Proceedings of the Eighth Asian Congress of Fluid Mechanics
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# VORTICITY MANIPULATION AS AN EFFECTIVE MEANS FOR AERODYNAMIC NOISE SUPPRESSION

Michio Nishioka
(Osaka Prefecture University College of Engineering, 1-1, Gakuen-cho,
Sakai, Osaka, 599-8531, Japan)

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(Department of Aerospace Engineering, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan)

**ABSTRACT:** We have been working on the problem of aerodynamic noise suppression. For the case of the noise caused by subsonic flow past solid body it is the vorticity fluctuations that govern the quadrupole and dipole sources. To suppress the aerodynamic noise it is therefore quite reasonable to manipulate the near-wall vorticity field and thus to alleviate the unsteady vortical motions. What we have proposed for manipulating the near-wall flow in this sense is to cover the surface of solid body with what we call pile fabric(s), namely, fluffy cloth(s) with high density, fine fibers like fur or down. The proposed method has been developed for constructing Railway Technical Research Institute's Large-Scale Low-Noise Wind Tunnel, and we have succeeded to cut the background noise in the test section down to 75dB(A) at 300km/h (83m/s) under the open-jet flow condition. The present paper summarizes results of our recent studies on the problem of aerodynamic noise suppression. Important results obtained from the vorticity manipulation using pile fabrics are described for the case of circular cylinder wake and for turbulent boundary layer under zero pressure gradient to emphasize the proposed vorticity manipulation as a powerful means for aerodynamic noise suppression.

## Ⅰ. INTRODUCTION

The present paper is concerned with the aerodynamic noise caused by subsonic flow past solid body. Our main interest is focused on the problem of aerodynamic noise suppression. The problem presents a real challenge for researchers in the field of turbulence control. Indeed, for the noise suppression, we need skillful turbulence management or control, as it is vortical motions that govern the aerodynamic sound at subsonic speeds. In other words, it is most important to alleviate such vortical motions. Focusing attention on this point, the present paper discusses a new method for reducing the aerodynamic noise caused by the flow past a solid body. The method has been developed in a project research aimed at constructing a quiet wind tunnel[1,2], as described below.

## Ⅱ. LARGE-SCALE QUIET WIND TUNNEL

In 1996 Railway Technical Research Institute (RTRI) in Japan constructed a large-scale quiet wind tunnel to facilitate experimental researches of aerodynamic and aeroacoustic problems involved with high-speed trains like the Shinkansen (bullet trains). The wind tunnel is really of large scale as shown in Fig.1. The anechoic test section room is 22m × 20m in area, and under the open-jet operating condition the collector (namely, the inlet of the diffuser duct for return flow to the fan) is located 8m downstream from the nozzle exit, whose cross section is 3.0m in width and 2.5m in height. The maximum operating wind speed is 400km/h (111m/s) for the open-jet operation, and 300km/h (83m/s) for the closed duct operation. The most challenging among various performance requirements given by RTRI to the maker, Mitsubishi Heavy Industries, Ltd. was to suppress the background noise down to 75dB(A) at 300km/h (measured at a selected reference point, 1.0D downstream from the nozzle exit and 1.5D sideways from jet center axis, D being the reference nozzle diameter) under the open-jet condition. Although eventually achieved, the cited low-noise requirement was a real challenge, felt initially almost impossible to accomplish, considering that the background noise level of then existing wind tunnels was beyond 85dB(A) even at 280km/h. The present author was asked to join the project during the initial design phase and could have a good opportunity of studying the aerodynamic sound problem.

Generally speaking, the largest noise source is the fan which generates the flow through the tunnel. Today, however, it is not so hard to prevent the fan noise from propagating into the test section room. In fact, for the case of the constructed RTRI wind tunnel, the fan noise is almost perfectly reduced by using a pair of silencers installed in the midway ducts, one between the fan and the nozzle, the other between the collector and the fan. Sound absorbing porous materials are also used for the duct walls effectively.

During the initial design phase we played using small-scale models in order to identify the dominant sound sources contributing to the background noise. In accordance with our prior inference, we found that the nozzle wall and the collector wall regions were the site where strong aerodynamic sound was generated to dominate the background noise. It should be emphasized that we had to kill the aerodynamic sound at its generation site although no such technique had been developed nor proposed. With the understanding noted earlier in the introduction, we tried several approaches to develop useful methods for alleviating unsteady vortical motions near the nozzle and collector walls.

