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【Review Paper】

Forefront of Wind-Tunnel Experiment on Turbulence Structure*

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Abstract

Many interesting and important basic problems still remain unsolved or ever untouched in the fields of experimental fluid dynamics. The present report explains a variety of newest results of wind tunnel experiments conducted chiefly in our laboratory with respect to the features of large scale quasi-isotropic turbulence, anisotropic turbulence, three-dimensional vortical structure in the wake of a sphere, the process of vortex pairing in a two-dimensional jet, the proposal for a new model on a boundary layer transition in a view point of hairpin or horse-shoe vortex and lastly the analysis on spontaneously generated internal gravity waves in a stably stratified mixing layer. These results, the author guesses, will promise the future possibility in the fields of experimental fluid dynamics.

Key words: Turbulent Flow, Flow Control, Vortex, Shear Flow, Transition, Wind Tunnel, Stratified Flow

1. Introduction

Recently, the highly improved performance of computer system makes it possible for CFD to detect the detailed characteristics of coherent structure in turbulence fields. As a result, the fields of experimental fluids dynamics have become more strongly demanded to produce large amount of reliable and minute data on, such as, the fine structure of turbulent motions or the statistical characteristics of large-scale turbulence fields. The present article intends to give some commentaries on the resent results of our experiments from the view point of the dynamics of turbulent eddies and coherent vortices in various turbulence fields.

2. Structural Characteristics of Turbulent Eddies in Large-Scale Turbulence Fields

The clarification of turbulence phenomena in large-scale turbulence fields with the turbulence Reynolds number $R_{\lambda} \geq 10^3$, such as atmospheric and oceanic flows, has now become increasingly important in connection with the meteorological and especially environmental problems. The author’s laboratory has devoted to examine the nature of the large-scale turbulence field by realizing atmospheric-like turbulence in a laboratory scale wind tunnel and by analyzing the transition process of the internal gravity wave in a strong stably-stratified flow. It is generally known that wide-ranged scales of turbulent eddies must exist in a large-scale turbulence field. However, the Reynolds numbers obtained in the conventional grid turbulence of about $R_{\lambda} \leq 10^2$ are not satisfactorily large to verify the hierarchical nature of turbulence fields. Because, it can not be endowed with a wide inertial subrange satisfying the -5/3 law for more than two orders of magnitude in wave number in the spectrum. This fact means that the turbulent eddy motions could not accomplish most essential roles in transfer mechanism in such a small-scale turbulence field. Also in the field of CFD, a number of researchers have challenged to analyze the nature of high $R_{\lambda}$
turbulence fields as one of the most important targets of a numerical simulation using large computer systems like the earth simulator. But, their results have not yet accomplished the complete understanding of the statistical nature of turbulence, though they discovered the existence of fine-scale eddy-like structures and their clusterization (1).

Fig. 1 shows the turbulence generator designed in our laboratory. It is composed of an oscillating grid with many agitator wings and installed just downstream of the contraction nozzle of a wind tunnel with conventional scale. Its driving mode is computer-controlled and can realize homogeneous quasi-isotropic, uniformly sheared turbulence fields and thick turbulent boundary layers by placing a shear flow generator upstream of the active grid. Their Reynolds numbers reached $R \lambda \approx 400\sim800$ which almost corresponds to $Re_M \approx 10^6\sim10^7$.

In Fig. 2, our resultant spectra are compared with those obtained in other typical turbulence fields (3)-(6). The turbulence generator gives random low frequency disturbances to the turbulence field and the energy levels are apparently enhanced in the low wave number ranges in the spectra. Resultantly, the inertial subranges of more than two orders of magnitude in wave number are obtained for all of our cases, though the present width of the inertial subrange is still narrower than those of the atmospheric and the oceanic turbulence. However, we would like to assert that they could have attained at least satisfactorily realistic turbulence characteristics indispensable to basically examine the nature of the actual large-scale turbulence fields.

Kinds of simulations in the actual large-scale turbulence fields have been conducted on such as atmospheric turbulence diffusion and wind environment around an architecture. In our diffusion experiments, the meandering motion of a smoke plume is realized for the first time in a conventional scale wind tunnel as shown in Fig. 3 (7). It must be noticed that the scales of the meandering motion are almost the same as the integral scales of main flow turbulence. For the building-wind simulation, strong blows into behind the buildings are most intensely caused, when the interaction occurs so effectively between the coherent vortices shed from the building and the large-scale turbulent eddies in the main flow having about the same scales. These facts suggest that the large-scale turbulent eddy, usually as a statistical concept, has somehow similar functions with the coherent vortex.

