Mach numbers and initial liquid column diameters was studied. Presenting the obtained results in dimensionless terms show that the data points lie along a similar line. The maximum lateral deformation of the water column was lower than that of a spherical water droplet although their maximum lateral deformation occurred at a similar dimensionless time. The drag coefficient was evaluated for the various water columns and compared to that of a spherical droplet.

In Chapter 5, an experimental study of two water columns in tandem, interacting with a planar shock wave is presented. The behavior of the water columns is compared to that observed for the case of a single water column. It was found that the front water column behavior is similar to that of a single water column. From the experimental results the water column deformations, displacements and accelerations are investigated. The interaction between the two water columns is studied as well. It was found that the rear water column was significantly affected by the presence of the front water column and hence its displacement and drag coefficient were lower than those of the front water column. These results are compared to those of tandem spherical droplet droplets subjected to shock wave loading;

In Chapter 6, the conclusions of this thesis are drawn.

審査結果の要旨

衝撃波と干渉して液滴が変形、分裂さらに微粒化する現象の解明は、複雑媒体中の衝撃波現象の解明に関する基礎研究課題であるばかりでなくて、液滴を含む高速気流あるいは噴霧燃焼における液滴変形の素過程の解明など重要な応用につながる。本論文は、衝撃波を負荷した液滴の内部に現れる波動とその波動がその後の液滴の挙動に与える影響を明らかにするために衝撃波管の中に円筒形状の水柱をおいて、衝撃波と水柱との干渉を実験的、数値解析的に定量的に解明した研究成果をとりまとめたもので、全6章よりなる。

第1章は緒論である。

第2章では、衝撃波管内で衝撃波の負荷によって引き起こされる円筒形状水柱の分裂をホログラフィー干渉計法で観察し、定量的に数値解析の結果と比較している。水柱の内部に気中の衝撃波に先行する圧縮波が現れることを初めて実証し、その挙動が水柱の分裂に影響を与えることを明らかにしている。これは創意ある研究手法の開発であるばかりでなく大きな成果である。

第3章では、空気と水の界面のような大きな密度変化を有する二相媒体に衝撃波が負荷された場合に有効な高解像風上型差分法について述べ、非粘性モデルではあるが従来の計算法の不備を改良して有効な知見を導いている。

第4章では、分裂する円筒水柱を有限干渉縞ホログラフィー干渉計法で撮影して、干渉縞写真をフーリエ縞解析法で解析し、高解像の定量的画像処理方法を開発している。また、その結果を数値解と比較して良い一致を得て、水柱に働く非定常抗力係数を求めている。この画像処理法と計算との対比は今後の実験と数値解析研究の進むべき方向を示すもので評価に値する。

第5章では、衝撃波伝播方向に並んでおいた二つの水柱の挙動に関する実験研究のとりまとめ、下流においた水柱が遅れて変形し崩壊する過程を詳細に明らかにしている。また、水柱に働く時間平均抗力係数の計測に成功している。

第6章は結論である。

以上要するに本論文は、円筒形状水柱と衝撃波の干渉現象を衝撃波管実験と光学可視化、画像処理法を組み合わせ実験により、また、数値解析により定量的に解明したもので、高速気体力学および衝撃波工学の発展に寄与するところ少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。