621.634

Unsteady Flow Phenomena in Centrifugal Fans *

(1st Report, Rotating Flow Patterns in an Inlet Duct)

By Tadanobu KUBO ** and Susumu MURATA ***

In order to make clear the unsteady flow in the inlet duct of a centrifugal fan operating in the state of rotating stall, this paper presents a method of measuring the flow by a capped hot-wire probe whose directional characteristic is very excellent. The following results are obtained. The flow mentioned above is composed of two different flow regions. One of them is a reverse flow region near the duct wall, and the other is a forward one. These flow regions are not axisymmetric and rotate at constant speed which is determined only by flow rate. In a certain range of flow rates a helical stream tube moving forward is formed at the center of the duct near the impeller, and it rotates around the duct center. Furthermore, time averaged flow is measured by Pitot tube and compared with unsteady flow mentioned above.

1. Introduction

It is well known that the flow in the suction duct of a centrifugal turbo-machine operating at low flow rates has generally a reverse flow region where the fluid rotates with a large circumferential velocity component.⁽¹⁾ Up to this time this flow has been measured as a time-averaged flow using conventional probes and the reports about measurement of the fluctuating flow patterns in the suction duct have not been published yet.

On the other hand, there are a few papers about the occurrence of rotating stall in the centrifugal turbo-machines such as compressors or pumps.^{(2) (3) (4)} In these papers, only the speed of stall propagation was measured and the fluctuating flow patterns in the suction duct were not measured.

In this paper, the method of measuring the unsteady rotating flow is described and the characteristic fluctuating flow in the suction duct of a centrifugal fan operating in the state of rotating stall is revealed.

2. Nomenclature

- C : axial clearance between duct end and impeller, mm
 D_2 : impeller outer diameter, m
 L : axial distance from duct end to measuring section, mm
 n : impeller speed, rpm
 P : pressure rise of fan, mmAq
 Q : flow rate, m³/s
 Q_n : normal flow rate, m³/s
 R : radius of duct, mm
 r : radial distance, mm

- u_1 : peripheral speed of outer edge of impeller inlet, m/s
 u_2 : outer peripheral speed of impeller, m/s
 v_z : axial component of flow velocity, m/s
 v_θ : rotational component of flow velocity, m/s
 ω_s : absolute angular velocity of stall cell, rad/s
 ω : angular velocity of impeller, rad/s
 ρ : air density, kgf·s²/m⁴
 $\phi = 4Q/\pi D_2^2 u_2$: flow rate coefficient
 $\psi = 2P/\rho u_2^2$: pressure coefficient

3. Experimental apparatus

The general view of a fan used in our experiment is shown in Fig.1. Figure 2 shows the geometry of an impeller used in this experiment. A detail drawing of the junction

Fig.1 Experimental apparatus

Fig.2 Impeller

* Received 14th August, 1974

** Graduate Student, Faculty of Engineering, Osaka University, Suita.

*** Professor, Faculty of Engineering, Osaka University.

of the duct with the impeller is shown in Fig. 3. The radial clearance between the duct and the impeller is constant, but the axial clearance C is variable. During the experiment, the axial clearance was kept constant at 0.5 mm and the impeller speed was 1220 rpm.

The characteristic curve of the fan shown in Fig. 4 was obtained in the following way. The flow rate Q was measured in the section 1400 mm upstream of the impeller with a Pitot tube according to the fan testing method of JIS. In order to determine the suction static pressure, many static pressure taps were located at the duct wall lengthwise and the static pressure was measured at each tap. When each value of measured pressure was plotted along the duct, they fell into a straight line except in the range of rotating reverse flow. Therefore, we extended the line to the inlet of fan and obtained an extrapolated value of static pressure. A dynamic pressure in the suction duct was calculated using the mean velocity of flow in the duct. In regard to discharge pressure, atmospheric pressure was selected as the discharge static pressure, because air flowed out of the diffuser directly into atmosphere. The discharge dynamic pressure was calculated using the mean velocity of flow at the diffuser exit.

Fig. 3 Connection between impeller and duct

Fig. 4 Characteristic curve of fan

4. Measurement with Pitot tube

The flow was measured with a three hole arrow-head type Pitot tube in the duct section at $L = 36, 156, 336, 541, 1141$. Some examples of measured velocity distributions are shown in Fig. 6.