Anisotropy is one of the most difficult problems to be overcome for theoretically understanding the complicated nature of turbulence. With the help of a wide-spread spectral distribution where an inertial subrange obeying -5/3 law spreads for well more than two
orders of magnitude in wave number, the authors challenged to realize strong two- and three-dimensional anisotropic turbulence fields by cutting the large-scale turbulent eddies by a ladder slit or a honeycomb downstream of the turbulence generator, based on a concept somehow similar to the LEBU(8). Quite strongly anisotropic cigar-shaped and, maybe for the first time for wind tunnel experiments, pancake-shaped turbulence are generated in the test section as shown in Fig. 4(9). The result shows that the strongly pancake-shaped anisotropic turbulence shifts at first to be the cigar-shaped one and then decays into the isotropic turbulence. The results seem to keep good coincidence with the second order anisotropic model of SSG(16) as shown in the Lumley’s triangle shown in Fig. 4. Of course, the change in aspects of these processes is a function of $Re$ number, initial degree of anisotropy and shape of turbulent eddy. But, the author thinks it more important to point out that the each stage of energy exchange between three components shifts rather stepwisely than asymptotically. Conceptually, the large scale turbulent eddies can be considered to hold somehow similar characteristics to the coherent vortices.

3. Strouhal Number and Vortex Structure in the Wake of a Sphere

The wake of a sphere is one of the most basic examples of the three-dimensional flow fields, usually accompanied by quite complicated vortical structures. Due to the difficulty in measurement, the dynamics of vortex behaviors has never been completely understood, especially in the transitional range of about $800<Re_D<20000$. There, two kinds of vortical structures are known to exist; usually called a high mode vortex and a low mode vortex. Generally, the Strouhal number of the high mode vortex shedding, $St_H$, has been considered to monotonously increase with the Reynolds number, $Re_D$, whereas the low mode Strouhal number is kept almost constant at $St_L \approx 0.2$. The author has wondered this widely spread recognition, judging from the idea that “the vortical structures have the coherence”, which means that they must have the self-similar configurations with some characteristics scales. Then, the author presumed that $St_H$ shall change in a completely different way like stepwise.

We conducted detailed measurements on the wake of a sphere for $1700<Re_D<20000$ by using a circular multi-hotwire probes and smoke wire visualization as shown in Figs. 5-7. Fig. 5 shows the results of flow visualization. As shown in Fig. 5(a) for $Re_D=2000$, several small-scale (high mode) vortices are observed in a large-scale meandering structure (low mode vortex). The number of high mode vortices contained inside of each low mode vortex increased with $Re_D$ from 2 to more than 6~10, though they appear sometimes even and sometimes odd. At $Re_D \sim 20000$, the high mode vortices begin to more tightly interact with

![Fig. 3 Particle diffusion(7).](image)

![Fig. 4 Process of return to isotropy(9).](image)
each other as their number increases and the small-scale vortices begin to merge each other and cause the turbulent transition inside of the large-scale structure as shown in Fig. 5(b). Such features seem to well coincide with the result of a numerical calculation (20).

The author made a hypothesis that an integral number of the high mode vortices must be contained in each low mode structure, if both of the vortices have well rigid coherent constitutions, i.e., their own determinative self-similar configurations and roles in turbulence transfer mechanism. Based on the hypothesis, detailed measurements were also conducted on the spectral profiles of velocity fluctuations in the wake. The results clearly show the stepwise change of the high mode Strouhal number which keep nearly constant in each short range of $Re_D$ (see Fig. 6). Now we consider that an integer number of horseshoe-like high mode vortices are connected with each other like a chain in a large-scale structure. On the other hand, the low mode Strouhal number is considered to be almost constant around $St_L \sim 0.2$. However, even the $St_L$ changes slightly, probably due to the effect of the two different shedding patterns of the high mode vortex; an alternating pattern and a helical pattern. Now, the author assumes that the number of high mode vortices in each low mode structure may exert some decisive influence on these two basic patterns of the low mode vortex shedding, i.e., the alternating and the helical, though father analyses are required to get the deterministic conclusion.

