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Alfred C. Buckingham

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INFERENCES DRAWN FROM SHOCK-ENHANCED TURBULENT MIXING ANALYSES*

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Alfred C. Buckingham
A/H-Divisions, Lawrence Livermore National Laboratory
Livermore, California 94550

ABSTRACT

This discussion concerns analyses of physical shock-tube and shock-boundary layer interaction experiments, supplemented by computations. The basic issue is that of evaluating the influence of reflected shock waves on enhancing the balance of turbulent kinetic energy and resultant turbulent material mixing during implosion and shock reflection intervals. Increases in random velocity amplitudes of a factor of 5 or greater implying turbulent kinetic energy increases of a factor of 12 or more have been observed in some low Mach Number shock-tube and boundary-layer shock wave interaction experiments. These results are analyzed to estimate their influence on increased turbulent material mixing subsequent to shock interaction. The analyses are developed with the assistance of two-dimensional, pseudospectral free turbulent field shock interaction numerical simulations as well as compressible turbulent boundary-layer shock interaction calculations. Of particular interest is the influence of Mach Number and pre-existing turbulent intensity on the enhancement ratios.

I. INTRODUCTION

This paper updates previous experimental analyses and results from numerical experiments based on pseudospectral simulations of the two-dimensional compressible Navier-Stokes equations.[1,2] In addition to data from the most recent numerical experiments, the present discussion summarizes the analysis of two recent shock-wave turbulent boundary-layer interaction experiments.[3,4] The purpose is to develop and verify the data on shock enhancement of turbulence.

At appropriate Reynolds Number, shock waves may create turbulence. Shocks may also enhance pre-existing turbulence. The existence of the phenomena is well recognized (although imperfectly understood) from observations in shock tubes, supersonic wind tunnels and high speed flight. This shock enhancement of pre-existing turbulence is a central issue in attempts to understand shock-enhanced material mixing and consequent enhanced-component reaction rates, accelerated combustion as well as detrimentally accelerated ignition, detonation, and deflagration processes. The present work adds computational simulations for situations in which experimental evidence is lacking and theory either suspect or contradictory relative to available evidence. The particular focus here is study of: shock-wave amplification of turbulence at Mach Numbers greater than four or five; reflected shock waves interacting with realistically vigorous turbulence relative intensities of ten percent or more; and of the quantitative effects on both the persistence and the dissipation of the amplified turbulence in the presence of real viscosity.

The presence of shock waves and their substantial influence on turbulence probably has frustrated experimentalists for over forty years. However, systematic analysis appears to have awaited the study of shock-induced noise. Moore[5] and Ribner[6], almost simultaneously, theoretically described the interaction of a shock wave with an inviscid flow field. Ribner subsequently expanded his analysis to examine spectral interaction characteristics and, more recently, to refine spectral descriptions of imposed and amplified turbulence.[7] It was determined that imposition of any single one of three possible flow disturbances: entropy (random density fluctuations), vorticity (random velocity fluctuations), or sound-acoustics (random pressure fluctuations), promotes all three disturbances after shock passage. The pre-existing disturbance is amplified, the wave phase is altered, and mode conversion takes place.

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Subsequent theoretical study included the linearized theory of McKenzie and Westphal who treated shock interaction in the limit of a linearized small disturbance theory. They applied a small disturbance expansion to the shock-jump conditions.[8] These informative results are strictly valid at low levels of pre-existing turbulence amplified at a plane, undeformed shock front.

Experimentally, it is evident that shock fronts deform after crossing a randomly disturbed media. The resulting pressure-wave breakup on interaction may lead to substantially enhanced disturbance amplitudes, perhaps even greater than those predicted by the linear theory.[9,10] Many important observations have been made in studies of shock-boundary layer interaction.[3,11] Pertinent theoretical/analytical work includes application of rapid (strain) distortion theory to shock-wave turbulent boundary layer interactions.[12] Unfortunately, unraveling the specific interaction influences from the complicated structure of a distorted, unstable or incipientally separated boundary layer is not inherently satisfactory. It requires many, perhaps unwarranted, assumptions. Some recent interpretations are presented here.

Shock-tube results, while promising, are, at present, limited to qualitative flow visualization information or limited quantitative information. Unfortunately, the results display substantial statistical variance.[13,14] Also, all of the presently available shock-tube studies appear to be limited to modest Mach Numbers (≤ 3.) and low relative turbulence intensities (< 2%).