5. Measurement with hot-wire anemometer

5.1 Characteristics of a capped probe
Hot-wire probes on the market are insensitive to the direction of flow, because they have characteristics shown by a dotted line in Fig. 7. They cannot distinguish the backward flow from the forward one. To remedy this defect, we conceived an idea of attaching a cap to the probe and tested various types of capped probes. The geometry of the cap used in our experiments and the directional characteristics of the capped probe are shown in Figs. 7 and 8.

The influences of the cap on flow velocity measurement and on responsiveness of the probe are checked in the following way. A capped probe and a bare probe are installed in a fluctuating flow caused by rotating stall of the impeller and output signals of each probe are recorded simultane-

Fig. 5 Test section

(a)

(c)

(b)

(d)

Fig. 6 Velocity distribution measured with Pitot tube

ously. The maximum values of velocity are read from the recorded signals of each probe using the calibration curves obtained in a steady flow in a wind tunnel and compared with each other. From the coincidence of these two values, it is ascertained that the velocity of unsteady flow can be measured with the capped probe as well as with ordinary hot-wire probes. As for responsiveness, the steepness of recorded waves shows that the capped probe can respond to a fluctuating flow of fairly high frequency. Since the purpose of our experimental study is to make clear the unsteady flow of comparatively low frequency caused by rotating stall, we used a coated hot-wire probe which was insensible to the high frequency flow fluctuation of turbulence or vane wake. Coating has the same effect as a low pass filter used in the instrument circuit.

5.2 The number of stall cells i and the speed of stall propagation ω_s

The measurement was made with two hot-wire probes which had been installed in the same section of the duct as shown in Fig.5 (b). The angular separation of these probes is θ_p . When the directions of these probes are properly selected, cyclic output signals are obtained on an electromagnetic

Fig.7 Directional characteristics of a probe

Fig.8 Probe cap

Fig.10 Rotational speed of stall cell

oscillograph as shown in Fig.9. From these records, the period T and the phase difference ΔT are read as shown in Fig.9. Then i and ω_s are obtained by the following equations :

$$i = \frac{360^\circ}{\theta_p} \frac{\Delta T}{T}, \quad \omega_s = \frac{2\pi}{i T}$$

Experimental results showed that i was always one at flow rate of 0 to 0.17. Figure 10 shows the relation between the rotational speed ratio and the flow rate. The angular velocity ω_s was dependent on the flow rate only and independent of the position where the measurement was made.

5.3 Flow patterns in the suction duct

5.3.1 Method of measurement and the drawing procedure of flow patterns

Output signals from hot-wire anemometers are recorded on an electromagnetic oscillograph and also these are observed in a synchroscope for monitoring continually. Figure 11 shows the angle β which defines the direction of the probe.

The measurement was made in the following way. First, one probe is installed in the hole ① of the duct perpendicularly to the wall as shown in Fig.5 and its depth and direction are varied to obtain the most cyclic and clear shape of output wave. When such a wave is obtained, the probe is fixed there and its output wave is used as a standard wave for phase estimation. Next, another probe is installed in the hole ② and its radial position r/R and direction β are varied. The output waves from the second probe are recorded together with the standard wave simultaneously.

Next, we describe the method of drawing flow patterns from those recorded waves. Several waves which were recorded at $r/R = 0.95$ in the duct section at $L = 36$ in the case of $Q/Q_n = 0$ are shown in Fig.12. The upper wave of each record is the same and used as a standard wave. The lower one is a record for various values of β . When the output wave has a clear shape and maintains

Fig.9 Reading of oscillogram

Fig.11 The setting angle β of the probe

the maximum value longer than others, we decide it to be a representative of recorded waves. In the case of Fig.12, compared with the waves for $\beta = 130^\circ, 90^\circ, 65^\circ$, those for $\beta = 115^\circ, 75^\circ$ are representative. According to the definition of β as previously shown in Fig.11, the flow for $\beta = 115^\circ$ is a reverse one and that for $\beta = 75^\circ$ is a forward one. Since the waves obtained from reverse flow were generally clearer than those for forward one, we enclosed the reverse flow region only with a solid line in the figure.

The extent of a flow region is determined in the following way. In the first place, maximum flow velocity $v_{\max}$ is read from a wave through the use of calibration curve for the probe. Then, a line is drawn at the level of $v_{\max}/2$, and $t (=MM')$ is obtained as shown in Fig.9. We regard t as a period of time during which the direction of flow agrees with that of probe. We can determine the circumferential length of the reverse or forward flow region as $360^\circ \times t/T$. This operation was performed for several cycles of a wave and mean value of them was taken. When a recorded wave

Fig.12 Examples of oscillogram at $Q/Q_n = 0$, $L = 36$

contained signals of small amplitude (for example as shown in Fig.15), only the signals of large amplitude were picked up to read.

