Suppression of Swirl in a Conical Diffuser By Use of J-Groove

KUROKAWA J., KAJIGAYA A., MATUSI J., IMAMURA H.
Dep. of Mechanical Eng., Yokohama National University, Yokohama, Japan

ABSTRACT

In order to control and suppress a draft tube surge in a Francis turbine, a new passive device using shallow grooves machined on a casing wall is proposed. To reveal the possibility and the effect of the present device on controlling and reducing the swirl strength of a runner outlet flow, a steady rotational flow in a conical diffuser of divergent angle of 30° is studied experimentally. The results show that the shallow grooves with adequate dimensions can reduce the swirl rate of the main flow by about 85% of the inlet swirl rate. The additional hydraulic loss is negligible and the static pressure becomes much uniform over the whole outlet section, though the range of the forced vortex core with reverse flow becomes larger around the center axis.

The above considerable effect of shallow grooves is caused by the groove flow which is driven by the pressure gradient of the main flow. The flow loses the angular momentum when entering into the groove, and absorbs the angular momentum of the main flow by mixing when leaving from the groove.

1. INTRODUCTION

In the part load operation of a Francis turbine, a vortex rope appears in the draft tube and causes pressure fluctuation. The pressure fluctuation becomes violent, when cavitation is induced in the vortex core (Nishi et al. 1980, Fisher et al. 1980). This phenomena is called as the draft tube surge, and often induces severe power swing in an electric generating system. To alleviate the pressure fluctuation and to develop an effective method of controlling and suppressing this anomalous phenomena, various attempts have been made (Grein 1980, Nishi 1996). An active control device such as air injection and a passive control device such as fins installed in the inlet cone of a draft tube are popular means. However, active devices demand complicated mechanisms; utilize additional machinery and eventually decrease the overall efficiency and reliability. Passive devices proposed so far also require additional apparatus such as fins or cylinder and tripod (Grein 1980) and eventually decrease the reliability.

The present authors have developed a very simple method of controlling and suppressing a swirl of rotational flow by use of shallow grooves machined on a casing wall. Radial shallow grooves of proper dimension mounted on a diffuser wall could suppress a rotating stall in a vaneless diffuser perfectly for the entire flow range, and the mechanism of suppressing a rotating stall was made clear theoretically (Kurokawa et al. 1997). This device could also suppress a performance curve instability characterized by a positive slope of head-capacity curve perfectly over the whole operating range of a mixed flow pump (Kurokawa et al. 1999). If the swirl strength of a runner outlet flow could be controlled and reduced in a Francis turbine, the draft tube surge might be suppressed. The above device should be effective to suppress a draft tube surge, as it is caused by the swirl of a runner outlet flow.

The present study is thus aimed to newly propose a very simple common passive device of suppressing a draft tube surge utilizing shallow grooves machined on the casing wall of a draft tube. The main concern is to reveal the possibility and the effect of shallow grooves on controlling and reducing the swirl strength of a runner outlet flow, and thus a steady rotational flow in a conical diffuser is measured using air flow instead of water flow in a draft tube.

As a strong flow is induced in the shallow grooves due to a pressure gradient, it is of key importance to provide the grooves parallel to the direction of the pressure gradient. Such shallow grooves machined parallel to the pressure gradient are termed as "**J-groove**". Hereafter groove means J-groove.

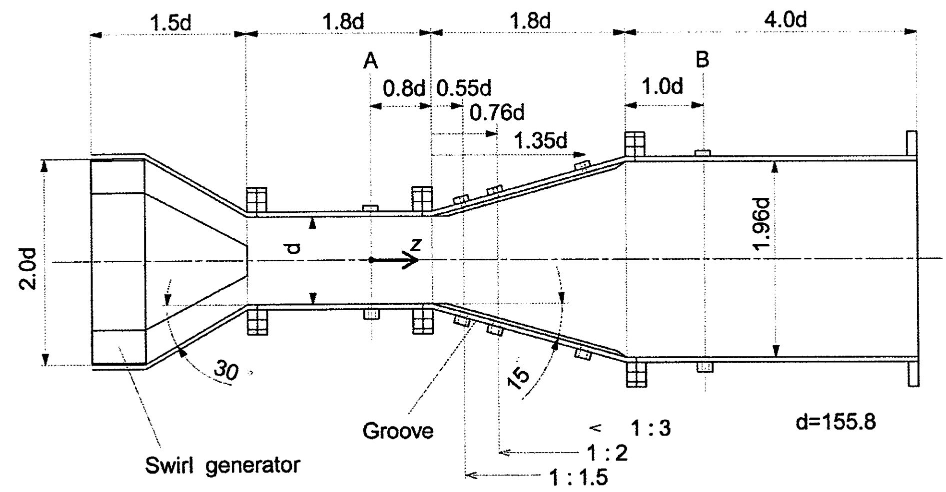


Fig. 1 Conical diffuser test stand

2. MECHANISM OF SUPPRESSING SWIRL BY J-GROOVE

In a groove mounted parallel to the pressure gradient on a casing wall in the rotating flow field, a strong reverse flow is induced in the groove due to the pressure gradient of the main flow. This reverse flow makes the swirl of the main flow reduce considerably. Even though the groove is very shallow such as h=1mm, the increase in the main flow angle due to both the decrease of swirl velocity and the increase of radial velocity is significant.

