GUST FRONTS GENERATED IN A MULTI-FAN WIND TUNNEL

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ABSTRACT

We tried to generate a gust front in a multi-fan wind tunnel in order to evaluate wind loads by a gust front to structures. The multi-fan wind tunnel was driven based on the time series similar to the velocity change in actual gust fronts. The conditional measurements were made by using an X-probe, a reference I-probe and hotwires. Though the present gust fronts did not have the nature of gravity current, they were found to have the velocity profiles of low level jets similar to those of actual gust fronts or downbursts. This fact shows that the multi-fan wind tunnel is useful for the investigation on the effect of gusty wind to structures.

KEYWORDS: GUST FRONT, MULTI-FAN WIND TUNNEL, HOTWIRE MEASUREMENTS

Introduction

Gust fronts [Wakimoto (1982)] are commonly observed under thunderstorms but sometimes cause severe wind disasters. Downbursts [Hjelmfelt (1988)] also afford severe damages. These are kinds of gravity current and have the low-level jet type velocity profile. Generally, such flow fields are simulated using heavy fluid such as salt water, milk and so on [Simpson (1977)]. But, the quantitative measurement is difficult in these flow field. Therefore, it is preferable for wind engineering use that the flow field has velocity profile and velocity change similar to gust fronts under neutral condition. The present experiment aims to generate such flow field in the multi-fan wind tunnel.

Experiments

The multi-fan type wind tunnel in Miyazaki University shown in Fig.1 has 99 fans

Figure 1: Experimental setup
controlled independently by a computer [Nishi and Miyagi (1995)]. Its test section is 2.5 m wide and 1.8 m high. The multi-fan type wind tunnel can simulate vertical velocity profile of a gust front with the other fans in higher line. Such case may be useful for investigating gust affecting tall buildings, but it cannot realize the entire low-level jet type velocity profile of the gust front. Because our focus in the present study was to simulate the total structure of the gust front, only 9 fans in the lowest line were driven and the gusty wind blew from the lowest duct as shown in shaded area in Fig.1. The velocity profile was initially stepwise but became a jet type due to skin friction of the floor and mixing.

The control data are shown in Fig.2. Case 1 is a simple gust with trapezoidal velocity change, and Case 3 has long time span of 5 times of Case 1. Case 2 simulates the velocity change of downbursts [Hjelmfelt(1988)]. The $X$ and $Z$-axes are set streamwise and upperwise from the floor center of the inlet of the test section. Measurements were made with an X-probe and hotwires at various heights on $X = 1, 2$ and 5 m. The control volume of the X-probe made by tungsten wires of 5$\mu$m in diameter is $0.7 \times 0.7 \times 0.5$ mm$^3$. The instantaneous velocity components, $u$ and $w$ were conditionally sampled for 5 seconds in reference to the signal from an I-probe located just downstream of the duct and 10 times ensemble averaged. The sampling frequency was 6 kHz and the resolution of A/D converter was 14bit.

We also made flow visualization with a smoke wire method. The smoke wire made from a nichrome wire of 0.2 mm in diameter was set vertically from the floor at $X = 1$ m. It was electrically heated when the gust front pass through this point. The movement of smoke pattern was filmed through a hi-speed camera at 300 fps.

**Results and Discussion**

The velocity profiles at the time when the maximum wind velocity was observed at $X = 1$ m are shown in Fig.3. The maximum velocity, $U_{max}$, and the height where the maximum velocity appears, $H$, listed in Table 1 were obtained to fit the profile of downbursts [Hjelmfelt(1988)] by using least square methods. The peak height and the maximum velocity are almost the same in all case. Comparing to the mean height of actual downbursts, $Z = 80$ m [Hjelmfelt(1988)], the simulated gust front corresponds to the miniature of 1/1600. The Reynolds number based on the peak height and the maximum velocity is 67000. Though it is far smaller than that of actual flow, e.g., Re $\sim 10^8$, turbulence can be fully developed in the simulated gust front. The resultant velocity profiles shown in Fig.3 are almost similar to the

![Figure 2: Time series of fun control signal](image-url)
low-level jet profile of downbursts except for near the peak, $Z/H = 1$. The depression near peak may be caused by a rapid contraction from the fan to the test section. We expect to get better velocity profile by the extension of the contraction duct to develop a duct flow.