Previous efforts on development of pseudo-spectral collocation procedures for simulating inviscid compressible instability growth[15,16] have provided incentive for the present study of fully viscous flows. Viscous flows are examined because of interest in the influence of vorticity diffusion and viscous dissipation. At present, both diffusive shock-capturing and shock-fitting procedures are being applied to study shock-wave turbulence enhancement.[1,2]

The use of shock-fitting with pseudospectral methods is stimulated by the published results of studies on inviscid nonlinear shock turbulence interaction by ICASE and NASA-Langley scientists.[17-19] Their pioneering efforts with the fully nonlinear Euler's equations compare quite well with linear theory,[8] at least up to critical incident shock-wave (vortical) disturbance wave intersection angles, and with modest levels of pre-existing turbulence.

II. ANALYSIS OF EXPERIMENTAL BOUNDARY LAYER RESULTS

While three-dimensional vortical influences and the dominance exhibited by unsteady large scale, almost periodic, near-surface structures inhibit straightforward interpretation of shock-wave turbulent boundary-layer interaction experiments; continuing aerodynamic interest has established a generous experimental data base for comparison. To make use of these experiments, one needs to provide a consistently effective approximation for interpreting the turbulent enhancement. The basic analysis procedure requires systematic application of compressible, nonsimilar Reynolds-averaged turbulent boundary layer solutions.[2] Solutions must be obtained for the boundary-layer momentum integrals, Eq. (1) at various streamwise stations, x, upstream and downstream of the position at which the shock-wave interacts. Third-order boundary-layer theory is used to "impress" the effects of a shock wave. Impressment consists of imposing the influence of shock-generated vorticity through a functional variation in the external entropy applied as an outer boundary condition. The compressible boundary-layer momentum integral is defined at a streamwise position, x^*, by:

$$I_\theta \equiv \int_0^\delta \frac{\rho(y)}{\rho_\infty}\,\frac{u(y)}{u_\infty}\left(1-\frac{u(y)}{u_\infty}\right)dy\,\Bigg|_{x=x^*} \qquad (1)$$

In Eq. (1) ρ is the density and u is the velocity component parallel to the wall. The subscript, ∞, refers to values at the outer edge of the boundary layer. The upper limit, δ, is the boundary layer thickness. The distance measured parallel to the wall is χ while that measured perpendicular to the wall is y. The "wall" is at y=0.

Figure 1 illustrates computed and experimental velocity profiles in the turbulent boundary layer

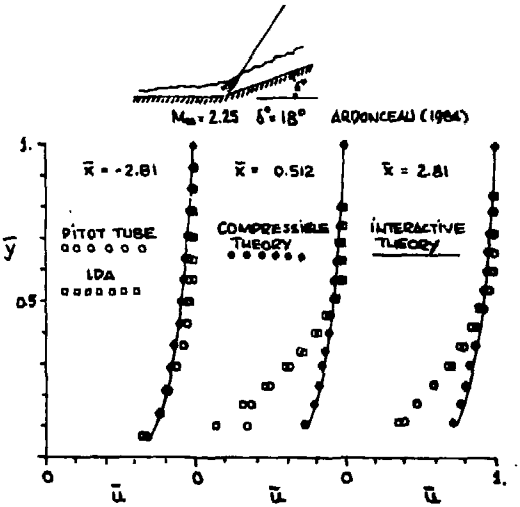


Fig. 1. Measured and computed velocity profiles in the turbulent boundary layer before and after shock interaction, Ardonceau's experiments (Ref. 3).

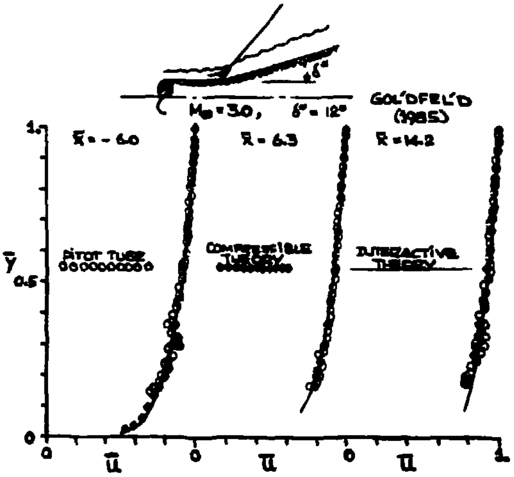


Fig. 2. Measured and computed velocity profiles in the turbulent boundary layer before and after shock interaction, Gol'dfel'd's experiments (Ref. 4).

based on Ardonceau's[3] experiments at Mach No. 2.25 for a wedge angle of 18°. Figure 2 illustrates similar results from the Gol'dfel'd experiments[4] at Mach No. 3 for a Cone Angle of 12° in axially symmetric flow. The parallel component of velocity, $\bar{u}$ is ratioed to the outer edge velocity, u_∞, at the appropriate, x station. The spatial coordinates x and y are ratioed to the boundary layer displacement thickness, δ_0, well ahead of the shock interaction region. Values of x<0 refer to positions ahead of the shock-wave intersection with the boundary layer, while values, x>0, refer to those behind shock-wave intersection.