Fig. 7 gives the contour map of streamwise component of velocity fluctuation measured by a multi-channel circular hot-wire probe. At $Re_D = 2000$ in Fig. 7(a), alternating and helical patterns of the low mode structure appear randomly with time. At $Re_D=5000$ shown in an elongated contour map of Fig. 7(b), several high mode vortices are clearly recognized.
Similar measurements are minutely conducted for $1700 < ReD < 20000$. The results showed that helical and alternating patterns were observed by turns, but the alternating pattern became gradually dominant for $ReD = 2000 \sim 6000$. The turbulence transition inside of the low mode structure was observed for $ReD \geq 6000$, as typically shown in Fig. 5(b).

4. Pairing Process of Roll Vortex in a Parabolic Two-Dimensional Jet

Symmetrically and antisymmetrically roll vortices are irregularly shed in a parabolic two-dimensional jet. Detailed analyses on the process of their mutual interaction, i.e., vortex pairing after their three-dimensional deformation, are indispensable to understand the turbulent transition of the jet. However, the pairing process occurs quite unsteadily, and it was almost incapable of conducting statistical measurements on each process of the three-dimensional deformation of the roll vortex, for example, by using hot-wire probes.

The author tried to acoustically regulate the occurrence of each vortex arrangement in a low mode structure.

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and to quantitatively determine how strong the difference in vortex arrangement affected the aspects of streamwise development of the coherent vortices.

In the case of a natural (unexcited) jet, the roll vortex begins to vent gradually downstream. As apparently shown in Fig. 8, the pairing occurs randomly in time and space between two vortices aligned in the streamwise direction on each side of the jet. When they are acoustically excited with single sinusoidal wave, the vortex tubes make wavy deformation almost at the same wave length along the vortex tube (see Fig. 8b), though it was hard to regulate the starting position of the pairing.

Then, bimodal excitation was examined, changing the strength of excitation and the initial phase difference. The authors succeeded to constantly generate the vortex pairing almost at the fixed position around $X/2h \approx 8$, as shown in Fig. 9. Further more, it is also examined to catch the longitudinal rib structure by hot-wire measurements as recognized by smoke wire observation. The peak or valley of the wavy deformation of the roll vortices was minutely locked up by attaching small tabs around the jet exhaust at every $\Delta Z=36\text{mm}$ which is the averaged wave length for the single mode excitation.

Fig. 10 shows the contour maps of vorticity calculated from the velocity vectors measured by conditional hot-wire measurements. The results show the characteristic features of the pairing process in which the peak of weaker trailing vortex $B_3$ shifted more inward than the stronger leading vortex $B_2$ and is elongated downstream by the local mean velocity. Then, they begin to merge as the trailing vortex is entangled by the leading vortex. Now, the generation of rib structures and their role in the pairing process are analyzed by conducting more detailed hot-wire measurements.

5. A Universal Model for Boundary Layer Transition as the Interaction Process of Hairpin (or Horseshoe) Vortex

In the conventional model of boundary layer transition, the T-S wave develops downstream in a laminar boundary layer. The turbulent spots generated as the consequence of three-dimensional growth of the T-S wave merge each other to cover the whole wall surface. Coles & Barker\(^{(22)}\) pointed the similarity between the grown up turbulent spot and the bulge in the outer turbulent boundary layer. The author has intended to construct a new model which can interpret the whole process of boundary layer development including laminar to turbulent boundary layer transition in terms of the interaction process of hairpin (horseshoe) vortices. We have presumed that some hairpin like vortical structures enhanced through the mutual interaction of the turbulent spots may survive to conform initial turbulent bulges having strong horseshoe-like sculpture as schematically illustrated in Fig. 11.

A pair of turbulent spots was artificially induced in a laminar boundary layer and their merging process was minutely examined through 30 channel X-hotwire measurements. Fig. 12(a) illustrates instantaneous figures of a single grown-up turbulent spot. Inside of the turbulent spot, several longitudinal vortices are observed as the pairs of accelerated and decelerated streaky structures conforming the legs of hairpin vortex having a lateral vortex at its head. It is also observed that a new vortex is generated around the wide deceleration regions at the wing tips of the turbulent spot, as the spot grows larger.

The decelerated region at the inside wing tips of the merging turbulent spots (Fig. 12b) is strongly strengthened through the interaction between the longitudinal vortices, where upward ejection is intensely induced as schematically illustrated in Fig. 12(c). The spots grow upwards there and the two longitudinal vortices beside the center plane develop to conform a larger horseshoe vortex with stronger construction. It seems to have structure and scales quite resemble to those of the turbulent bulges in the downstream fully-developed turbulent boundary layer. Such results seem to support our hypothesis which describes the turbulent transition of a wall boundary layer as the interaction process among the hairpin (horseshoe) vortices.