Eventually, we came up with two key ideas. One is the use of pile fabrics for covering the nozzle and collector walls as indicated in Fig.1. The noise reducing effect of the pile fabrics is the main subject of the present paper and will be discussed later in detail. Here, we use the term "pile fabric(s)" to describe fluffy cloth(s) with fine and high density fibers like fur or down. The other idea is to control the jet-entrained flow so that it runs smoothly along the collector wall. It is a unique feature of the RTRI wind tunnel that the outside air can enter the test section room through penetrating paths with silencers around the nozzle, and a part of the tunnel flow can escape from the midway duct through breathers (release outlet) to the outside. The rate of the secondary flow communicating with the outside may be adjusted by the breather opening so as to control the jet-entrained flow into the collector.

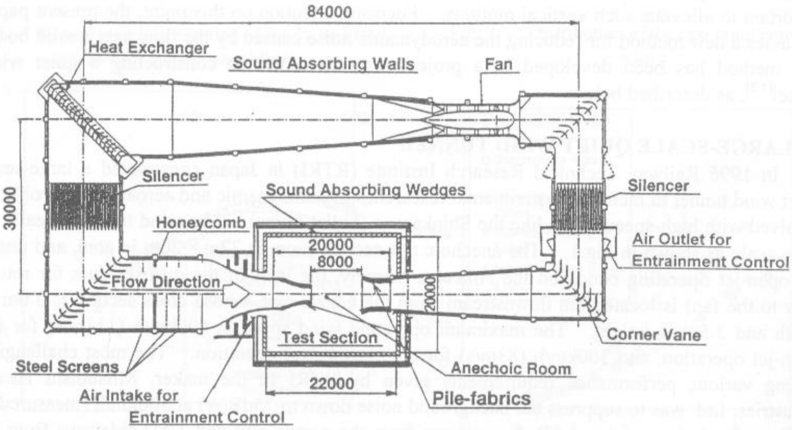



Fig.1 RTRI Quiet Wind Tunnel.

With these effective means for alleviating the unsteady vortical motions, the RTRI wind tunnel has been verified to attain the required low background noise performance under open-jet condition. The background noise is cut down to 42, 55, 75 and 86 dB(A) at 100, 200, 300 and 400 km/h respectively as shown in Fig.2. The noise level increases in proportion to the 8th power of the flow speed beyond 200km/h. We will discuss this point later. For more details of RTRI wind tunnel and the performance, see Nishimura et al[1].

## III. AERODYNAMIC NOISE SOURCES

The theory of aerodynamic sound shows Lighthill's quadrupole term to be the source of noise in an unbounded flow. With a solid body placed in the flow a distribution of dipoles appears over the whole surface of the body, their strength density being the stress (or the pressure) exerted on the body surface. For the theory of aerodynamic sound see, for instance, Curle[3] and Powell[4]. For the case of wind tunnel of open-jet type, Fig.3 illustrates the important aerodynamic noise sources. The main noise source at the nozzle is considered to be pressure fluctuations associated with unsteady vortical motions in the nozzle-wall turbulent boundary layers. Also important are the phenomena occurring at and immediately downstream of the nozzle exit, namely the shedding of boundary layer eddies and the vortex formation in the shear layers due to the instability of the jet mixing layers.

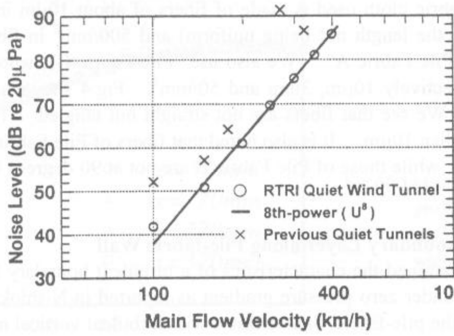



Fig.2 Wind tunnel background noise.

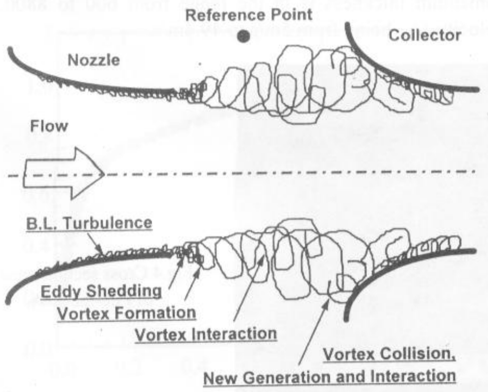



*Fig.3 Aerodynamic noise* sources in open-jet type wind tunnel.