Next, we shall show the method of determining the angular separation of two different flow regions. In Fig.9, the middle point N of MM' corresponds to the center of flow region. The phase difference (or time lag) between the middle point of upper wave and that of lower one, for example $\Delta T'$ shown in Fig.12(b), is read for several cycles of wave and mean value is calculated. In consideration of the angular separation θ_p between two probes and the angular velocity of flow region ω_s , true angular separation between two different flow regions is fixed as $360^\circ \times [\Delta T' - (\theta_p/\omega_s)]/T$. The circumferential extent of flow regions and their relative position are determined by the method mentioned above, using output waves obtained at various measuring points in a section of duct. Thus, we can draw the flow pattern as shown in Fig.20(a). In this figure, the line ABC is a center line of flow, corresponding to the middle point N of many representative waves. From the direction and magnitude of flow velocity (i.e. β and $v_{\max}$), the axial and circumferential velocity components v_x , v_θ are calculated. The velocity distributions of v_x , v_θ along the center line ABC are shown on the right side in the figure.

Next, we shall show an instance in which the circumference is occupied by two different reverse flow regions. An example of recorded waves (at $Q/Q_n = 0$, $L = 336$, $r/R = 0.95$) is shown in Fig.13. Upper trace is a standard wave obtained at $r/R = 0.95$, $\beta = 134^\circ$. From these waves, we perceive that two different reverse flow regions exist on the circle of radius $r/R = 0.95$, and we can decide the extent and relative position of

Fig.13 Examples of oscillogram at $Q/Q_n = 0$, $L = 336$

flow region by the method described previously.

Next, we shall treat the relation between the flow patterns in different duct sections at the same flow rate. Figure 14 shows two standard waves obtained at the same time in different sections. Probes used to obtain these waves are installed in the same circumferential position ② of different sections of the duct as shown in Fig. 5. On the basis of these records shown in Fig. 14, we can determine the relative situation of flow patterns obtained in different sections (for example, in case of $Q/Q_n = 0$, the angle between AO in Fig. 20(a) and AO in Fig. 20(b)).

Figure 16 shows an example of recorded waves at $L = 336$, $Q/Q_n = 0.17$. As we obtain such a wave for all the measured radii, the flow is axisymmetric in this case as shown in Fig. 20(i).

5.3.2 Flow patterns near the duct center

At flow rate ratio $Q/Q_n = 0.13$ or 0.17 , a peculiar phenomenon is observed near the duct center at $L = 36$, 156 . We shall explain this in the case of $Q/Q_n = 0.13$, $L = 36$.

When a probe is turned slowly from the direction of large β to that of small β at the center of the duct and the waves of output signal are observed continually in a synchroscope, we observe a cyclic wave in the

Fig. 14 Oscillograms in different sections

Fig. 15 Example of oscillogram at $Q/Q_n = 0.13$, $L = 336$

Fig. 16 Example of oscillogram at $Q/Q_n = 0.17$, $L = 336$

range of about $\beta = 30^\circ \sim 20^\circ$ as shown in Fig. 17 (a). After observing irregular waves of small amplitude as shown in Fig. (b), we again get a cyclic wave in the range of $\beta = -20^\circ \sim -30^\circ$ as shown in Fig. (c). The radial extent in which such cyclic wave are observed in two symmetrical directions of β is $r/R = 0.2 \sim 0.3$ from the duct center. At radial position $r/R = 0.3$, a wave with a sharp tip is obtained when a probe is turned to the direction of negative value of β . In the range of $r/R > 0.45$, cyclic waves are not obtained in the direction of negative value of β any longer. In the direction of positive value of β , a cyclic wave similar to that obtained at the duct center is still observed in $r/R > 0.3$, but it contains irregular signals. Such a wave at $r/R = 0.6$ is shown in Fig. 17(d) and the signals similar to those observed at the duct center are shown by arrows. In the range of $r/R > 0.6$ such a characteristic wave does not appear and other fluctuating waves are obtained as shown in Fig. 17(e). From these waves the center line of flow COD is obtained, as indicated by the chain line in Fig. 20(d), by using the method described in the preceding

Fig. 17 Examples of oscillogram at $Q/Q_n = 0.13$, $L = 36$

section. The velocity distribution along COD is also shown on the right side of the figure. The segment BC of the velocity distribution is drawn by a dotted line. This segment corresponds to $r/R > 0.45$ where only irregular waves were obtained in the direction of negative value of β as mentioned above.