Experimental findings and theoretical considerations(Kurokawa et al. 1997) revealed that the remarkable effects of J-groove are caused by the following two mechanisms; one is a remarkable decrease in tangential velocity at the diffuser inlet owing to mixing between the main flow and the groove reverse flow, and the other is a remarkable increase in radial velocity due to the groove reverse flow. Both effects have the same contribution to increase the flow angle.

3. TEST APPARATUS AND PROCEDURE

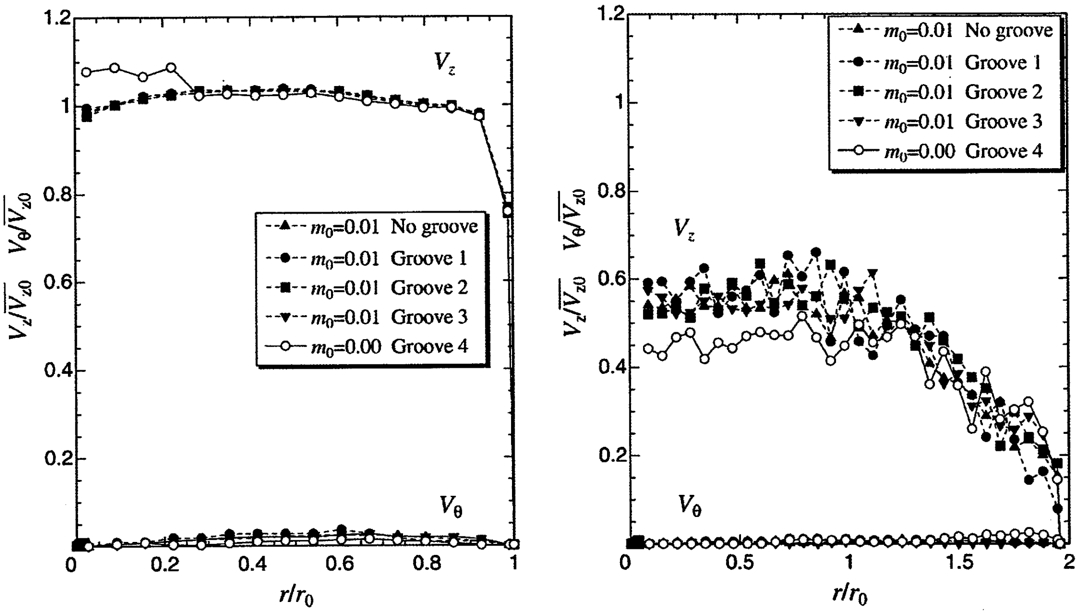
The present study is aimed to reveal the effect of J-groove on controlling the swirl strength in a divergent channel. For this purpose the swirling flow in a conical diffuser is studied using the test stand shown in Fig. 1. To produce a swirl flow an axial flow impeller is set at about 3.3d upstream of the diffuser inlet, where d (=156 mm) is the inlet pipe diameter. The supplemental blower is arranged at far upstream of the divergent channel to change the flow rate widely. At the downstream of the conical diffuser is connected a straight pipe of the length 4.0 d. The angle of divergence α of the conical diffuser is 30° and the radius ratio of the inlet pipe to the outlet pipe is 1.96.

In order to control and suppress the swirl of the main flow, four kinds of shallow grooves are provided by attaching thin rubber plates of which thickness is equal to the groove height h over the whole wall of divergent channel as shown in Table 1. In the Grooves 1, 2 and 3 the groove sectional area wxh is kept

Table 1 Dimensions of the J-groove tested

	w [mm] x h [mm] x l [mm] x n
Groove 1	5 x 4 x 288 x 30
Groove 2	10 x 2 x 288 x 30
Groove 3	20 x 1 x 288 x 20
Groove 4	(11.3~26.9) x 4 x 288 x 30

□□ w : width, h : height , l : length, n : number constant.



(a) Inlet section A (b) Outlet section B

Fig. 2 Velocity distributions in the inlet and outlet sections of diffuser in the no swirl case (m_0=0)

In the Groove 4 the rubber plate attached has the dimension of 5 mm^w×4 mm^h×30^n, and then the groove dimensions are 11.3 mm^w×4 mm^d×30^n at the inlet of the divergent channel and 26.9 mm^w×4 mm^d×30^n at the outlet.