On the collector wall strong pressure fluctuations may be induced when vortices having formed in the mixing layer of the free jet collide with the wall. When a strong vortex approaches the collector wall, the anti-phase vorticity will be generated on the wall to roll up into a vortex. The two vortices no doubt interact with each other. These phenomena characterize the aerodynamic noise sources on the collector wall. Vortex formations and interactions occurring in the free jet work as quadrupole sources. Their contributions are important at high speeds. The quadrupole and dipole sources are thus governed by the vorticity fluctuations. In order to suppress the aerodynamic noise, it is therefore quite important to manipulate the near-wall vorticity fluctuations and then alleviate unsteady vortical motions. As already described, what we have proposed for manipulating the near wall flow in this sense is to cover the body surface with pile fabrics. Such a body surface will be called a pile-fabric surface (or wall). In the followings we will show that for the case of pile fabric wall the near-wall vorticity can be much reduced as compared with the case of smooth wall.

## IV. MANIPULASTION OF NEAR-WALL VORTICITY BY USING PILE FABRICS

To see how the pile-fabric wall can manipulate the near-wall vorticity field we studied experimentally (1) turbulent boundary layers and (2) circular cylinder wakes.

### 4.1 Pile fabrics

The pile fabric cloth used is made of fibers of about 10μm in diameter, 10mm in average length (actually, the length not being uniform) and 500/mm$^2$ in fiber density. This pile-fabric cloth is called "Pile Fabric A". We also use "Pile Fabric B", whose fiber diameter, length and density are respectively 10μm, 3mm and 50/mm$^2$. Fig.4 shows a cross section photograph of Pile Fabric A. We see that fibers are not straight but tangled. This makes the effective fiber diameter larger than 10μm. It is also noted that fibers of Pile Fabric A are planted nearly normal to the base cloth, while those of Pile Fabric B are not at 90 degrees but much inclined to the base cloth.

### 4.2 Turbulent Boundary Layer along Pile-fabric Wall

We first examined the characteristics of a turbulent boundary layer along a pile-fabric wall (Pile Fabric A) under zero pressure gradient as reported in Nishioka and Hirai[5]. The purpose was to see how the pile-fabric wall interacts with turbulent vortical motions and modifies the near wall vorticity field as compared with the corresponding smooth wall case. The examined Reynolds number based on the momentum thickness is in the range from 600 to 8800, the corresponding range of freestream velocity $U_\infty$ being from 5m/s to 49.4m/s.

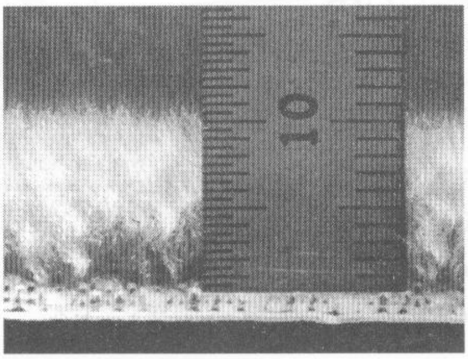



Fig.4 Cross section view of Pile-fabric A.

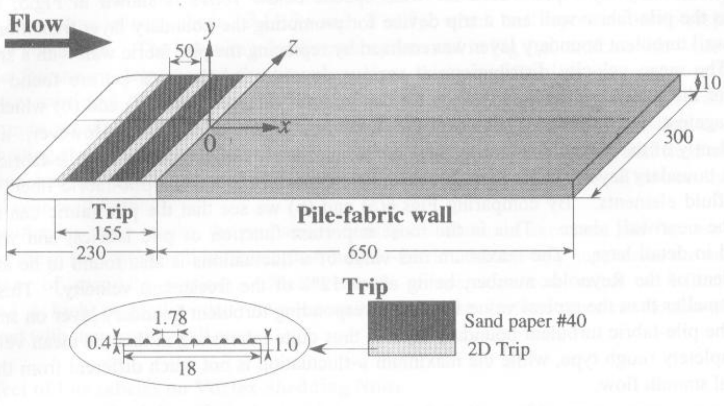



Fig.5 Boundary layer plate covered with pile fabric (Dimensions in mm).