We also tried to develop a single bulge-like horseshoe vortex appearing after the
Then, we conducted an experiment on the interaction between a pair of horseshoe vortices for the cases of in and out of phase in order to understand how the difference in a manner of the mutual interaction affects the construction of the resultant large-scale vortex and what kind of small-scale vortices are newly generated around the merged vortex after the interaction, as often observed as the small-scale coherent structures in natural turbulent boundary layers. The results show that the various kinds of small-scale coherent vortices are
generated by the different manner of the interaction, but some of the small-scale vortices seem to develop into longitudinal streaks with stronger vorticity (Fig. 15). The author dreams if the ejection and entrainment accompanying the horseshoe vortex may give chances to regenerate, grow and clusterize small-scale coherent structures to be a new large-scale horseshoe vortex in the turbulent boundary layer, as observed by Tomkins & Adrian\textsuperscript{(25)}.

Based on the above mentioned results, we hope to interpret the whole process of the boundary layer transition by only one keyword “the hairpin vortex or the horseshoe vortex” as illustrated in Fig.11.

6. Spontaneous Generation of an Internal Gravity Wave

Internal gravity waves\textsuperscript{(26)(27)} are known as one of the most interesting thermo-fluid dynamical phenomena occurring under a large negative density gradient in stably-stratified flows with local Richardson numbers exceeding 0.25\textsuperscript{(28)}. Usually, a large density gradient is easier to realize in a water channel experiment. But, it is difficult to get quantitative data in it than in a wind tunnel. The author has developed a low turbulence wind tunnel equipped with a thermal stratification generator and realized a strong stably-stratified mixing layer with a local temperature gradient of more than 1000K/m. The thermal stratification generator was installed upstream of a 8.16:1 contraction nozzle to minimize background turbulence level in the test section. Sixty channels of independently controllable coil heaters can realize various types of temperature profiles in the test section. We employed a temperature-controlled ceiling and vacuum-glass sidewalls to get rid of the thermal contamination from the outside. The authors also have designed a new high precision thermo-anemometer system to get the higher order correlation terms, especially the instantaneous heat flux in a stratified flow field. The cold- and hot-wire system has a temperature compensation circuit, an automatic frequency compensation circuit for the thermometer that compensates a thermal time constant of a sensor and prongs. Its automatic time-delay circuit can equivalently minimize the gap error between the cold- and the hot-wires.

Fig. 16 shows the energy spectra of a vertical velocity fluctuation, \(w\), at each height of maximum local temperature gradient. The energy level is extremely low at \(x/D=0\) (\(D=0.42m\); height of the test section), and increases downstream in the low frequency region. Three peak frequency components of 1.0Hz, 1.8Hz and 2.8Hz are recognized at
$X/D=9$, satisfying the three-wave resonant condition. The fact must be noticed that the internal gravity waves are spontaneously induced in a wind tunnel without giving any finite disturbances. The negative heat transfer and the turbulent production were precisely measured as the wave decayed into turbulence in the strongly stably-stratified mixing layer. The results made it possible to conduct detailed quantitative analysis throughout the process from the generation to the collapse of the internal gravity wave.

Fig. 17 compares the vertical distributions of time-averaged vertical heat flux, $-\dot{w} \theta / U_0 \Delta \Theta_{\text{max}}$, and local temperature gradient, $d\Theta/dZ$, at same streamwise locations as Fig. 16. In the lower layer at $X/D=9$, the heat transfer is enhanced with increasing temperature gradient. On the other hand, the heat transfer in the upper layer was remarkably suppressed against the local temperature gradient. As the internal gravity waves develops, the phase difference between $w$ and $\theta$ approaches $\pm \pi/2$. There, the internal gravity waves become to actively affect the mechanism of heat transfer in the stratified flow. At $X/D=11$, the counter-gradient heat flux apparently occurs as shown by the wide negative range in the upper layer, whereas the down-gradient heat flux dominates in the lower layer. Conclusively the counter-gradient heat flux is quantitatively analyzed for the first time in the wind tunnel by the present research.

7. Conclusion

Experimental fluid dynamics has an unignorable merit that we can directly observe interesting fluid dynamical phenomena occurring in actual flow fields, though it does not afford us the microscopic figures of vortical structures as the computational fluid dynamics. Now, the experimentalist is required to make a bold hypothesis on the subjects based on this original concepts, to develop new techniques of flow measurements and to make elaborate analyses in order to discover undiscovered characteristics of the flow fields.

References


