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A study of volute tongue and passage design on the performance of centrifugal turbomachines

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Abstract

The performance of six fan volutes have been investigated experimentally using a large-scale model of an overhang turbocharger compressor volute. Three-hole and five-hole yaw probes were used to obtain detailed measurements in the diffuser and volute. The investigation studied the impact of the size of the re-circulation port and the design of the tongue on the performance of the volutes. It is shown that performance was improved by the introduction of the re-circulating port. A modified volute design procedure that was applied to two of the designs did not lead to improved performance. It was shown that the shape of the tongue leading edge had an impact on performance particularly at high flow rates.

Introduction

The basic design procedure of spiral-shaped volutes for centrifugal turbomachines is based on a free vortex flow pattern and the assumption of a circumferentially uniform flow at the design condition. For the actual three-dimensional flow in a volute, the inlet flow angle cannot be maintained constant with azimuth angle. To maintain constant flow angle with azimuth angle and to obtain stable compressor performance at low flow rates, a re-circulating flow port at the volute tongue is usually adopted.

Yao et al.(4) proposed a design procedure that no longer considered the flow angle at volute inlet to be constant. This approach, which was further developed by Qi et al.(3), allows alternative volute profiles to be developed by varying the volute inlet flow angle with azimuth angle. Dilin et al.(1) applied this procedure to re-design a turbocharger volute and assessed its potential theoretically.

The design procedure described by Qi et al is applied here to modify the volute passage design of an overhang volute. The volute designs are then further developed to investigate the design and location of the tongue. By modifying the tongue design, and location, the area of the re-circulation port was modified, see Table 1. This had a significant effect on the flow separation from tongue leading edge and, as a consequence, improved the fan performance at high flow rates.

An experimental investigation was performed using a large-scale model of a compressor volute so that precise measurements in the diffuser and volute could be made through the use of three-hole and five-hole yaw probes.

Volute Design

The volute is usually designed through the application of a one dimensional analysis assuming a free vortex flow from volute inlet to the centre of the volute passage. Eck(2) showed that the radius of the volute passage is given by

$$r = \sqrt{\frac{\theta R_c q_v}{360\pi C_{u2} R_2} - \left(\frac{\theta q_v}{720\pi C_{u2} R_2}\right)^2} \qquad (1)$$

For many applications, particularly where installation constraints are important, overhang volute designs are employed. The amount of overhang must be specified. The magnitude of the overhang was specified as a linear function of azimuth angle such that

$$R_c - r = a + b\theta \qquad (2)$$

Where a and b are constants, R_C is the radius to the centroid and r is the radius of the volute passage. For the turbocharger volute design used in the experimental investigation it was observed that the linear relationship.

$$R_c - r = 0.1811 - 15.24\theta / 360 \times 10^3$$

accurately described the overhang of the volute.

In this study six overhang type volutes with square cross section are investigated

FA	A model of the turbocharger volute which was designed using the basic free vortex procedure.
FC	Same design procedure as design FA but with a re-circulating flow port.
NA	A modified passage design using a procedure which applied a high flow angle at small azimuth angles.
NC	Same as design NA but with a re-circulating flow port.
FCT	A modification of design FC but having a rounded tongue at the entrance to the re-circulating flow port.
FCT2	As design FCT, with a rounded tongue, but with a reduced re-circulating port area to reduce the frictional loss of the re-circulating flow.

Design NA was obtained by applying the Qi procedure with a high flow angle at low azimuth angles, see Fig.5. This had the effect of increasing the passage flow area at the low azimuth angles. The consequent re-circulating flow areas are given in Table 1.

Notation

ψ: pressure coefficient $\psi = P_S / \rho u_1^2$

φ: flow coefficient $\phi = C_{m2} / C_{u2}$

q_v : volume flow rate
P_s: static pressure
P_t: total pressure
ρ: density of fluid
u : peripheral velocity of impeller
C_m: meridian component of velocity
C_u: tangential component of velocity
θs: azimuth angle
α: flow angle
C_p: static pressure recovery coefficient

$$C_P = (P_{S3} - P_{S2}) / 1/2 \rho C_2^2$$

ξ: total pressure loss coefficient $\xi = (P_{t2} - P_{t3}) / 1/2 \rho C_2^2$

Subscripts
0 : impeller inlet
1 : diffuser inlet
2 : volute inlet (diffuser exit)
3 : volute exit

Apparatus and Instrumentation

The test facility is shown in Fig.1,2. For this investigation the rotational speed of the impeller was fixed at 4500 rpm. For the evaluation of velocity at the impeller exit, the slip factor of Wiesner was employed. A parallel walled vaneless diffuser was used. The basic design specification of the impeller and diffuser as follows:

