Study on the Interaction between Low-Mach-Number Grid Turbulence and Spherical Shock Wave

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Abstract Characteristics of low-Mach-number grid turbulence interacted with a spherical shock wave are investigated by means of laboratory experiments using a wind tunnel and a diaphragm-less shock tube. Turbulence-generating grids are installed at the entrance to the test section of the wind tunnel to generate nearly isotropic turbulence. A shock wave propagates spherically from the open end. A shock wave was generated by the diaphragm-less shock tube using a quick piston valve, and was emitted from the open end of the shock tube, which was directed vertically downward across the turbulent flow. A shock wave propagates spherically from the open end. The shock wave generator could be driven automatically with good repeatability. Instantaneous streamwise velocity before and after passing a shock wave is measured by hot wire anemometry. The probe is set up in the upstream of the open end of the shock tube. The results show that streamwise turbulent intensity is increased and the streamwise integral length scale is decreased after interaction with a shock wave.

Introduction

A sonic boom is known as one of the flight problems on the supersonic transport (SST). It is known that over-pressure and rise time of the sonic boom are affected by atmospheric turbulence. In past studies[1]-[5] , experimental study on a high-Mach-number grid turbulence interacted with a shock wave or numerical simulation on the interaction between homogeneous isotropic turbulence and a shock wave were mainly investigated. Keller and Merzkirch[1] measured density fluctuations, and revealed that Taylor's microscale λ increases by the interaction with a shock wave. Additionaly, Honkan and Andreopoulos[2] also showed that streamwise turbulent intensity and the dissipation length scale are increased by the interaction with a shock wave. On the other hand, Agui et al. [3] showed that the streamwise integral length scale is decreased by the interaction with a shock wave. Moreover, Barre et al. [4] found that the streamwise integral length scale is decreased, and the high wavenumber energy is increased by the interaction with a shock wave. As mentioned above, in the past studies, there is an agreement on the behavior of turbulent kinetic energy; the energy is amplified. However, the length scales need further investigation. Moreover, previous studies have not yet focused on the interaction between low-Mach-number turbulence and a shock wave, which appears in atmospheric turbulence.

In this study, therefore, we experimentally investigate the characteristics of low-Mach-number turbulence interacted with a spherical shock wave using a grid turbulence and a diaphragm-less shock tube.

Experiments

A schematic view of the experimental apparatus is shown in Fig. 1. A shock wave is generated by a diaphragm-less shock tube using a quick piston valve, and is emitted from the open end of the shock tube, which is directed vertically downward across the turbulent flow. The low pressure room of the shock tube is 3,565 mm in total length and 21.3 mm in internal diameter. Dry air of 900 kPa is used as a driver gas. The shock tube is driven automatically, and it generates shock waves in succession with good repeatability. Mach number M_s is measured by using two pressure sensors (H112A21, PCB Piezotronics Inc.), which are set up in the shock tube. Average mach number $M_{s\ Ave}$ on 100 measurements is 1.62, and its standard deviation is 0.1%. We installed turbulence-generating grids (Table 1.) at the entrance to the test section of the wind tunnel to generate nearly isotropic turbulence. The experimental conditions of grid turbulence are tablated in Table 2. Instantaneous streamwise velocity is measured by using hot wire anemometry (DANTEC, Streamline). The open end of the shock tube is set up 1,500 mm downstream of the grids, and the hot wire probe is set up 600 mm upstream from the open end. The experiments are performed 250 times for each condition in order to obtain reliable statistics. The sampling rate is 100 kHz. Frequency response of hot wire anemometry is about 60 kHz at U_{mean}~10 m/s, and is about 100 kHz at U_{mean}~20 m/s, where, U_{mean} is a mean wind velocity.

Table 1. Detail of grids

M [mm]	d [mm]
15	3
25	5
50	10
100	20

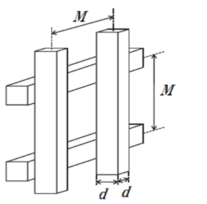

Table 2. Experimental Conditions

Mesh size M [mm]	15	25	50	100
U_{mean} [m/s]	10~18	10~18	10~18	10
Re_λ	49~70	64~92	105~148	159

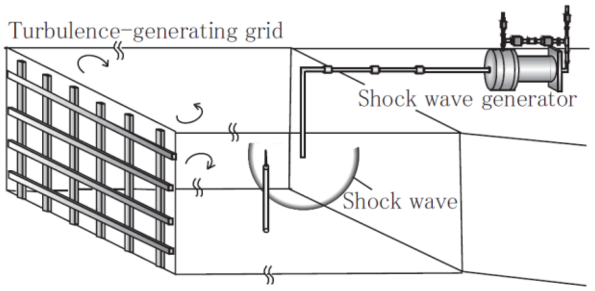

Figure 1. Schematic diagram of the experimental apparatus.