The time-averaged velocity distributions at four sections including the inlet section A and the outlet section B indicated in Fig. 1 are measured by traversing a 3-hole Pitot probe set perpendicular to the wall. The wall static pressure distribution was also measured at 5 points in the stream direction. The test Reynolds number $Re = \overline{V_{z0}}\, d/\nu$ based on the mean inlet axial velocity $\overline{V_{z0}}$ and the inlet pipe diameter d is (1.9~3.1)x10^5.

The swirl strength is evaluated by the swirl rate m defined by the following equation;

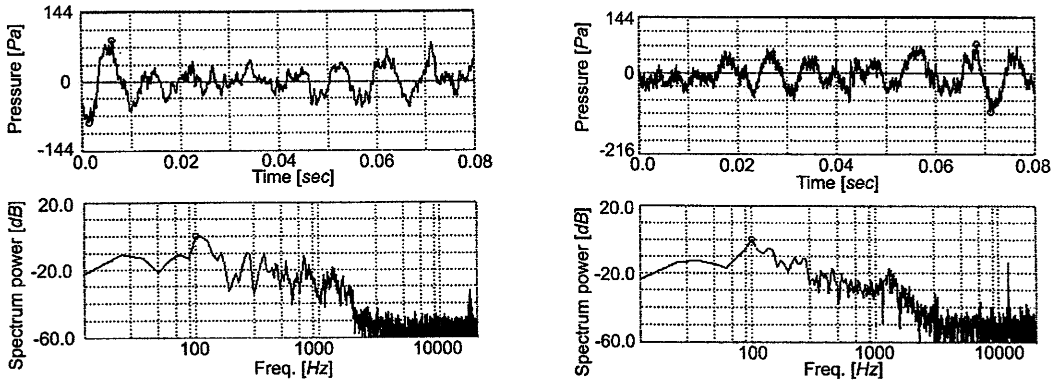
$$m = \int V_\theta V_z r^2 dr \Big/ \frac{d}{2} \int V_z^2 r dr \tag{1}$$

where, r, V_z and V_θ are the radius, the axial and tangential velocity components, respectively. The swirl rate in an actual draft tube takes the value of (1.0~2.0) (Nishi et al. 1982), when the draft tube surge occurs under the low cavitation number. Four kinds of swirl strength m are then selected to reveal the effect of J-grooves by changing the impeller speed from 0 to 1315 *rpm* and the mean axial velocity $\overline{V_{z0}}$ from 18 to 29 *m/s*. The corresponding swirl strength measured at the inlet section A is m_0 = 0, 0.64, 1.10 and 1.88 in average.

4. RESULTS AND DISCUSSION

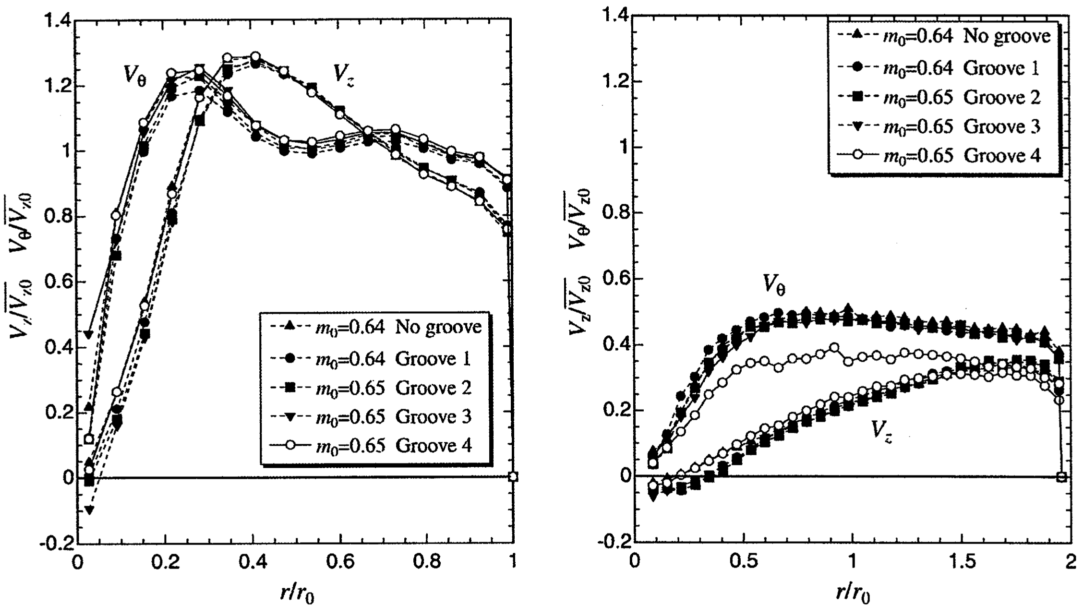
4.1 Velocity distribution

The measured velocity distributions in the inlet section A and the outlet section B are compared in Fig. 2 for the no swirl case (m_0= 0). The velocity profiles of the grooved case is also compared. Though the 300 data obtained in 30 sec. were time-averaged for each plot, the scatter of the axial velocity data V_Z in the outlet section is very large as shown in Fig. 2(b),



