Investigation Concerning Rotating Stall and Surge Phenomena within Centrifugal Compressor Channels

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Rotating stall and surge were examined by detecting mutual interference of flow patterns within each part of compressor channels. A surge was recognized in case of a larger channel volume. On the other hand, there was no surge with a smaller volume. After comparing both cases, fluctuating flow patterns were measured without the surge. Under the rotating stall condition, an unsteady fluctuating reversed flow existed at the exit of the inducer channel, but a jet and wake flow pattern disappeared downstream. When the flow rate became far lower, another reversed flow appeared at the exit of the impeller. These phenomena were in close relation to the variation of the performance characteristics of the compressor tested and also the influence of these flows upon the surge and stalls were observed to be present.

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NOMENCLATURE

\[ C = \text{absolute velocity} \]
\[ E = \text{output voltage of hot-wire} \]
\[ P = \text{pressure} \]
\[ U = \text{peripheral speed} \]
\[ W = \text{relative velocity} \]
\[ dC = \text{fluctuation of absolute velocity} \]
\[ dW = \text{fluctuation of relative velocity} \]
\[ \theta_0 = \text{angle of flow direction in case of calibration} \]
\[ \theta = \text{angle between meridional plane and normal to hot-wire sensor (plus for impeller rotation)} \]
\[ \eta = \text{efficiency} \]
\[ \phi = \text{angular speed} \]
\[ \psi_s = \text{static pressure ratio (P/P_a)} \]
\[ \varphi = \text{flow coefficient (C_{2r}/U_2)} \]

Subscripts

\[ a = \text{atmospheric condition} \]
\[ d = \text{design point condition} \]
\[ m = \text{values within meridional plane} \]
\[ r = \text{radial direction} \]
\[ y = \text{values measured by means of yaw probes} \]
\[ \theta = \text{tangential direction} \]
\[ \text{imp} = \text{impeller} \]
\[ 2 = \text{impeller exit} \]
\[ \text{LP} = \text{values measured through low pass filter of 300 Hz} \]
\[ \text{P.S.} = \text{pressure side} \]
\[ \text{S.S.} = \text{suction side} \]

INTRODUCTION

Centrifugal compressors are now being required to attain high pressure ratios with compact size for their application in refrigeration systems, gas turbines, turbochargers, etc. However, when the designers try to fulfill these requirements, operating ranges and performance characteristic curves become very narrow due to the limitation of the surge and choke. Usually, their optimum operating conditions exist near the surge lines to attain higher efficiencies. Therefore, the performance characteristics near the surge condition become more critical. It is well known, however, that when a compressor is operated at lower flow rate than the design point, there appears first a rotating stall as the flow rate decreases and, subsequently, a full stall in accompany with the surging.

Considerable investigations, both on the performance characteristics and on the internal flow near surge, have been conducted. H. W. Emmons, et al. (1) clarified the nature of the stalls and surge and T. Iura, et al. (2) published the experimental results of rotating stalls for axial-flow compressors. Also, W. Jansen (3) treated the rotating stall in a radial vanless diffuser both experimentally and theoretically. For centrifugal compressor with high pressure ratios, C. Rodgers (4) defined surge and choke criteria for straight, radial-bladed compressors with many types of inducers and diffusers. Moreover, from the standpoint of predicting performance characteristics of centrifugal compressors, M. R. Galvas (5) showed a method to estimate the choke limit and referred to the effect of surge-to-choke margin. On the other hand, as to the internal flow problem of centrifugal compressors, R. C. Dean, Jr., and Y. Senoo (6) constructed the idea of the jet and wake flow model. Furthermore, D. Eckardt (7) measured the instantaneous flow patterns within impeller channels by employing the laser two-focus velocimeter.

However, in all of the afore-mentioned reports, the relationship between performance characteristics and the internal flow at lower flow rate near surge has not yet been fully clarified in spite of their importance for understanding the nature of these phenomena.