Figure 3 summarizes a representative collection of shock-tube and shock-wave boundary-layer turbulence enhancement results. The significant amplification of the velocity perturbation level (infinity designates ahead of and two designates behind the shock front) as well as the modest Mach Number range is typical of the available experimental data.

III. NUMERICAL PROCEDURE

Neglecting body force, flow relations expressing conservation of mass, momentum and energy for a

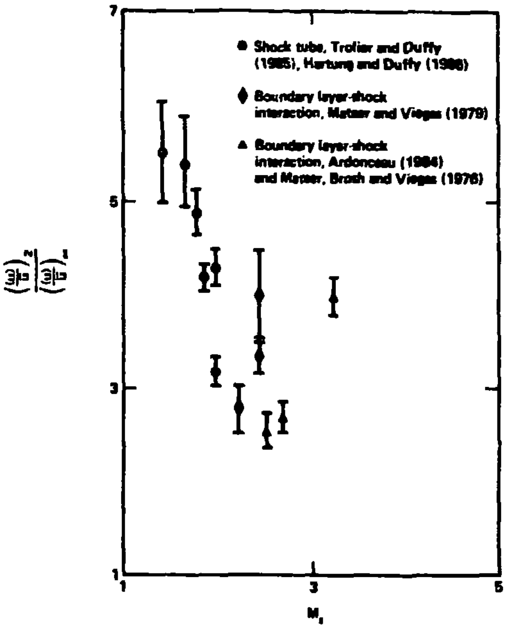


Fig. 3. Experimental observations of pre-existing turbulence velocity enhancement by shock waves.

viscous, heat conducting, calorically perfect gas are written in two-dimensional Cartesian coordinates, x^i, $i = 1,2$, for unsteady, nonuniform density, $\rho(x^i,t)$ and flow velocity, $u^i(x^i,t)$:

$$\rho_{,t} + (\rho u^j \delta^{ij})_{,i} = 0 \,, \tag{2}$$

$$(\rho u^i)_{,t} + (\rho u^i u^j + p\delta^{ij} - \tau^{ij})_{,j} = 0 \tag{3}$$

$$(\rho e)_{,t} + (\rho e u^j \delta^{ij} + p u^j \delta^{ij} - q^j \delta^{ij})_{,i} - \Phi = 0, \tag{4}$$

$$\text{where } \delta^{ij} = \begin{cases} 1, & i = j \\ 0, & \text{otherwise} \end{cases} .$$

Partial derivatives with respect to time and space are denoted by subscripts $(,t,j)$, respectively. The pressure is denoted by p, the specific internal energy by e, and the heat flux vector, q^j, is defined by,

$$q^j = k_\theta \theta_{,j} \,, \tag{5}$$

where k_θ is an associated thermal conductivity coefficient, and θ is the scalar temperature. The stress tensor, τ^{ij}, and viscous dissipation, Φ, are obtained using Stokes' hypothesis (negligible bulk viscosity),

$$\tau^{ij} = \mu[(u^i{}_{,j} + u^j{}_{,i}) - 2/3\ \delta^{ij}\ u^i{}_{,j}] \,, \tag{6}$$

$$\Phi = (\tau^{ij} u^j \delta^{ij})_{,i} \,. \tag{7}$$

For the present computations, all significant scales of motion are to be directly simulated. To do this, the Reynolds Number is set at a value of 3000 by rescaling the viscosity,

$$\mu = (\rho\ u\ \lambda)/3000 \,. \tag{8}$$

Here the characteristic dimension, λ, is the span width of the computational domain. For consistency, the heat flux vector, eqn. (5) is appropriately scaled by setting the value of thermal conductivity in accordance with a unit Prandtl Number,

$$k_\theta = \mu\gamma\left(\frac{e}{\theta}\right),\ \gamma = \text{polytropic exponent} = \frac{7}{5}. \tag{9}$$

For computational convenience, dimensionless forms of the variables are introduced:

$$\begin{aligned} &\rho = \rho^0/\bar{\rho}_2\ ;\ u = u^0/\bar{u}_2;\ e = e^0/(\bar{u}_2)^2\ ; \\ &p,\tau = (p^0,\tau^0)/(\bar{\rho}_2\bar{u}_2{}^2);\ q = q^0/(\bar{\rho}_2\bar{u}_2{}^3); \\ &x^j = x,y = (x^0,y^0)\cdot(2\pi/\lambda)\ . \end{aligned} \tag{10}$$

Here the superscript zeroes denote dimensional variables, while subscript (2) and the overhead bar denote average-state values behind the advancing shock front.