(a) No swirl case(m_0=0) (b) Largest swirl case(m_0=1.88)

Fig. 3 Pressure fluctuation in the outlet section B in the case of no groove



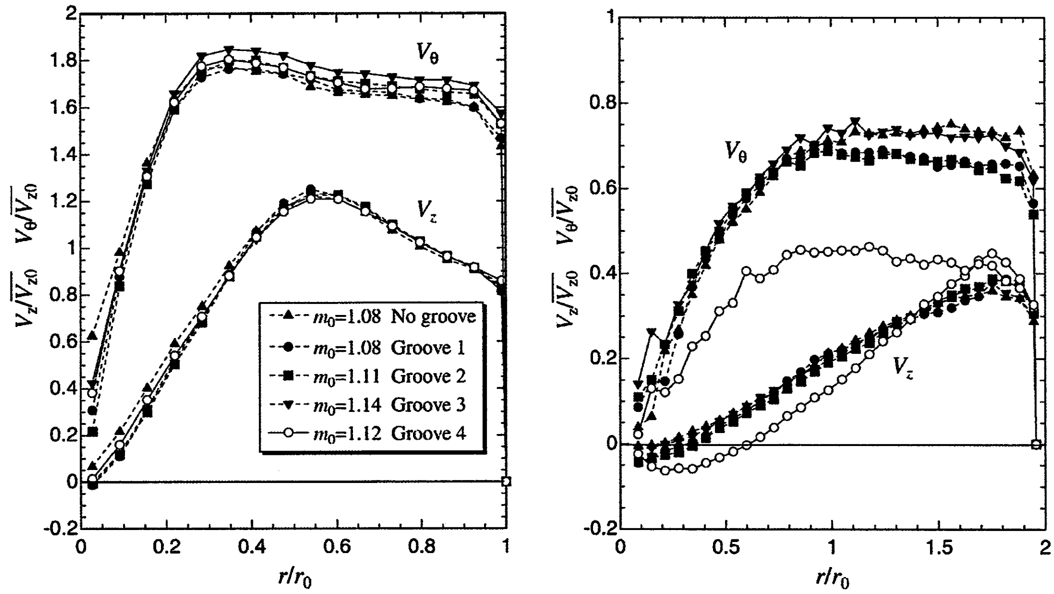
(a) Inlet section A (b) Outlet section B

Fig. 4 Velocity distributions in the inlet and outlet sections of diffuser in the case m_0= 0.64

which means that the outlet flow is unsteadily changing due to unsteady flow separation. To show the flow unsteadiness, the pressure fluctuation and the frequency analysis at the diffuser outlet section A is illustrated in Figs. 3(a) and (b). It is clearly seen that the peak frequency of 100 Hz is dominant in both figures. This fluctuation is observed through all measurements in the grooved case and the no groove case with swirl or no swirl, and might be caused by unsteady flow separation in a divergent channel.

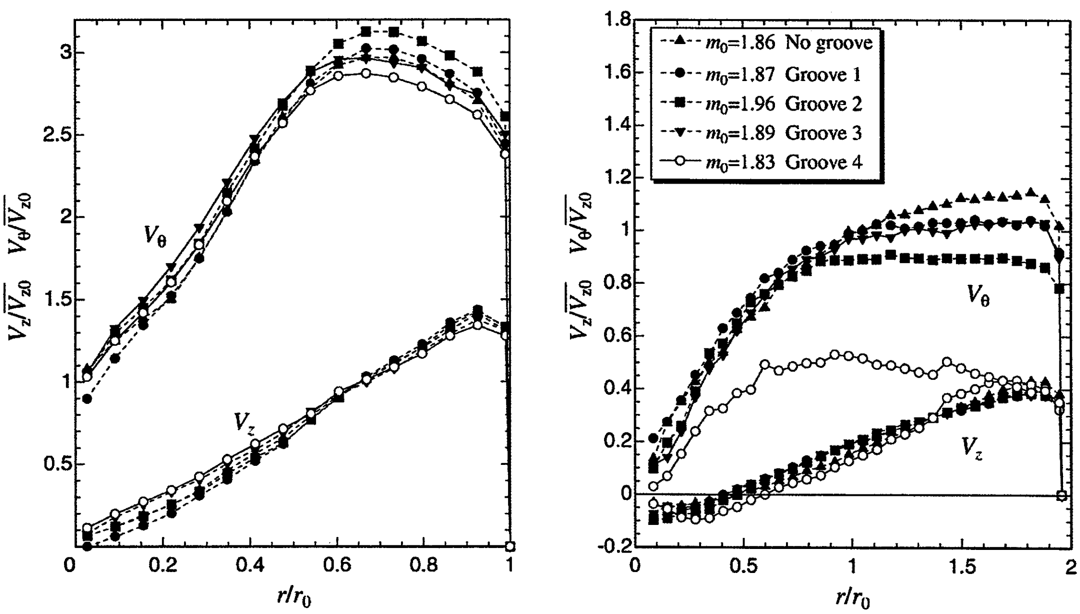
When the swirl is given by the impeller, the velocity distribution in the inlet section changes remarkably as shown in Figs. 4(a) and (b) in the case of m_0=0.64. The velocity profiles is characterized by two regions; the forced vortex core with or without reverse flow around the center axis and the outer region with nearly constant tangential velocity. In the outlet section B a reverse flow appears in the central region of a forced vortex as shown in Fig. 4(b). In Figs. 4(a) and (b) is also compared the velocity profiles of the grooved cases.