The present authors (8-10) already showed 1 Numbers in parentheses designate References at end of paper.
the time-averaged flow pattern measured by yaw probes at the design point and lower flow rate. In these results, however, the cause of occurrence of the stalls and surge was not examined. In this paper, in addition to yaw probes, a hot-wire anemometer, semi-conductor pressure transducers and a real-time digital analyzer were employed to detect the unsteady nature of the flow pattern within single-stage, scroll-type compressor channels. We studied that the seemingly discontinuous flow patterns between the stalls and surge were invoked by continuous interference of the flows within each component of the channels. Above all, circumferentially skewed flow within the vaneless diffuser and the variation of the compressor system volume were observed to be the major cause of the fluctuating flow formation of
TEST RIG AND MEASUREMENT

Experimental Facility Arrangement

The experimental facility arrangement is shown in Fig. 1. A tank of 0.221 m$^3$ in volume was installed midway along the discharge duct when the surging was examined. A detailed configuration of the compressor was already reported in Fig. 1 of Reference [8]. The impeller had nine straight radial blades with the inducer of circular arc along its mean camber line. The design point flow coefficient was at $\varphi = 0.330$. A radial vaneless diffuser was used at the impeller exit. The sites of the measurements in the meridional plane within the channel are shown in Fig. 2(a). The measurements were taken at the points where the sections and the flow surfaces crossed. The flow patterns within the impeller channels were measured at sections Nos. 3, 6, and 9 in Fig. 2(b). The circumferential instrumentation at the inlet duct, diffuser, and scroll was distributed as shown in Fig. 2(c).

Measurement Technique

A slip ring was installed instead of mechanical seals to transmit the electrical signal from the rotating impeller to the stationary measuring system. The hot-wire signals from the impeller channel were synchronized with the rotation by the photo-tachometer, and were transmitted to the data recorder through the slip ring. Afterwards, the signals were analyzed by a digital analyzer. Low-pass filters prepared specifically for the present study were employed and their ranges were selected according to the output ranges of the signals. Usually, the output signals from the rotating impeller contain noises of the slip ring. To check the noise level, frequency analysis was conducted on the hot-wire output signals of the turbulent boundary layer in a low turbulence wind tunnel. Subsequently, the same output signals were also examined through an electrical closed circuit mounted on the rotating impeller including the slip ring. By comparing these results, the noise was known to exist over the frequency of 2500 Hz and was excluded by the 2500-Hz low pass filter. The noise did not affect the time-averaged outputs.

In the present measurements, there appeared both the unsteady fluctuating throughflow and reversed flow, the throughflow being designated as the flow passing through the inlet toward the delivery duct and the reversed as the flow passing toward the inlet.

Fig. 3 Covered-probes and their angular characteristics

Since it is very difficult to measure these types of flows, both the common I-shaped hot-wire sensors and additional covered-probes similar to those used by S. Murata [11] were used to make it possible to accurately detect the reversed flow. Fig. 3 shows these covered-probes and their angular characteristics.

Measurements of Stalls within Inlet Duct

A covered-probe was placed on the inlet duct wall 10 mm upstream of the inducer leading edge. This sensor was fitted to the wall at an angle of $\theta = 10$ deg from the meridional plane to measure the reversed flow with the tangential velocity. In measuring the rotating stall cells, two covered-probes were installed to the line C and F in Fig. 2(c) and the time difference of the output signals, $\Delta T$, was calculated by the cross correlation function and the number of the stall cells was subsequently obtained.

Unsteady Flow Pattern within Impeller Channel

Unsteady fluctuating flows, including both the through and reversed flows, existed also within the impeller channels. The covered-probes, though they could detect the reversed flow, could not respond to both flows instantaneously. On the other hand, the degree of the velocity fluctuation...
ation should be counted as the sum of both flows. Therefore, both flows were measured, respectively, by the covered-probes and, in order to measure the velocity fluctuation, ordinary I-shaped sensors were employed.

The results thus obtained by the hot-wire were compared with those by the yaw probes (8). The difference with respect to the time-averaged velocities between them tended to increase as the amplitude of the fluctuation, \( \frac{dW}{W_m} \), exceeded 0.34. In the present case, as the covered-probes possessed small apertures at their inlet sections, they could not measure correctly skewed three-dimensional fluctuating flows with larger amplitudes. Therefore, the qualitative nature of the fluctuating flows will be discussed in the following.

Flow Patterns within Vaneless Diffuser

The circumferential velocity fluctuation was measured by the I-shaped probe within the vaneless diffuser. The stall cells were measured in the same manner as the inlet duct.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To denote the nature of the fluctuating flow patterns, three parameters were defined as follows.

1. Degree of Velocity Fluctuation (D.V.F.). This was measured by the same method as used for the turbulence. However, in the present case, as the turbulence thus obtained included a cyclic fluctuation caused by the stalls owing to the impeller rotation, the intensity might be represented by the D.V.F. \( \frac{dW}{W_m} \) was applied for the rotating impeller and \( \frac{dC}{U_2} \) for the stationary casing.