Figure 4 shows time-height velocity distributions of averaged gust fronts. In these figures, the wind flows rightward and $t = 0$ sec. is the trigger time when the reference probe observes $U = 5$ m/sec. The color contour denotes wind speed. The gust fronts are shown by the abrupt increase of wind speed and the existence of upward flow. Their heights reach more than $Z = 600$ mm even at $X = 1$ m in all cases as shown in Figs.4(a–c). There noses locate from $Z = 300$ mm to $400$ mm which slightly vary by the case. The horizontal vortex existing just behind of the gust front is observed in all cases. The vortical motion is not clear in the upper side of the horizontal vortex because the velocity fields are mapped in Eulerian frame. But, its behavior is clearly demonstrated by the smoke wire method as shown in Figure 5. The vortex rolling up the smoke flow downstream with the gust front. Unfortunately, the velocity in the gust front was too fast to visualize the velocity profile. The strongest wind region is observed in the lower layer behind the horizontal vortex in Figure 4. Such velocity distributions in Case 1 and Case 2 are quite resemble to those of gust fronts observed by [Wakimoto (1982)] and downbursts by [Hjelmfelt (1988)]. The gusty wind maintained 4 and 3 seconds in Case 1 and Case 2, respectively. For Case 3, the temporal velocity change is gradual as shown in Fig.2, then the structure of gust front seems to be diffused streamwise in Fig.4(c). The lifetime of the gust front in Case 3 was more than 5 seconds which is the sampling period.

The gust front of Case 1 maintains its structure up to $X = 2$ m as shown in Fig.4(d), but it collapses and only upper flow is observed at $X = 5$ m in Fig.4(e). The present experiments were made under the neutral condition and the simulated gust front does not have the property of gravity current. Therefore, the horizontal vortex of the gust front diffuses rapidly due to
The present flow field in Case 1 can simulate the actual gust front well in $X < 2$ m.

As shown in table 2, the propagation speeds of the strong wind region and the gust front are 1~3 m/sec. and 2~3.8 m/sec., respectively. The horizontal vortex shown in Figure 5 also flowed downstream at the same speed as that of the gust front in Case 1. The present gust front propagates at 1/6 of the maximum velocity and the horizontal vortex behind it becomes larger. Such tendency is most remarkable in Case 3. The propagation speed is lower than that of the actual gust front, namely $0.67U_{\text{max}}$ [Goff (1976)]. Of course, such fact is also caused by the neutral condition of the present experiment. The present gust front is not accelerated by the gravity force [Simpson(1987)]. If we transfrom from the lifetime to the spatial scale of the...
Table 2: Propagation speed of gust fronts and high speed region

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<td>1.7</td>
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<td>1.9</td>
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Figure 5: Flow pattern visualized with the smoke wire method. $T=0[s]$ is a moment when the gust front reached the wire.

The gust front with the propagation speed of the gust front, the streamwise length of the simulated gust front is 14 m, which corresponds to 22 km in actual scale. Such value is similar to that of the actual gust front observed by a Radar [Wakimoto(1982)].

Figure 6 shows an instantaneous velocity anomaly from the ensemble averaged velocity field. The large anomaly observed near the gust front may be caused by the
fluctuation of the propagation speed. The layer in \( Z = 120 \) to 220 mm and near the floor in \( t < 1.3 \) seconds also have large anomaly. This fact shows that the flow is highly turbulent in these regions. The instantaneous velocity traces, however, show the different patterns between \( Z = 8.2 \) mm and \( Z = 196.8 \) mm as shown in Figures 7 and 8. The velocity fluctuation near the floor is quite random as shown in Figure 7. The high speed wind almost occurs with downflow, and then the momentum flux, \(-\rho u'w'\), has a large positive value. Such event is

![Figure 6: Streamwise velocity anomaly in the lower layer of a gust front.](image)

![Figure 7: Traces of velocity anomaly (a) streamwise velocity fluctuation \( u'\), (b) vertical velocity fluctuation \( w'\), (c) cross correlation \( u'w'\) at \( Z=8.2\) mm](image)

![Figure 8: Traces of velocity anomaly (a) streamwise velocity fluctuation \( u'\), (b) vertical velocity fluctuation \( w'\), (c) cross correlation \( u'w'\) at \( Z=196.8\) mm](image)
referred as ‘sweep’, i.e., the downward motion of the high momentum fluid [Willmarth and Lu(1972)]. The damages by downbursts and gust fronts apt to localize in far smaller area than the scale of the those gusty wind [Fujita and Wakimoto(1981)]. The sweep may be one of origins of such localization.

The wave traces at $Z = 196.8$ mm clearly show periodic wavy motion in spite of large turbulence intensity in Figure 8. The wavy motion may correspond to the Kelvin-Helmholtz instability wave occurring in the upper stably stratified shear layer of a gravity current [Simpson(1987)]. The simulated gust front also realizes the K-H instability wave, despite under the neutral condition without stratification.

Figure 9 shows power spectra of velocity fluctuation at $Z = 8.2$ mm and $Z = 196.8$ mm. The spectra have clear inertial subrange following the $-3/5$ law at both the heights, which shows that the turbulence is fully developed in these flow fields. The peak at $f = 16$ Hz shows the periodic wavy motion due to K-H instability.

Conclusions

The multi-fan wind tunnel was confirmed to easily simulate many characteristics of gust fronts; such as velocity profile, horizontal vortex, K-H instability and so on. We need some improvements for the velocity profile near the peak and downstream evolution, but our simulated flow will be helpful to investigate the turbulent structure of gust fronts and wind load to structures by gusty wind.

References