Figure 4(a) reveals that the inlet velocity profile changes little by the J-groove. Comparison of the



(a) Inlet section A (b) Outlet section B

Fig. 5 Velocity distributions in the inlet and outlet sections of diffuser in the case m_0 = 1.10



(a) Inlet section A (b) Outlet section B

Fig. 6 Velocity distributions in the inlet and outlet sections of diffuser in the case m_0 = 1.88

tangential velocity of the no groove case with that of the grooved cases in Fig. 4(b) reveals that the swirl strength is reduced over the whole outlet section to about 70 % by the Groove 4, but it is little influenced by the Grooves 1, 2 and 3.

When the inlet swirl rate is increased to m_0=1.10, the effect of J-groove becomes more remarkable as shown in Figs. 5(a) and (b). Figure 5(b) reveals that the maximum swirl velocity decreases to about 60 % by the Groove 4, and 90 % by the Grooves 1 and 2, although the Groove 3 gives little influence on the swirl strength. Figure 5(b) also reveals that the peak axial velocity increases and the reverse flow region around the center axis becomes much

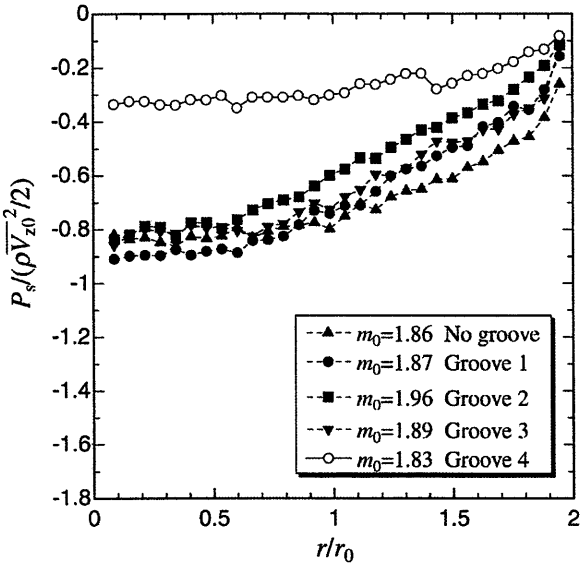
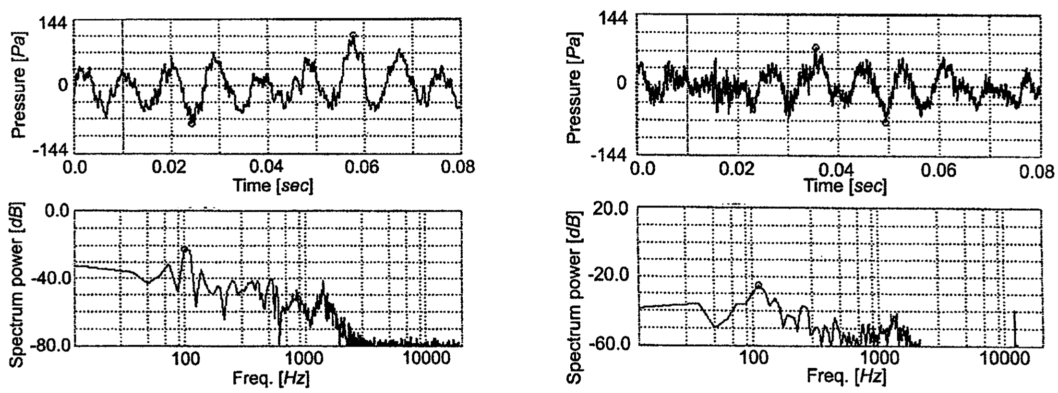


Fig. 7 Static pressure distribution in the outlet section (m_0 = 1.88)



(a) No swirl case(m_0=0) (b) Largest swirl case(m_0=1.88)