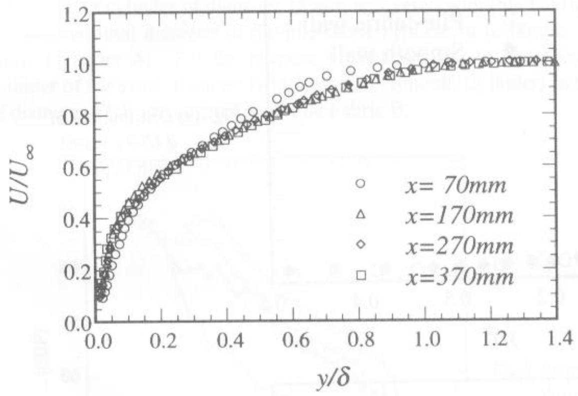



Fig.6(a) Mean velocity profiles for the case of pile fabric wall.

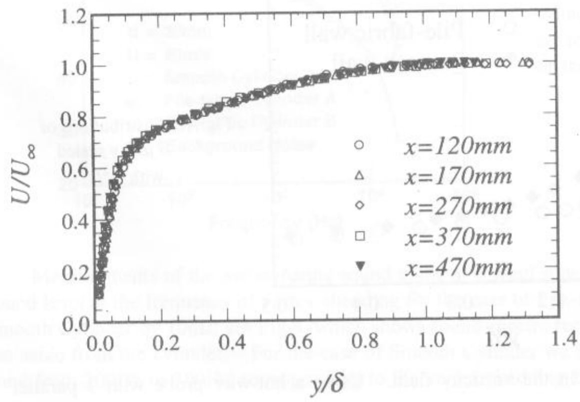



Fig.6(b) Mean velocity profiles for the case of smooth wall.

The boundary layer plate used for wind speeds below 10m/s is shown in Fig.5, which illustrates the pile-fabric wall and a trip device for promoting the boundary layer transition. A smooth wall turbulent boundary layer was realized by replacing the pile fabric wall with a smooth plate. The mean velocity distributions at various downstream distances ($x$) are found to be similar for the pile-fabric wall as well as for the smooth wall, see Figs.6(a) and (b) which plot $U/U_\infty$ against $y/\delta$, where $\delta$ denotes the boundary layer thickness. However, almost independently of the Reynolds number, they are of completely rough type for the pile-fabric-wall turbulent boundary layer. This is quite reasonable considering that the pile-fabric fibers exert drag on fluid elements. By comparing Figs.6(a) and (b) we see that the pile fabric can much reduce the near-wall shear. This is the most important function of pile fabrics, and will be discussed in detail later. The maximum rms value of $u$-fluctuations is also found to be almost independent of the Reynolds number, being about 12% of the freestream velocity. This is a little bit smaller than the typical value for the corresponding turbulent boundary layer on smooth wall. The pile-fabric turbulent boundary layer is thus quite interesting in that the mean velocity is of completely rough type, while the maximum $u$-fluctuation is not much different from that of the typical smooth flow.

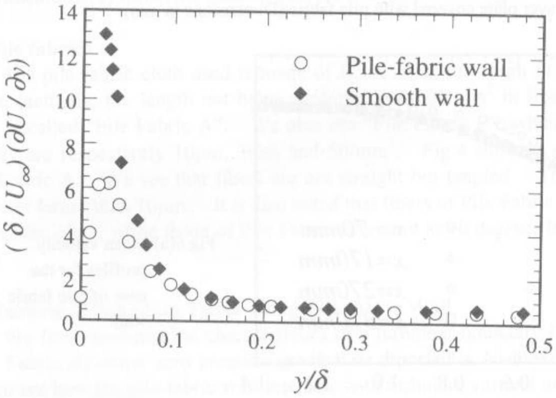



Fig.7(a) Distributions of $\partial U / \partial y$ scaled with $U_\infty/\delta$.

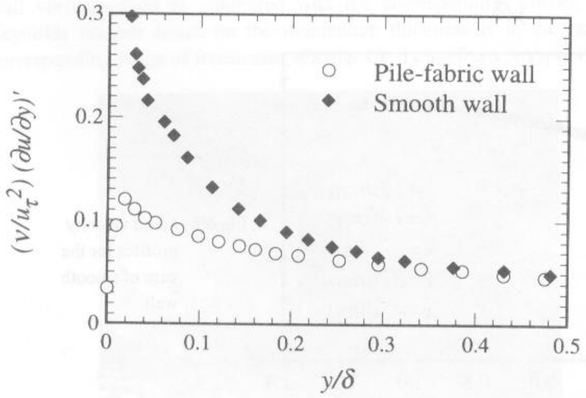



Fig.7(b) Distributions of $\partial u / \partial y$ scaled with $u_\tau^2/\nu$.