Now, the velocity v_0 is nearly constant in a certain range near the center of the duct. Such a velocity distribution is obtained in the following flow model. Consider in a duct section an eccentric circular region whose center is O' and suppose that this circular region revolves around the duct center O and also rotates around its own center O' as shown in Fig.19. Since the peripheral velocity component v_0 of the fluid particles which pass the flow region is a vectorial sum of the revolving velocity and the rotational one, these two angular velocities (revolving and rotational) must be the same in magnitude but opposite in direction so that the velocity distribution of v_0 may be constant. Under such a condition, we can find the magnitude of v_0 constant and its direction parallel to XX' everywhere in the region.

The size of the circle of this flow region is able to be determined in the following two ways ;

- (1) A method of guessing it from oscillograms
- (2) A method of deciding it by the shape of center line

In the former method, the radial position

Fig.18 Examples of oscillogram at $Q/Q_n = 0.13$, $L = 156$

Fig.19 Flow model

where the signals shown by arrows in Fig.17 (d) begin to appear is decided as the farthest point on the circle from the duct center and the radial position where similar cyclic waves in each symmetric direction of β are observed as the nearest point on the circle. In the latter method, the diameter of the circle is decided by the segment of center line which is nearly straight (for example the segment CD' in Fig.20(d)). The size and eccentricity of two circles which were determined by two methods differ a little. It seems that these differences are caused by the facts that the boundary of the flow region is not so clear and that the shape of the region differs from a circle of exact roundness. In this paper, the size of the circle and eccentricity are determined by the method (1) and the portion of the center line which is nearly straight is selected as the axis OO' of the circle.

We can suppose a stream tube by putting the eccentric flow region together continuously along the duct. This stream tube is twisted, that is to say, each axis of eccentric circles in different sections takes a different direction.

Moreover, we describe the method of deciding the center line of flow pattern when a stream tube is formed near the duct center.

Fig.20 Flow patterns ($Q/Q_n = 0$)

An example of recorded waves at $Q/Q_n = 0.13$, $L = 156$ is shown in Fig.18. In this case, two different cyclic waves are observed in forward direction near the wall, though such a wave shown in Fig.18(b) is not observed in the section at $L = 36$. The wave obtained in the direction of larger β is more disturbed than that of smaller β is. So we read necessary values from the latter (Fig.(b)). As a result, the shape of the center line of flow at $L = 156$ differs from that at $L = 36$.

5.3.3 Flow patterns

Measurements with capped probes were made in the sections at $L = 36, 156, 336$ at the flow rate $Q/Q_n = 0, 0.13, 0.17$. Flow patterns were drawn on the basis of various recorded waves by the method previously described. These are shown in Fig.20, where the symbol -- shows reverse flow region and ++ shows forward one.

6. Consideration

6.1 Consideration about flow patterns

(1) In the case of $Q/Q_n = 0$

Flow patterns in this case are shown in Fig.20(a)~(c). As seen in Fig.20(a), a reverse flow region is formed near the wall and the fluid particles in this region have a large peripheral velocity component $v_\theta \neq u_1$. A little upstream in the duct, the reverse flow region widens its circumferential extent and the flow velocity becomes small (Fig.(b)). More upstream in the duct. The whole circumference near the wall is occupied by a reverse flow and there exist two different flow regions in it.

(2) In the case of $Q/Q_n = 0.13, 0.17$

Flow patterns in this case are shown in Fig.20(d)~(i). In Fig.(d),(g) it is shown that the reverse flow in the section at $L = 36$ has a large peripheral velocity component $v_\theta \neq u_1$. In the section at $L = 156$, the reverse flow region increases in its circumferential extent (Fig.(e),(h)). In the section at $L = 336$, the reverse flow region becomes narrow (Fig.(f)), or disappears and the flow becomes axisymmetric (Fig.(i)). In Fig.(d), (e),(g),(h) we notice that a stream tube moving forward is formed near the duct center. The rotational speed of the eccentric circle measured in a certain section is the sum of the angular velocity at which the stream tube revolves and the angular velocity at which the flow region shifts by moving the stream tube forward. The shifting velocity derived from the procession of the stream tube is calculated using the axial velocity of fluid near the duct center and the pitch of twist of stream tube. Then, by adding this shifting angular velocity to the measured rotational angular velocity, we obtain a revolving angular velocity of the stream tube. The revolving speed of stream tube calculated in this way is about 50~60 % of impeller speed.