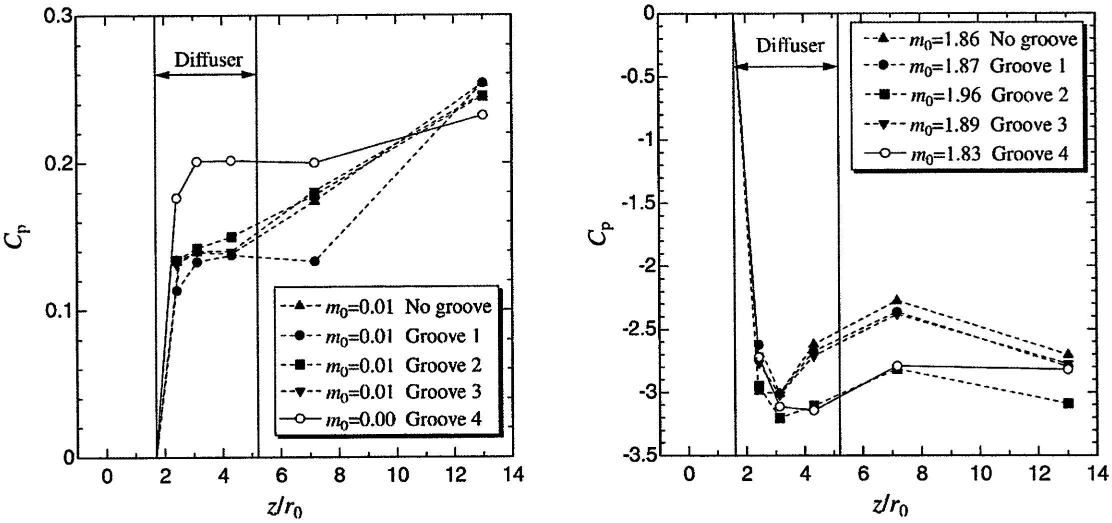
Fig. 8 Pressure fluctuation in the outlet section B in the case of Groove 4

larger by the Groove 4 in the outlet section, while the axial velocity profile changes little in the Grooves 1, 2 and 3.

With further increase in the inlet swirl rate to m_0=1.88, the J-groove effect becomes remarkable as shown in Figs. 6(a) and (b). The maximum swirl velocity drops to about 46 % by the Groove 4, and 78 % by the Groove 2. The Groove 1 (n=30) and 3 (n=20) have almost the same effect on the swirl suppression. These results reveal that the shallow but wide groove is much more effective than the deep but narrow groove, which is because the hydraulic radius of the former groove is larger than the latter. As for the reverse flow region around the center axis, the most effective groove, Groove 4, makes the reverse flow region wider but the other grooves do not increase the reverse flow region as shown in Fig. 6(b).

The distribution of static pressure for this case in the outlet section B is compared in Fig. 7. It is clearly seen that the static pressure becomes much more uniform over the whole outlet section than that of the no groove case due to a sudden drop of swirl velocity.

To reveal the J-groove effect on the flow unsteadiness, the pressure fluctuation and frequency analysis are illustrated in Figs. 8(a) and (b) for the Groove 4 in the no swirl case and the largest swirl case, respectively. As the Strouhal number $St = fd / \overline{V_{z0}}$ of a fluctuating



(a) No swirl case ($m_0 = 0$) (b) Largest swirl case($m_0 = 1.88$)

Fig. 9 Static Pressure distribution on the channel wall

pressure in a draft tube is in the range of (0.5~1.0) (Nishi et al. 1982), the frequency f of the pressure fluctuation is in the range of (60~180) Hz in the present case. In both figures the peak frequency is 100Hz, but this frequency is also observed in the case of no swirl as shown in Figs 8(a) and 3(a). Then the peak pressure fluctuations of 100Hz is not caused by the swirl of the main flow.

Comparison of Figs. 8(a) and (b) with Figs. 3(a) and (b) reveals that the amplitude of the pressure fluctuation is smaller in the grooved case. This suggests that the J-groove suppresses not only the swirl strength of the main flow but also the amplitude of the pressure fluctuation. The same results were obtained when suppressing a rotating stall in a vaneless and a vaned diffusers of a centrifugal impeller and also suppressing the performance curve instability of a mixed flow pump by use of the J-groove (Kurokawa et al. 1997, 1999).

4.2 Pressure distribution along the wall and the groove flow

The static pressure distribution along the diffuser wall is shown in Figs. 9(a) and (b) for the no swirl case and the largest swirl case, respectively.

Figure 9(a) reveals that the pressure recovers not only in the divergent channel but also in the downstream pipe in the no groove case. This reveals that a large separation occurs in the divergent channel and the separation zone elongates to the downstream pipe where significant pressure recovery is attained. It is also recognized that the Groove 4 gives higher presser recovery in the diffuser channel than that of the no groove case. This implies that the groove of proper dimension is effective to suppress flow separation in a divergent channel. However, the maximum Cp value of each case lies in the range of 0.22~0.26 and is much lower than the attainable Cp value in the literature. From the literature (JSME, 1979), the maximum attainable Cp value of a conical diffuser of the same dimension attached with a downstream pipe is about 0.5 for the divergent angle of α=30°. This discrepancy might be because the length of the downstream pipe is so short that the separation zone does not reattach to the wall in the present case, resulting in a low pressure recovery.