Our main interest here is in the vorticity field. Using a hot-wire probe with 3 parallel sensors separated in the normal-to-wall direction ($y$), we measured the time mean velocity shear and the fluctuating velocity shear, $\partial U/\partial y$ and $\partial u/\partial y$, which well represent the corresponding spanwise vorticities. The hot-wire measurements presented in Fig.7(a) indicate that when scaled with the freestream velocity and the boundary layer thickness, the time mean near-wall shear (spanwise vorticity) is less than 20% of that of the corresponding smooth-wall flow. Furthermore, we observed similar features for the fluctuating shear, see Fig.7(b), where rms value of fluctuating shear is scaled with the viscous scale $u_\tau^2/\nu$. It can be imagined that fluid elements easily run into the pile-fabric wall and come out with reduced velocities. This results in the reduced near-wall vorticity.

Confirming these results, the probability density distributions, skewness and flatness factors of $u$ and shear fluctuations all indicated that the pile-fabric wall strongly suppresses the near-wall generation of spanwise vorticity. Measurements of spanwise correlation of $u$-fluctuations indicated a high possibility that the near-wall streamwise vortices become double-sized as compared with the smooth wall case.

### 4.3 Effect of Pile fabrics on Vortex Shedding Noise

We next examined the effect of pile fabrics on the formation of Karman vortex street behind a circular cylinder and the related aerodynamic sound as reported in Nishioka and Kume [6]. A solid circular cylinder of diameter 18 mm is covered with Pile Fabric A as mentioned above. So the nominal total diameter of the pile-fabric cylinder, $d$ is 38mm. This cylinder is called Pile-fabric Cylinder A. For the purpose of comparison, we examined the flow around a smooth cylinder of the same diameter (which is called Smooth Cylinder) as well as Pile-fabric Cylinder B of diameter 42.5mm, covered with Pile Fabric B.

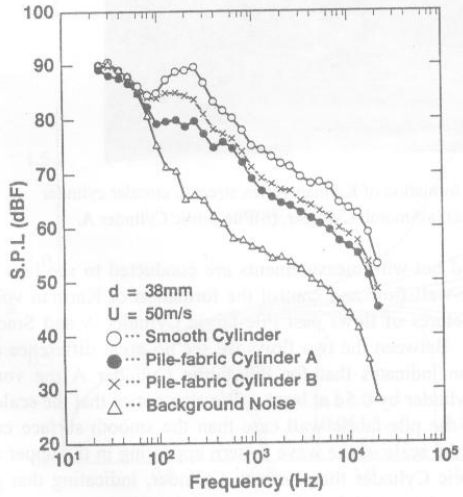



Fig.8 Aerodynamic noise caused by vortex shedding from a circular cylinder. Pile-fabric Cylinders are compared with smooth one on their noise spectra.

Measurements of the aerodynamic sound made at a wind speed of 50m/s indicates that the sound level at the frequency of vortex shedding for the case of Pile-fabric Cylinder A is less than Smooth Cylinder by 10dB: see Fig.8, which shows sound spectra recorded by a microphone set at 1m aside from the cylinder. For the case of Smooth Cylinder we see a blunt spectral peak in a band from 200Hz to 300Hz corresponding to the vortex shedding frequency, while such a blunt peak almost disappears for Pile-fabric Cylinder A. For the case of Pile-fabric Cylinder B the total diameter is larger than Smooth Cylinder by 10%. The fiber density of Pile Fabric B is not so high as Pile Fabric A. Nevertheless it can also reduce the vortex shedding noise by about 4dB as compared with Smooth Cylinder. It should be further stressed from Fig.8 that the pile fabrics examined are effective for a very wide frequency range up to 20kHz in reducing the noise.