In both shock-fitting and shock-capturing procedures the dependent variables and their derivatives are given by their spectral representations. A truncated Chebyshev series represents the streamwise range, $x = [0,x^*]$ and a truncated Fourier series the spanwise range, $y = [0,y^*]$. Symbolically the nth-time epoch state for the function ϕ is given by:

$$\phi^n(x,y,t) = \sum_{p=0}^{P} \sum_{m=0}^{M} \phi^n(p,m,t) T_p(y) \exp\left[2\pi i m \frac{x}{x^*}\right], \tag{11}$$

where the Chebyshev function, $T_p(y) \equiv \cos(p\cos^{-1} y)$.

For the Reynolds Number = 3000 limit imposed, the modal truncation, $P,M = 32$, appears adequate to resolve all of the explicit scales down to the dissipation range.

In the shock-fitting method, x^* represents the moving shock-wave front and is a real boundary dividing two computational domains, one behind and one ahead of the advancing shock. One determines the instantaneous position and profile of the advancing shock front $x_s(y,t)=x^*$, in accordance with the Rankine-Hugoniot conditions and method-of-characteristics matching.[1,2,20] Coordinate and contravariant velocity component transformations are required for the time developing domain. Other information is available in separate publications.[1,2] Fast Fourier transforms to phase space yield the spatial distribution of variables and their derivatives. Inverse transforms to configuration space preface evaluation of the nonlinear advection terms. Both procedures are incrementally updated in time using a third-order explicit Runge-Kutta method.

IV. EXAMPLES OF NUMERICAL EXPERIMENTS

The vorticity amplification from an initial single-wave vorticity perturbation disturbance imposed at a 30° angle to an advancing Mach 6 shock is shown in Fig. 4. This illustrates the spanwise distribution of vorticity at three specified locations behind the advancing shock wave. Here the calculation had continued sufficiently long to permit the shock wave entrainment of the entire initial vortical disturbance. The spatially integrated vorticity behind the shock wave adjusted for the shock jump conditions, is ratioed to the total initial vorticity disturbance ahead of the shock wave to evaulate the shock transmission amplification.

Figures 5 and 6 illustrate the time-dependence of this process of shock entrainment of the imposed downstream disturbance. The figures show the evolution of spanwise distributions of spanwise perturbation velocity induced velocities at three positions behind the advancing shock wave, but at two succeeding intervals of time. The evolutionary character of the turbulence enhancement requires continuation of the calculation for a sufficient period to insure shock wave transit and entrainment of the entirety of the initial disturbance.

The noteworthy, shock-fitted inviscid computations of the NASA-Langley group[17-19] and the linear theory[8] are compared with the current viscous shock-capturing results in Fig. 7. Computed results have been obtained up to Mach 10. The significance of the errors produced when an insufficient computational time prevents entrainment of the entire disturbance are illustrated. Compare the viscous results (open circles) reported previously[1] to the present results where complete disturbance entrainment occurs (filled circles).

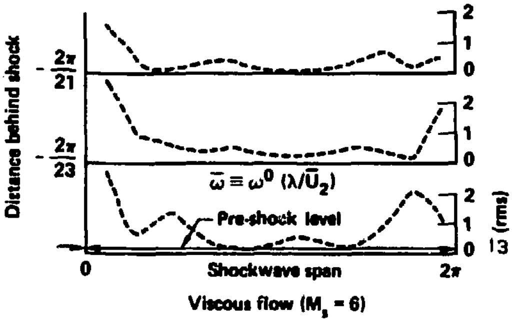


Fig. 4 Vorticity amplification at specified positions behind an advancing plane shock wave moving at Mach 6.

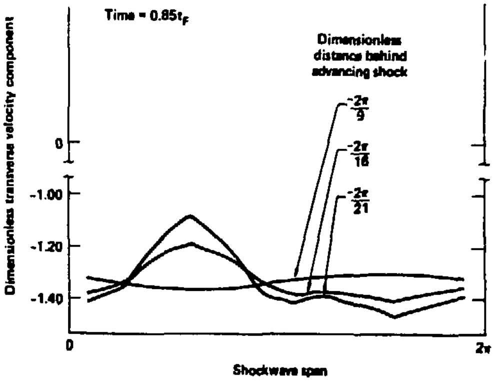


Fig. 5 Vorticity amplification induced spanwise perturbation velocity at specified positions behind advancing plane Mach 3 shock at time = 0.85 t_F.