2. Degree of Reversed Flow (D.R.F.). This was defined by the following equation.

\[
Z = \frac{W_p - W_B}{W_p + W_B}
\]

A similar factor was given by J. P. Johnston (12) designated as \( \beta \), where

\[
\beta = 100 \times \frac{t_B}{t_T + t_B}
\]

Here, \( t_B \) denotes the interval of the reversed flow and \( t_T \), that of the throughflow. When \( \beta \) was used to represent the reversed flow phenomenon, the rate of the reversed flow time interval to the total measured time could be obtained. However, in the present case, merely \( Z \) was used to denote the nature of the reversed flow. Be-
channels and the cyclic fluctuation became clear in Fig. 5(b), and marked difference in the amplitude of the velocity fluctuation within the vaneless diffuser due to variation of the circumferential position became more evident [Fig. 5(c)]. These phenomena revealed the severe circumferential nonuniformity of the flow within the vaneless diffuser as in case of the tank being not used. Then, the cyclical fluctuation times were constant at all the measuring points.

Thus, the afore-mentioned results were classified as follows. At $\varphi = 0.110$, there appeared a mild surge. This surge was amplified as the flow rate decreased, leading to a gradual change in performance. When the flow rate became $\varphi = 0.06$, there appeared a violent surge, which caused a large decrement in performance. Strictly speaking, the different flow patterns would depend on cases with and without the tank. However, as will be mentioned in the following, there occurred a change of the flow pattern due to the fluctuating reversed flow within the impeller channel and also the circumferentially skewed flow pattern within the vaneless diffuser without the tank at $\varphi = 0.165, 0.110, \text{ and } 0.04$. Therefore, though the behavior of the surge was affected by the channel volume as noted by J. L. Dussord (13), the real cause of the surging was considered to lie in the nature of the flow pattern within the impeller channel. Therefore, the surge pulse can be affected by change of the compressor capacity. In addition, this pulse would be governed by both the interference of the impeller rotation and circumferentially deviated flow pattern within the vaneless diffuser channel. The frequency of the impeller rotation was 67 Hz and the number of the blades was nine. On the other hand, there appeared no relationship between the surge pulse and the fluctuating flow pattern within the impeller channels, since the frequency of the surge pulse was observed at 5 Hz. Hence, the influence of the flow pattern within the impeller channel on the surge pulse was not clarified in the present study.

**Unsteady Flow Pattern within Inlet Duct**

The rotational velocity of the rotating stall cell at the inlet duct is shown in Fig. 6(a). Around the flow rate of $\varphi = 0.165$, stall cells appeared occupying the region from the wall to the mid span of the inducer blade and increased its $\omega_s$ toward $\varphi = 0.110$. $\omega_s$ became about 1.0 around $\varphi = 0.110$ and then, the stall was confirmed to be a full stall. A continuous reversed flow with inducer rotation was generated. This stall cell grew in size from the shroud to the hub as the flow rate decreased. Near the flow rate of zero, the whole fluid began to rotate and a full-span stall appeared. When these variations of the stalls were checked by the hot-wire signal waves, the waves with higher frequency of constant amplitude appeared at the design point [Fig. 6(b)]. The amplitude increased irregularly toward $\varphi = 0.165$ and then, reached the maximum value. But the time intervals of the adjacent peaks were not constant. In spite of the violent fluctuation accompanied by the reversed flow, the performance varied gradually at this flow rate. When the flow rate became far lower, the amplitude became smaller and at $\varphi = 0.04$, it showed the irregular small wave. Therefore, an increase in tank volume would act to align the time intervals of the waves between $\varphi = 0.165$ and $\varphi = 0.110$ and leading to appearance of the surge pulse.
Unsteady Flow Patterns within Inducer and Impeller Channel