Diameter of impeller inlet	d_0=152mm
Diameter of impeller exit	d=218mm
Impeller inlet blade angle (measured from tangential direction)	α_0=45
Impeller exit blade angle (measured from tangential direction)	α_1=60
Number of blades	20
Depth of diffuser passage	b_2=12.5mm
Diameter of diffuser inlet	d_1=248mm
Diameter of volute inlet	d_2=360mm

In this investigation six overhang volutes with a square cross sectional area were tested. For each volute the ratio of diffuser exit area to volute exit area (station3) was 1:0.84, and the area ratio to the discharged (station4) area was 1:1.32. Flow angle and pressure at the entrance of the diffuser was measured 15mm downstream of the impeller exit (station2) to avoid measurements in the jet-wake mixing region. The location of traverse measurement points for the three-hole and five-hole yaw probe is shown in Fig.4. The detailed internal flow near the volute tongue was also measured with a three-hole and five hole yaw probe. The pressure and flow angle at volute inlet (station2 in Fig.2) was obtained by mass flow averaging the three hole yaw probe traverse measurement data at 6 circumferential positions and 9 axial positions, a total of 54 locations. Similarly the data at volute exit (station3) were mass flow averaged from 54 five hole yaw probe measurements obtained in the plane normal to the exit duct.

Static pressures and total pressure losses were normalized by the dynamic pressure at the volute inlet. To evaluate the flow coefficient at volute inlet a free vortex flow was assumed through the vaneless diffuser.

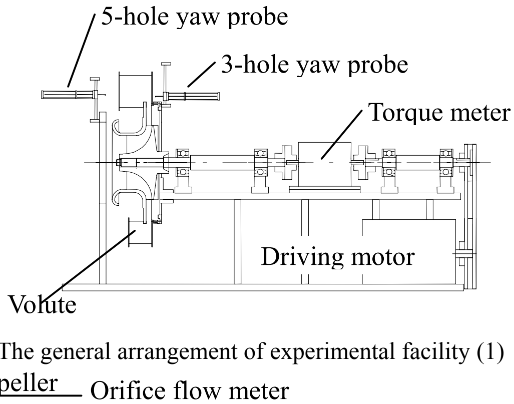


Fig.1 The general arrangement of experimental facility (1)

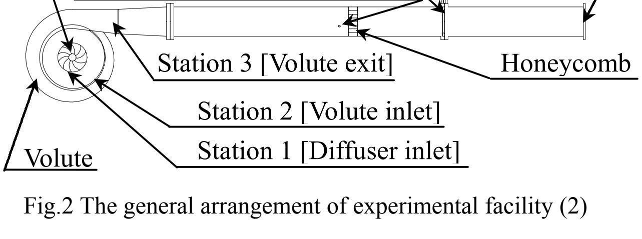


Fig.2 The general arrangement of experimental facility (2)

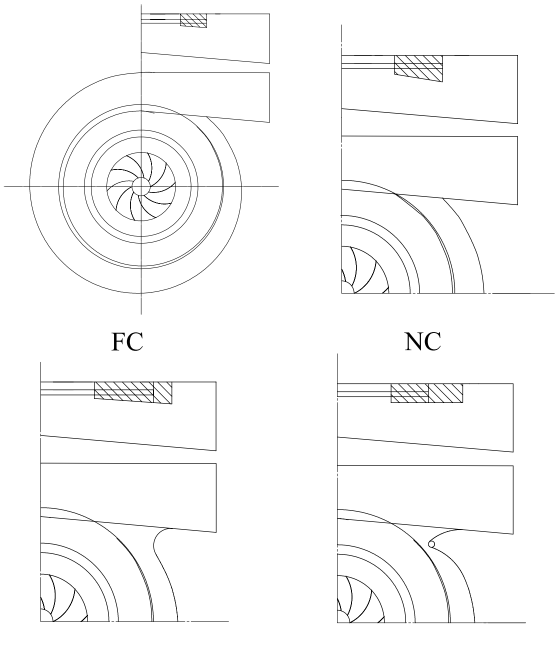
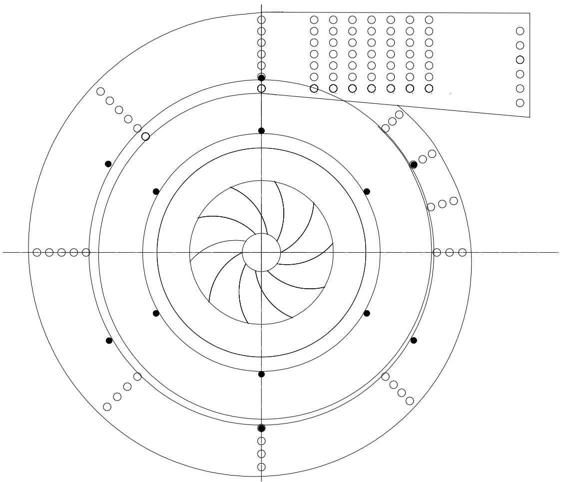