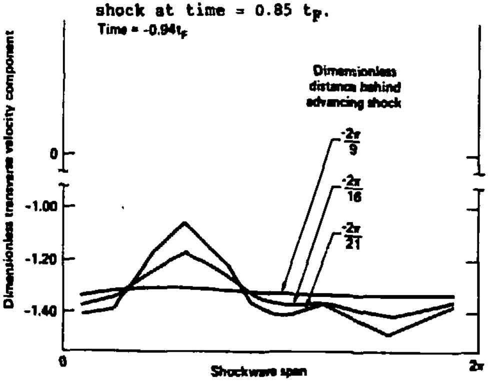


Fig. 6 Vorticity amplification induced spanwise perturbation velocity at specified positions behind advancing plane Mach 3 shock at time = 0.94 t_F.

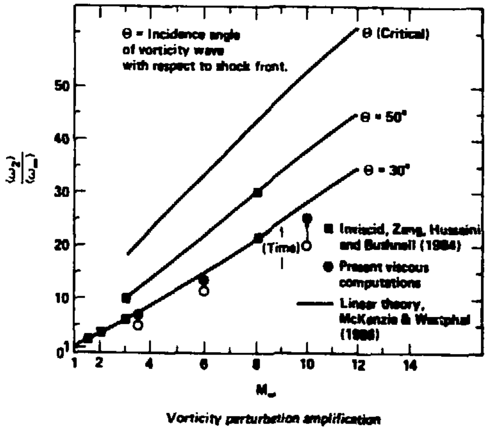
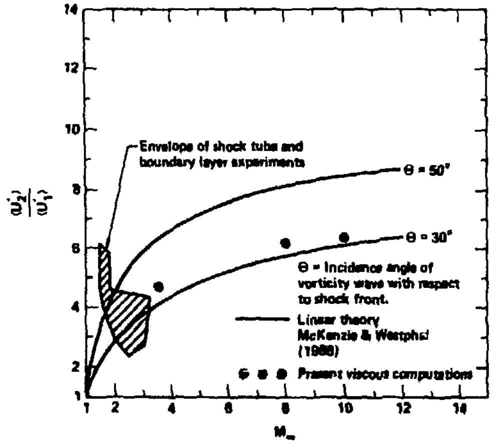


Fig. 7. Amplification of vorticity perturbation at various Mach numbers, comparing viscous with inviscid results.



Velocity perturbation amplification

Fig. 8. Vorticity amplification induced velocity component at various Mach numbers, comparing viscous with inviscid results.

The differences between these viscous results and the inviscid results, as well as the linear theory, are also shown. These differences are attributed to viscous diffusion and dissipation, although the shock-fitting viscous flow procedure requires a regularization of the shock profile prior to the remapping in physical (orthogonal) space. This may be a troublesome source of numerical error and is being re-examined.

Figure 8 shows the computed viscous velocity perturbation enhancement associated with the vortical amplification of the previous figure. Again we plot, for comparison, the linear theory results at two different, subcritical incidence angles. The viscous simulations were run only at a vortical-wave, shock-wave incidence angle of 30°. Also plotted, for convenience in referance, is the cross-hatched envelope bounding the experimental shock-tube and boundary-layer results shown previously in Fig. 3.

V. CONCLUDING REMARKS

A numerical procedure for simulating compressible, unsteady Navier-Stokes flow has been applied to a particular turbulence situation for which there is a paucity of experimental data. The flow simulations depict the enhancement of a pre-existing turbulence field by passage of shock waves.

Results on enhancement currently include both single- and multiple-wave perturbations. This, is clearly a very early stage in simulation development. The simulations will subsequently approach reality more closely by initiating with a random wave packet. A larger Reynolds Number will then be imposed (with a correspondingly increased-modal truncation limit, perhaps 128^2, to reproduce, with reasonable integrity, some of the spectral characteristics an initial turbulence field.

Increasing the intensity level, nonlinear interaction, added degrees of freedom, inhomogeneity, and anisotropy, all preface a significant later step: the extension of future simulations to three spatial dimensions.

Current results indicate that enhancement of initial turbulence energy by factors of about 20 may occur at Mach Numbers as low as 10. It remains to be seen whether or not this level of enhancement also is predicted with higher modal resolution, shock front (fitting) resolution, and a more realistic set of initial conditions for pre-existing turbulence.

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