In the section No. 3, at the flow rates lower than $\varphi = 0.165$, periodic fluctuations of the reversed flow were recognized both near the shroud and suction side on the hot-wire signals. The area of the reversed flow, where a three-dimensional skewed eddy was present (8), increased as the flow rate decreased ($W_{my}/U_2$ in Fig. 7). Moreover, the region having higher D.V.F. appeared near the suction side at $\varphi = 0.330$ while it shifted the position toward the hub below $\varphi = 0.110$. The O.L.W. examined revealed a greater uniformity in flow patterns over the whole section of the channels as the flow rate decreased. This tendency became more pronounced especially lower than $\varphi = 0.165$. Moreover, at the flow rates lower than $\varphi = 0.165$, the turbulence with lower frequency was produced in the No. 3 section. The frequency was at 67 Hz, which coincided with that by the impeller rotation. A throughflow appeared within the impeller channel, when the tongue of the scroll existed downstream. Then, the static pressure distribution within the vaneless diffuser showed a circumferentially deviated flow pattern as in Fig. 8. The lower pressure near the scroll was created by the separation of the flow with a lower through component and a higher tangential velocity at the tongue of the scroll. By this effect, the reversed flow with a three-dimensional eddy on the time-averaged velocity disappeared when the channel existed upstream of this point. Then, the flow at the hub near the pressure side changed its direction toward the impeller exit without joining the reversed eddy. The afore-mentioned variation of the flow pattern is shown in Fig. 9. These patterns were confirmed by the uniform total pressure loss distribution measured by yaw probes in Fig. 24 of Reference (8). Then, the jet and wake flow pattern disappeared. In this case, as the mixing loss seemed
Figure 8 Distribution of static pressure ratio within vaneless diffuser

$\phi = 0.165$

$\phi = 0.330$

$\phi = 0.110$

$\phi = 0.040$

Figure 9 Variation of flow pattern within impeller channel due to rotation at $\phi = 0.165$

The variation in the distribution of the O.L.W. and the D.V.F. showed the same mode of variation to the flow rate as in the No. 3 section. However, it caused a more uniform pattern throughout the section. When a periodic fluctuating flow with lower frequency was present in the No. 3 section as mentioned before, mixing might occur. The uniformity in the flow patterns downstream of the No. 3 section could be explained by this mixing.

At the exit of the impeller, i.e., the section No. 9 (Fig. 11), the foregoing explanation for the No. 6 section could also be applied. However, at the flow rates lower than $\phi = 0.110$, the D.R.F. decreased at the pressure side near the hub. This would be caused by the uniformity of the flow pattern on the blade-to-blade surface. The mean velocity at the pressure side became lower while that at the suction side did higher as in case of the potential flow. In addition to the disappearance of the wake and the more uniform flow pattern, the decrement of the mass flow caused another reversed flow. Therefore, two types of the reversed flow within the impeller channel were observed; one is due to the appear-
Flow Patterns within Diffuser Channel

At $\phi = 0.165$, the rotating stall of $\omega_s = 0.48$ to 0.55 was observed on the hub side. As the flow rate decreased, the turbulence with lower frequency increased due to the rotating stall (Fig. 12), but the stall disappeared as the flow rate became lower. On the other hand, the reversed flow entering into the impeller occurred on the hub side below $\phi = 0.110$ (Fig. 13). This reversed flow would occupy the dead space caused by the periodically reversed flow toward the inlet duct in the section No. 3 provided that the tongue of the scroll were located downstream. For this effect, the fluctuation of the flow within the entire part of the channels was considerably disturbed at $\phi = 0.060$. Then, this continuous reversed flow from the diffuser would affect the reversed flow both at the pressure side near the exit of the impeller channel and the No. 3 section. In this way, another highly disturbed flow would be supplied to the diffuser inlet. This flow precipitated the generation of a full stall, hence resulting higher loss of the total pressure within the vaneless diffuser channel.

CONCLUSIONS

Flow patterns within the compressor channels at lower flow rates were represented as products of the interference of flows within each part of the channels. When the flow rate decreased, the rotating stall cell at the inlet duct was enlarged by the reversed eddy within the inducer channels and flow patterns within the impeller channels were influenced by the circumferentially deviated pressure distribution within the vaneless diffuser. The periodic disturbances of the flow developed at the inducer exit. Under this effect, the flow patterns exhibited uniformity toward the impeller exit.

At the flow rates lower than that capable of creating the rotating stall condition, a full stall was observed at the inlet, and another time-averaged reversed flow was recognized near the exit of the impeller channel at the pressure side. Then, the turbulence at the entrance region of the diffuser increased. This type of flow afterward caused the full stall condition within the channels and, finally, remarkably deteriorated performance characteristics of the compressor.

As to the classification of stalls and surge, only the stall was recognized in case of a smaller channel volume. A violent surge was only formed by a larger channel volume. Thus, the surge and its behavior following the stalls also would be governed by the capacity of the compressor.
system. Under the afore-mentioned conditions, the jet and wake flow patterns were not observed. The present authors estimate that similar phenomena concerning the disappearance of the wake would occur even in case of the compressor with channel diffusers between the semi-vaneless region and the impeller channels.

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