From Fig. 9(b) it is revealed that the pressure drops considerably in the former half of the divergent channel and recovers gradually both in the latter half and in the downstream pipe.

The groove flow is driven by the static pressure difference dp per a wall length ds along the wall. From the theoretical consideration, the driving force $wh\,dp$ of the groove flow balances with the wall friction force $\tau_w(w+2h)ds$, where τ_w is the wall shearing stress. Then,

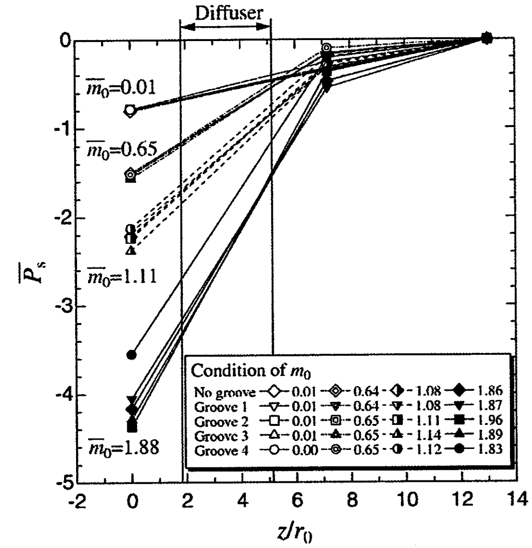


Fig. 10 Change of mass-averaged total pressure

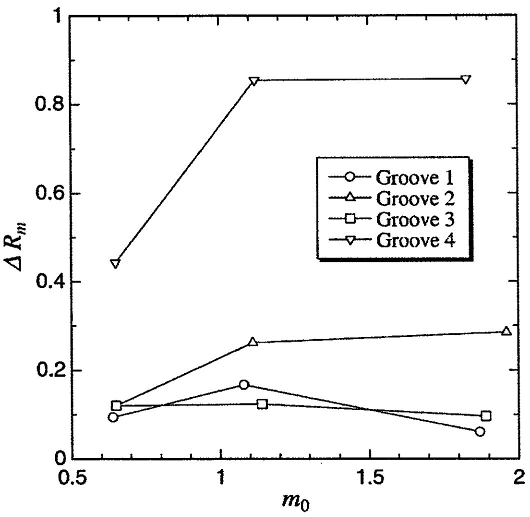


Fig. 11 Change of swirl parameter by J-groove

$$\tau_w(w+2h)ds = wh\,dp, \qquad where\ \ ds = dz / cos(\alpha/2) \tag{2}$$

The groove flow is thus formed parallel to the main flow direction from the upstream to the downstream in the former half. But in the latter half of the divergent channel the groove flow is in the reverse direction from the downstream to the upstream. In this case the groove flow in the former half is much stronger forming a strong jet flow. At the minimum pressure point in the divergent channel two jet flows in the groove coming from the upstream and the downstream collide with each other and leave the groove. The effect of J-groove on suppressing a swirl is thus consists of two effects; one is to lose the angular momentum when entering into the groove and the other is to absorb the angular momentum from the main flow by mixing between the groove outlet flow and the main flow

When the groove flow leaves the groove at the minimum pressure point, the far stronger jet from the upstream accelerates the main flow near the wall to the downstream direction as shown in the axial velocity distribution in Figs. 5(b) and 6(b). If the groove were elongated into the downstream pipe, the groove effect should become larger, since the pressure gradient in the downstream pipe can also be utilized. In Fig. 9(b) the static pressure decreases again in the downstream pipe, which might be caused by the decrease of the swirl strength.

The adoption of J-groove is necessarily accompanied with hydraulic loss. To determine the increase in hydraulic loss by the J groove, the mass-averaged total pressure is illustrated in Fig. 10. The increase in hydraulic loss created by the J-groove is seen to be very small and negligible.

To evaluate the groove effect totally on suppressing the swirl, the change of the swirl rate is calculated by using the swirl rate ratio $R_m = m/m_0$ of the outlet swirl rate to the inlet one. The R_m value of the no groove case increases in the flow direction in a divergent channel, and the groove effect can be evaluated by the relative value of the following swirl parameter;

$$\Delta R_m = (m/m_0)_{no-groove} - (m/m_0)_{grooved} \tag{3}$$

The swirl parameter ΔR_m represents the drop of the swirl rate by attaching the J-groove. The change in ΔR_m is plotted in Fig. 11 against the inlet swirl rate m_0. It is clearly seen that ΔR_m takes a positive value in all cases of the groove, that is, all the grooves have positive effect on swirl suppression. The Groove 4 is seen to take a large ΔR_m value and has a considerable effect on swirl suppression. The effect rises with an increase of the inlet swirl rate m_0 and takes the constants value of 0.85 in the range of $m_0 > 1.1$, which means that the Groove 4 makes the swirl rate drop by about 85% of the inlet swirl rate. When the largest swirl rate of $m_0 = 1.88$ is given, the outlet swirl rate is m=2.65 in the no groove case, and m=0.96 in the case of Groove 4. Then the Groove 4 reduces the outlet swirl to 36% of the no-groove case.