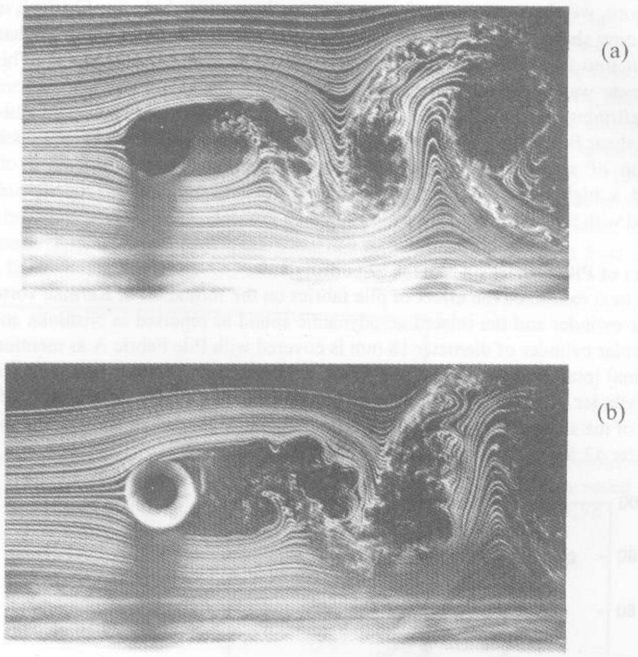
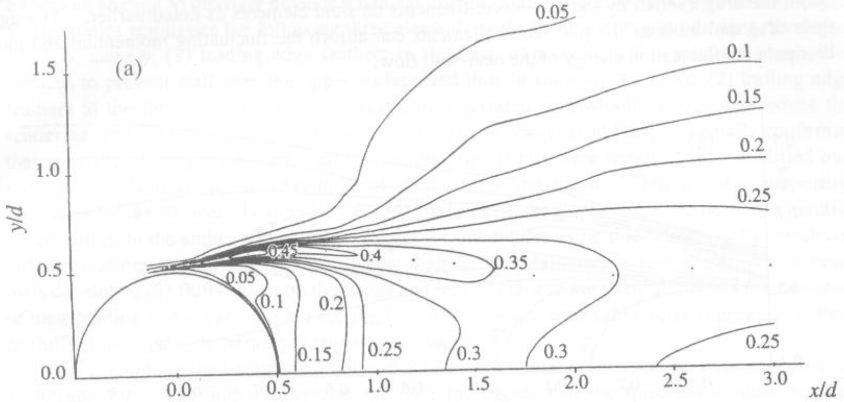



Fig.9 Smoke-wire visualizations of formation of Karman vortex street in circular cylinder wake at Reynolds number 8000:(a)Smooth Cylinder, (b)Pile-fabric Cylinder A.

Smoke-wire flow visualizations and hot-wire measurements are conducted to see how the pile-fabric wall can manipulate the near-wall flow and control the formation of Karman vortex street. Fig.9 compares visualization pictures of flows past Pile-fabric Cylinder A and Smooth Cylinder at a Reynolds number 8000. Between the two flows we see no great difference at a glance. However, a closer examination indicates that for Pile-fabric Cylinder A the vortex formation length is lager than Smooth Cylinder by 0.5d at least. We also notice that the scale of the vortex at its formation is larger for the pile-fabric wall case than the smooth surface case. Furthermore, it is important to note that the scale of the wave pattern appearing in the upper and lower shear layers is larger for Pile-fabric Cylinder than Smooth Cylinder, indicating that pile fabrics surely work to thicken the boundary layer and then the separated shear layer.

Hot-wire measurements made at a wind speed around 5m/s clearly show that these two flows are quite different. First compare Figs.10(a) and (b) which show distributions of rms *u*-fluctuations in the near-wake region of Smooth Cylinder and Pile-fabric Cylinder A. It is remarkable that the near wall flow is very calm for the case of Pile-fabric Cylinder A. In fact the maximum u-fluctuation is about 30% of the the freestream velocity, occurring at $x/d$=2.5 for

Pile-fabric Cylinder A, while it exceeds 45% at $x/d$=0.38 for Smooth Cylinder. Compare constant-intensity lines of 5, 10 and 15% for the two cases. The velocity fluctuations in the near wall region are really calm for the case of the pile-fabric cylinder. In Figs.10(a) and (b) the $y/d$ position where the rms $u$-fluctuation become maximum at each $x/d$ station (namely, the point of y maximum of $u$-fluctuation) is represented by a small dot. It is a well-known fact that in separated shear layers as well as in wakes the point of $y$-maximum of $u$-fluctuation coincides with the point of $y$-maximum of time-mean shear. By observing these dots in Figs.10(a) and (b) we see that the separated shear layer is much thicker and thus the shear is much weaker for the case of pile-fabric cylinder compared with the smooth cylinder case. This fact has been confirmed by hot-wire measurements, though the data are not shown here.