Fig.3 Volute configuration



● : Measured points by three-hole probe
○ : Measured points by five-hole probe

Fig.4 The locations for measurement points diffuser inlet volute inlet and volute exit flow.

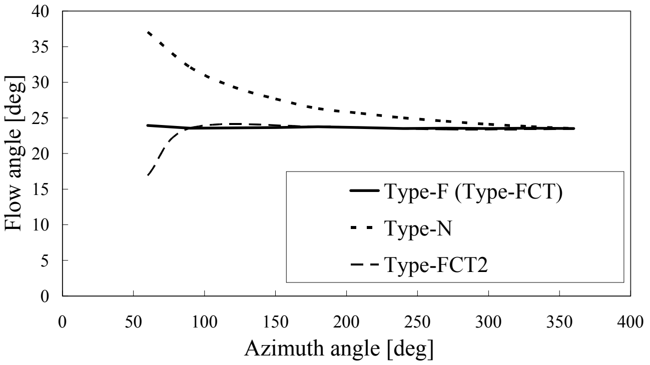


Fig.5 Specified inlet flow angle of the designed volute

Table.1 Area of re-circulating port normal to volute duct

Volute-type	F	N	FCT	FCT2
area(mm^2)	900	1764	1888.56	440.28

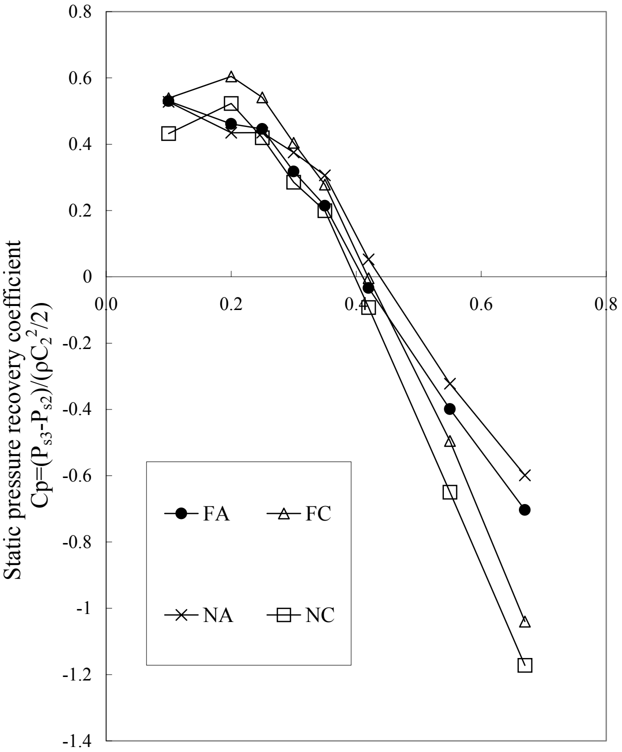


Fig.6 Static pressure recovery coefficient
(Station 2 to 3)

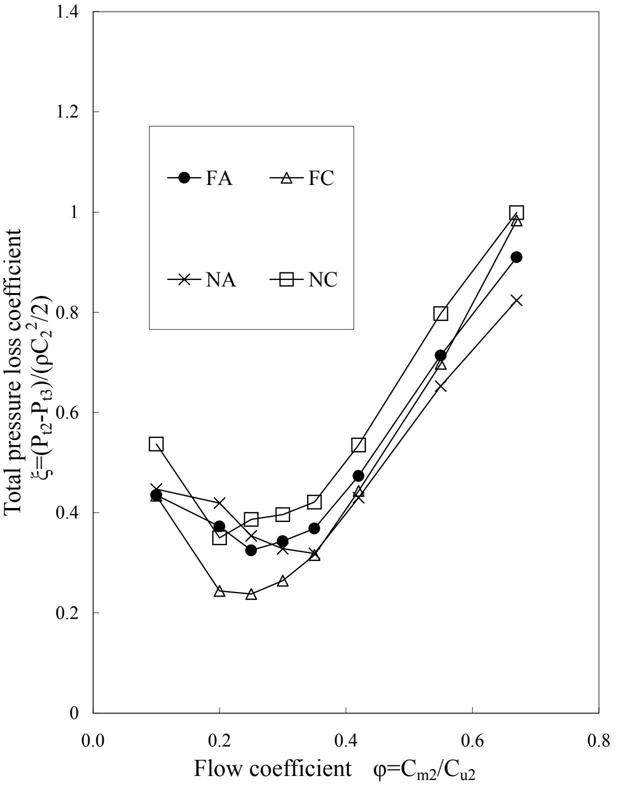


Fig.7 Total pressure loss coefficient
(Station 2 to 3)