5. CONCLUSIONS

A new passive device using the J-groove is proposed to control and reduce the swirl in a conical diffuser of divergent angle 30° aiming to suppress a draft tube surge. Remarkable effect of suppressing a swirl is confirmed experimentally. The main results are summarized as follows;

(1) The J-groove can reduce the swirl strength of a rotational flow in a conical diffuser considerably. The J-groove of adequate dimension can reduce the swirl rate by about 85% of the inlet swirl rate. In the largest swirl case m_0=1.88, the outlet swirl rate is reduced to about 36 % of the no-groove case. In this case, the groove effect on swirl suppression increases with an increase in the inlet swirl rate and becomes constant in the range of large swirl rate.

(2) The additional hydraulic loss created by the J-groove is negligible.

(3) The effect of J-groove is not only to reduce the swirl rate but also to reduce the amplitude of pressure fluctuation. Even if the groove dimension is relatively small, it has positive effect on swirl suppression and on reducing the pressure fluctuation.

(4) The pressure distribution in the whole outlet section becomes much uniform due to the reduction of the swirl by the J-groove of adequate dimension.

(5) The reverse flow region is formed in the outlet section in the case of no swirl, and the reverse flow region become larger by the J-groove.

(6) A shallow but wide groove is more effective than a deep but narrow groove on suppressing a swirl rate of the main flow.

(7) When the inlet flow has relatively large swirl, the wall pressure drops largely in the former half of the conical diffuser. The groove flow is driven by this pressure gradient and is in the downstream direction in the former half of the diffuser and in the upstream direction in the latter half. Both flows collide at the minimum pressure point and leave the groove forming a strong jet which accelerates the main flow near the wall.

NOTATIONS

Cp ; coefficient of wall pressure defined as $2(p_S - p_{S0})/\rho\overline{V_{z0}}^2$

d ; inlet pipe diameter

m ; swirl rate of the main flow defined by Eq. (1)

p_S, P_S ; static pressure and non-dimensional static pressure $(2p_S/\rho\overline{V_{z0}})$, respectively

h, l, n ; height, length and number of J-groove, respectively

r ; radius

$Rm = m/m_0$; ratio of the inlet swirl rate to the outlet one

V_z, V_θ ; axial and tangential velocity component,, respectively

$\overline{V_{z0}}$; mean axial velocity at the inlet section A
w : width of J-groove
α ; angle of divergence in conical diffuser
ρ, ν ; density and kinematic viscosity of fluid
Subscripts:
0 ; at the inlet section A

REFERENCES

(1) Fisher, R. K., Palde, U. and Ulith, P., Comparison of Draft Tube Surging of Homologous Scale Models and Prototype Francis Turbines, *Proc. 10th IAHR Symposium* (Tokyo), Vol. 1(1982), pp. 541-556.
(2) Grein, H., Vibration Phenomena in Francis Turbines: Their Causes and Prevention, *Proc. 10th IAHR Symposium* (Tokyo), Vol. 1(1982), pp. 527-539.
(3) JSME, Fluid Resistance of Pipes and Ducts(in Japanese), *Japan Society for Mechanical Engineers*,(1979), pp.57-60.
(4) Kurokawa, J., Saha. S. L., Matsui, J. and Kitahora, T., A New Passive Control of Rotating Stall in Vaneless and Vaned Diffusers By Shallow Grooves, *Proc. of JSME International Conference on Fluid Engineering*, Vol.2 (1997), pp.1109-1114.
(5) Kurokawa, J., Saha, S. L., Matsui, J. and Imamura, H.,.An Innovative Device to Suppress Performance-Curve-Instability in a Mixed-Flow Pump by Use of J-Grooves, *Proc. 3rd ASME/JSME Joints Fluids Engineering Conference*(San Francisco), (1999), FEDSM-7200.
(6) Nishi, M., Kubota, T., Matsunaga, S. and Senoo, Y., Study on Swirl Flow and Surge in an Elbow-Type Draft, *Proc. 10th IAHR Symposium* (Tokyo), Vol. 1(1982), pp. 557-568.
(7) Nishi, M., Wang, X. M., Yoshida K. , Takahashi T. and Tsukamoto, T., An Experimental Study on Fins, Their Role in Control of the Draft Tube Surging, *Proc. 18th IAHR Symposium (Balencia)*, Vol. 2(1996), pp. 905-914.