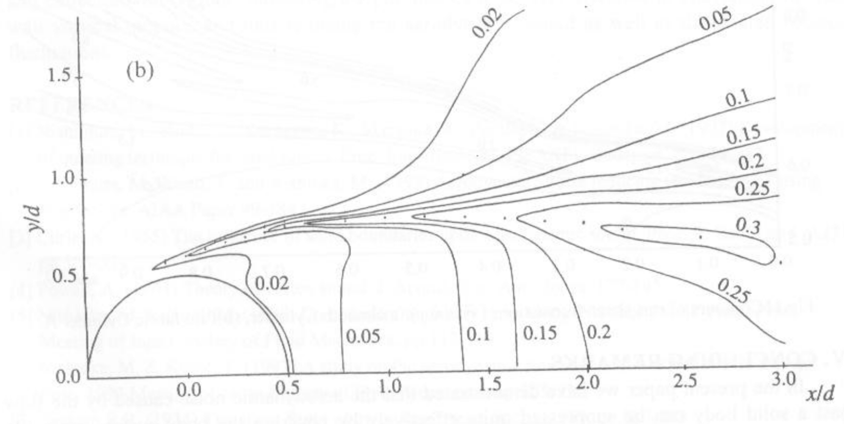




Fig.10 Contours of rms u-fluctuations in formation region of Karman vortex street: (a)Smooth Cylinder, (b)Pile-fabric Cylinder A.

Fig.11 shows distributions of rms shear-fluctuations for the cases of Pile-fabric Cylinder A and Smooth Cylinder. It is really surprising that the streamwise position of the maximum shear fluctuation is located at about $x/d=1$ for Pile-fabric Cylinder A, while it is at about $x/d=0$ (at the cylinder shoulder) for Smooth Cylinder. The maximum rms value of shear-fluctuations is 4 for Pile-fabric Cylinder A and it is 12 for Smooth Cylinder, when scaled with the freestream velocity and cylinder diameter. It is further noted that the nondimensional rms value does not exceed 2 at $x/d=0$ (at the cylinder shoulder) for Pile-fabric Cylinder A. In accordance with the observations obtained for the turbulent boundary layer along Pile-fabric wall, these results demonstrate that the pile fabrics effectively reduce the time-mean and fluctuating near-wall vorticities. From these findings and Fig.8 we have learned that the aerodynamic sound is closely related to vorticity fluctuations.

As for the mechanism by which pile fabrics reduce the near-wall vorticity, the key is no doubt the drag exerted by the pile-fabric filaments on fluid elements as noted earlier. Through their drag and motions the pile fabric filaments can absorb the fluctuating momentum and thus dissipate the fluctuation energy of the near-wall flow.

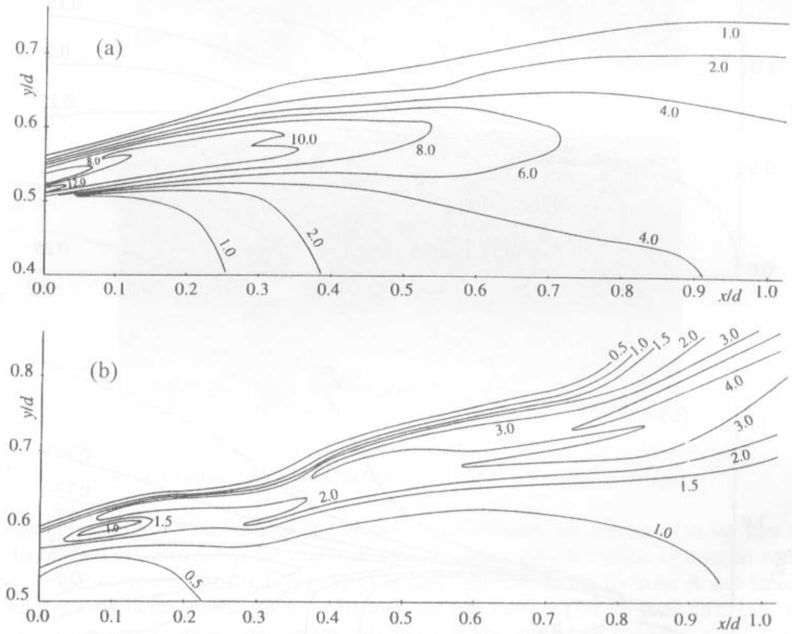



Fig.11Contours of rms shear-fluctuations ( $\partial u/\partial y$):(a)Smooth Cylinder, (b)Pile-fabric Cylinder A.