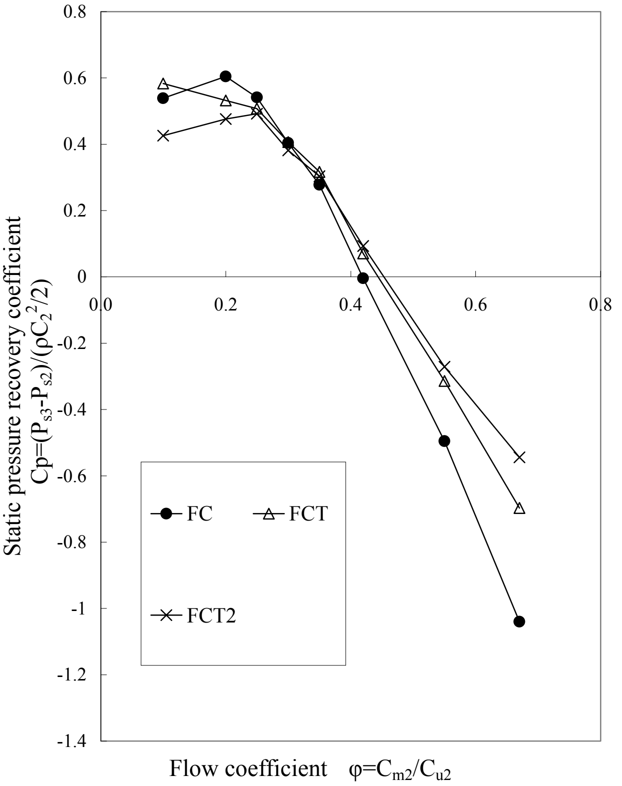


Fig.8 Static pressure recovery coefficient
(Station 2 to 3)

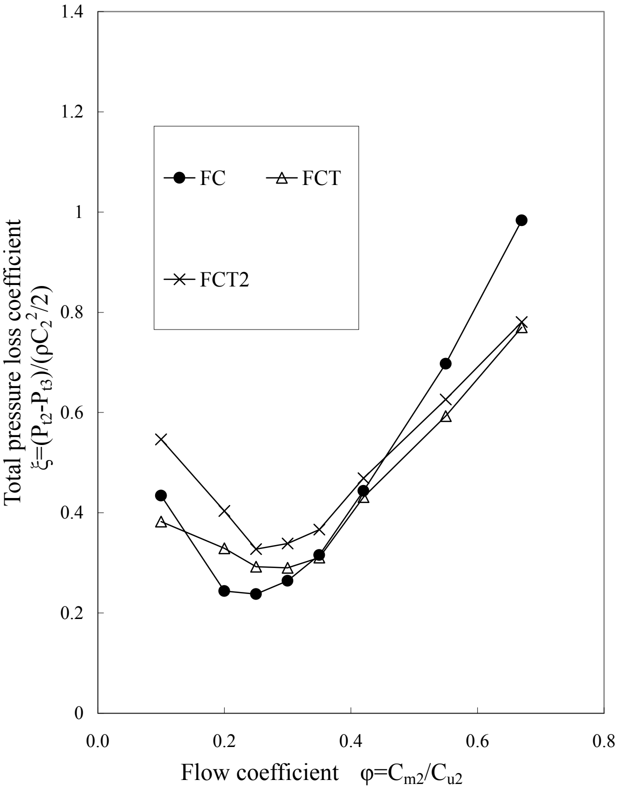


Fig.9 Total pressure loss coefficient
(Station 2 to 3)

Discussion of Results

The performance of the volutes is presented in terms of the pressure recovery coefficient and pressure loss coefficient across the volute as a function of the flow coefficient, C_{m2}/C_{u2}. Volute FA had a full tongue and did not provide a re-circulating port. By cutting back the tongue a re-circulating port was designed into volute FC. This inclusion of a re-circulating port led to an improved pressure recovery coefficient, Fig.6, and a reduced loss coefficient, Fig.7 for flow coefficients below 0.4. At flow coefficients in excess of 0.4 increased losses are shown by the introduction of a re-circulation port, volute FC, Fig.7.