6.2 Comparison of fluctuating flow with time averaged flow

Figure 6 shows the results of measurement with a Pitot tube and manometer. Since the Pitot tube has sufficient damping to attenuate fluctuations, the asymmetric fluctu-

ating flow is measured as a steady and axisymmetric one, that is, as a time averaged flow.

In Fig.6 the reverse flow has a large peripheral velocity and it appears near the duct wall, as many other experimental studies have shown, in the range of $Q/Q_n \leq 0.17$ where a clear rotating stall occurs in the impeller. The results of measurement of fluctuating flow and the time averaged flow show the same indications that a reverse flow appears near the wall and it has a large peripheral component.

6.3 Comparison with former studies

In this study, we used a fan which had a suction duct and vaneless diffuser but had not a volute casing. The impeller is a radial flow one whose outlet blade angle is 90° and the diameter ratio is about 0.45. A clear rotating stall occurs in the range of $Q/Q_n \leq 0.17$. In regard to axial flow impeller, it is known that rotating stall occurs when the flow rate is reduced below the designed one. When it is reduced still more, an axisymmetric complete stall occurs.(5)(6)

Next, we adduce some instances obtained by others, which show that a rotating stall of a radial flow impeller occurs below a certain flow rate and a complete stall does not occur even near zero flow.

Fig.20 Flow patterns ($Q/Q_n = 0.13$)

Fig.20 Flow patterns ($Q/Q_n = 0.17$)

Сазонов⁽⁴⁾ experimented on a pump with inducer and volute casing. The impeller had four vanes and its outlet blade angle and the diameter ratio were 25° , 0.83 respectively. He made measurements at the wall of a suction pipe using two pressure gauges and found out that a rotating stall occurred when $Q/Q_n < 0.6$ and that the rotational speed ratio was 0.4 at $Q/Q_n = 0$.

Селезнев⁽³⁾ made experiments on compressors, each of which had a ring diffuser and a casing. He tested three impellers whose outlet blade angles were 49° , 65° , 90° and the numbers of vanes were 16, 20, 12 respectively and their diameter ratio was 0.52. He found out that a rotating stall occurred in each impeller below the flow rates $Q/Q_n = 0.56$, 0.71, 0.81 and this lasted up to the flow rates $Q/Q_n = 0.40$, 0.43, 0.48 where a surge broke out. The rotational speed ratio of

stalled region was $0.13 \sim 0.14$, $0.25 \sim 0.27$, $0.30 \sim 0.32$ respectively.

As described above, in the case of a radial flow impeller, former studies show that an axisymmetric complete stall did not occur near zero flow rate. But in the literature (7) it is shown that, when a compressor was operated at lower speed than designed one, the region of rotating stall was separated from that of surge. However, when this compressor was operated at designed speed the region of rotating stall and that of surge joined each other.

According to the studies mentioned above, though it cannot be said that a rotating stall occurs in every centrifugal impeller, our experimental results do not seem to be a special case as compared with those obtained by others.

7. Conclusions

The results obtained in this study are summarized as follows:

- (1) A capped probe and methods of measurements with it were proposed to measure the fluctuating flow in a suction duct of a fan operating in the state of rotating stall.
- (2) A clear rotating stall occurred in the centrifugal fan which was operating at low flow rates and the characteristic flow in the suction duct of the fan was revealed by using the capped probe.
- (3) It was shown that asymmetric flow caused by rotating stall appeared to be axisymmetric as was seen in other studies when it was measured with a Pitot tube.
- (4) It was known that there exists a certain correspondence between the time averaged flow and the unsteady rotating flow.

Acknowledgment

We would like to express our appreciation to Noriyasu Saeki for his help with the experiments.

References

- (1) Murakami, M., Jour. Japan Soc. Mech. Engrs. (in Japanese), Vol.77, No.580 (1967-5), p.643.
- (2) Emmons, H.W., et al., Trans. ASME, Vol.77, No.4 (1955-5), p.455.
- (3) Селезнев К.П. и др., Энергомашиностроение, No.3 (1969-3), p.20.
- (4) Сазонов, А.А., Сб Лопаточные машины и ст-руйные аппараты, No.6 (1972), p.151.
- (5) Tanaka, S. and Murata, S., Bulletin of JSME, Vol.18, No.117 (1975-3), p.256.
- (6) Tanaka, S. and Murata, S., Bulletin of JSME, Vol.18, No.117 (1975-3), p.264.
- (7) Ершов В.Н., Неустойчивые режимы турбомашин, вращающийся срыв, "Машиностроение", 1966.