## V. CONCLUDING REMARKS

In the present paper we have demonstrated that the aerodynamic noise caused by the flow past a solid body can be suppressed quite effectively by covering the body surface with pile fabrics, that is, fluffy cloths made of high density, fine fibers like fur or down. Through the design and construction of a large scale quiet wind tunnel the proposed method is verified to be a powerful means for aerodynamic noise suppression.

When considering the aerodynamic effects of pile fabrics we may assume each pile-fabric filament to exert drag as if it were a solid cylinder placed in a low-Reynolds number flow. With this model we have derived the equations of motions. For the case of laminar boundary layer along pile-fabric wall, we have solved the modified boundary layer equations with the additional drag term. The corresponding experiments are also conducted to compare the velocity distributions with the solution. Preliminary results show a good agreement. Through those efforts we hope to obtain a reasonable model for the aerodynamic effects of the pile-fabric wall and open the way for numerical simulations of the turbulent boundary layer over the pile-fabric wall and the flow around the pile-fabric cylinder.

Here it should be cited that Graham[7], Kroeger et al[8] and Lilly[9]studied the silent flight of owls in an attempt to discover novel mechanism to reduce the noise associated with aircraft flight. These studies emphasize the following three elements as the noise suppression devices developed by owls, namely, (1) leading edge feathers in the form of a comb, which generate streamwise vortices to prevent stall over the upper surface and thus to suppress the noise, (2) trailing edge feathers in the form of a fringe, which resemble a serrated or sawtoothed edge and reduce the scattering, and (3) fluffy down on the wings and legs. Kroeger et al[8] experimentally confirmed that when the leading edge comb and the trailing edge fringe were removed such modified owl radiated sounds as strong as other birds of similar mass and speed. Thus we have supporting evidences for the devices (1) and (2). On (3) fluffy down, however, there has been no scientific observations, to the author's knowledge, except for our studies using pile-fabrics. The results of our observations strongly suggest that during their long evolutionary period of millions of years owls developed (3) fluffy down on the wings and legs to achieve the silent flight, the quintessence of their hunting technique. Again see Fig.8, which shows a remarkable noise suppression effect of fluffy down in a wide frequency range up to 20kHz.

In Fig.2 we see the background noise of RTRI wind tunnel to increase with the 8th power of flow velocity. The author interprets this fact to suggest that the quadrupole noise sources become dominant as a results of remarkably reducing the dipole noise sources in the nozzle wall and collector wall regions, indicating the pile fabrics to be very effective in alleviating the near-wall vortical motions and thus reducing the aerodynamic sound as well as the related pressure fluctuations.

## REFERENCES


[1] Nishimura, M., Kudo, T., Nakagawa, K., Maruoka, A., Zenda, Y. & Nishioka, M. (1997) Development of quieting technique for wind tunnel. Proc. Inter-Noise 97, OPAKFI, Budapest, pp.379-382.

[2] Nishimura, M., Kudo, T. and Nishioka, M. (1999) Aerodynamic noise reducing techniques by using Pile-fabrics. AIAA Paper 99-1847.

[3] Curle, N. (1955) The influence of solid boundaries upon aerodynamic sound. Proc. R. Soc. Lond. A231, pp.505-514.

[4] Powell, A. (1964) Theory of vortex sound. J. Acoust. Soc. Am., 36, pp.177-195.

[5] Nishioka, M. & Hirai, M. (1996) On turbulent boundary layer along Pile-fabric wall. Proc. 1996 Meeting of Japan Society of Fluid Mechanics, pp.117-118.

[6] Nishioka, M. & Kume, T. (1997) A study on the aerodynamic noise reduction effect of Pile-fabrics. Proc. 1997 Meeting of Japan Society of Fluid Mechanics, pp.225-226.

[7] Graham,R.R. (1934) The silent flight of owls. Roy. Aero. Soc. J. , 289, pp.837-843.

[8] Kroeger,R.A., Grushka,H.D. and Helvey, T.C. (1971) Low speed aerodynamics for ultra-quiet flight. AFFDL TR71-75, pp.1-155.

[9] Lilley, G..M. (1998) A study of the silent flight of the owl. AIAA Paper98-2340.