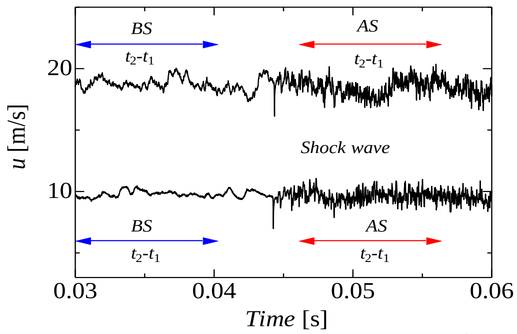

Figure 2. Instantaneous velocity signal before and after passing of a SW.

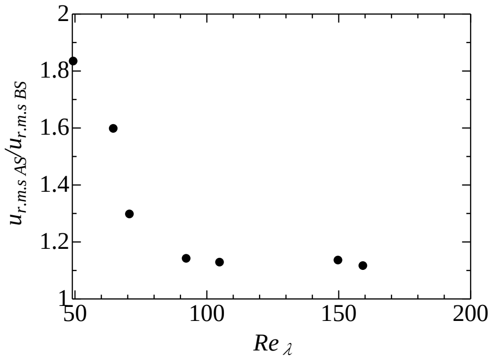

Figure 3. The relationship between the amplification ratio of $u_{r.m.s}$ and Re_λ.

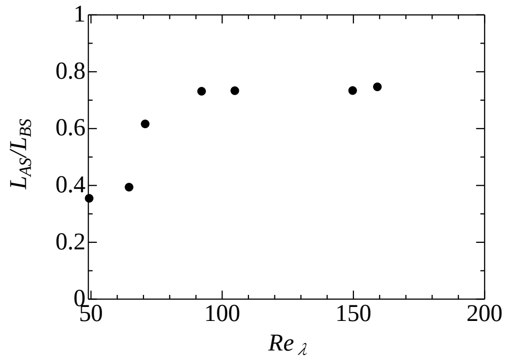

Figure 4. The relationship between ratio of the streamwise integral length scale and Re_λ.

Results and Discussion

Figure 2 shows the instantaneous velocity signal before and after passing of a shock wave (SW) for the case of M = 25 mm. The instantaneous velocity signals became discontinuity when a shock wave passed the hot wire probe. This tendency was seen in all cases. In order to investigate the root-mean-square values of streamwise velocity fluctuation $u_{r.m.s}$, following equations are used.

$$u_{r.m.s} = \frac{1}{N}\sum_{k=1}^{N}\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\left(u(t) - U_{ENS}\right)^2 dt\right]\cdots(1),\quad U_{ENS}(t) = \frac{1}{N}\sum_{k=1}^{N}u_k(t)\cdots(2)$$

Here, U_{ENS} is the ensemble averaged instantaneous velocity over 250 (= N) experiments and t_2-t_1=0.01024 s. The relationship between the amplification ratio of $u_{r.m.s}$ and turbulent Reynolds number Re_λ (=$u_{r.m.s}\lambda/\nu$; ν is the kinematic viscosity) is shown in fig. 3. It is found that streamwise turbulent intensities are increased after interaction with a SW and the magnitude of amplification is larger for weak turbulence (i.e. small Re_λ). The relationship between the ratio of the streamwise integral length scale and Re_λ is shown in fig. 4. Figure 4 shows that the streamwise integral length scales are decreased after the interaction with a SW. It is found that the ratio of $u_{r.m.s}$ and that of the streamwise integral length scale approach to the initial condition with increase of Re_λ for the same strength of a SW.

Concluding remarks

Characteristics of low-Mach-number grid turbulence interacted with a shock wave are investigated by means of laboratory experiments using a wind tunnel and a diaphragm-less shock tube. The results show that streamwise turbulent intensity is increased after interaction with a shock wave. The streamwise integral length scales are decreased after interaction with a shock wave. Other statistics such as energy spectrum and derivative quantity will be reported in a presentation.

References

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