Volute NA, with an increased passage area at low azimuth angles, did not provide improved performance over the flow coefficient range which yielded a positive pressure recovery coefficient, see Figs.6 and 7. Similarly no improvement was observed by the introduction of a re-circulation port. This is in contrast to the improvements shown by Qi and by the present authors for symmetric volute designs. A possible explanation for this is the nature of the swirl flow in the volute passage. For a symmetric volute two counter rotating vortices are set-up, whereas with an overhang design a single passage vortex is created. The two counter rotating vortices of the symmetric volute lead to increased blockage, and the increase in passage area by the design modification is effective in improving the performance.

The impact of modifying the tongue design of volute FC, the standard volute design, is shown in Figs.8 and 9. These figures compare the pressure recovery coefficients and loss coefficients obtained with volute FC with those obtained with the modified tongue designs, volutes T and T2. By introducing a rounded tongue, volute T, the performance was improved at high flow coefficients, and was comparable with the performance of volute FC at low flow coefficients. Further modification of the tongue design to reduce the area of the re-circulation port, volute T2, led to a reduction of the pressure recovery at low flow coefficients with no significant improvement at high flow rates.

The nature of the swirling flow in the volute passages of designs FC and NC is illustrated in Fig.10 for a flow coefficient of 0.2, that which gave maximum pressure recovery coefficient. The passage vortex is shown at azimuth angles of 60 and 90, where the modified design procedure led to an increase in the passage area, and at 10% section which is close to the centre of the vaneless diffuser passage. By increasing the volute passage area the strength of the vortex has been substantially reduced. For design NC at 60° azimuth angle the vortex is such that it does not fully fill the passage and it appears as if the passage size is now too large. At an azimuth angle of 90° the passage vortex for volute NC is more developed than that at 60° but is still weak compared to that of volute FC.

The nature of the flow around the volute with a modified tongue design is shown in Fig.11. This shows the flow pattern in the r-θ plane and at a cross-section coincident with the centre of the vaneless diffuser passage. At the highest flow coefficient of 0.67 the flow separates off the leading edge of the tongue of design FC. This leads to a substantial wake in the discharge duct. The degree of separation, and the consequent wake, is significantly reduced by the adoption of the rounded tongue. In the re-circulation passage the flow is very disordered in the region of the tongue. For design FC the flow in the re-circulation duct is in the reverse direction with air flowing backwards into the discharge duct.

Conclusions

Volute performance was improved by the introduction of a re-circulating port. Modifying the design of the volute passage according to the procedure described by Qi et al did not lead to improved performance. It is concluded that the design procedure is not as effective for overhang designs as it is for symmetric designs. However, the results shown by the measurement of the passage vortex suggest that the volute passage design was too large. It is possible that a reduced area, but larger than that given by the free vortex design, may lead to a performance improvement.

The design of the leading edge of the tongue has a significant impact on volute performance at high flow rates. A rounded tongue reduces the degree of flow separation and the magnitude of the following wake in the discharge duct. In addition the flow in the re-circulation passage was more orderly with the rounded tongue design.

References

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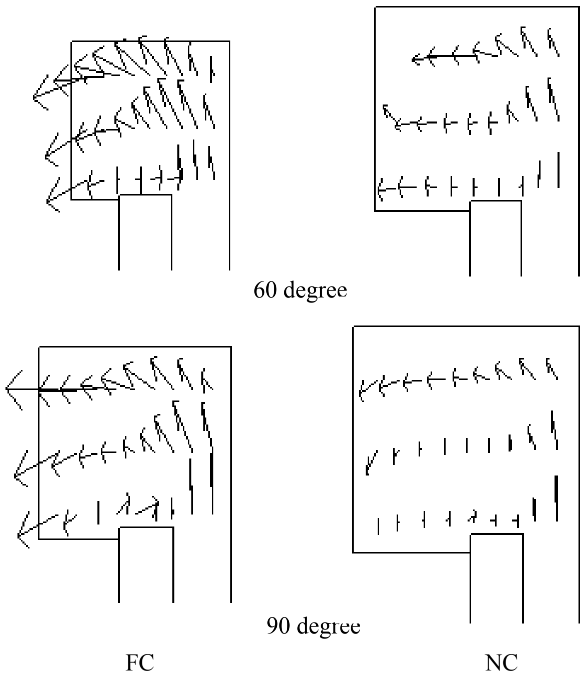

Fig.10 Distribution of meridian component of velocity (φ=0.20)

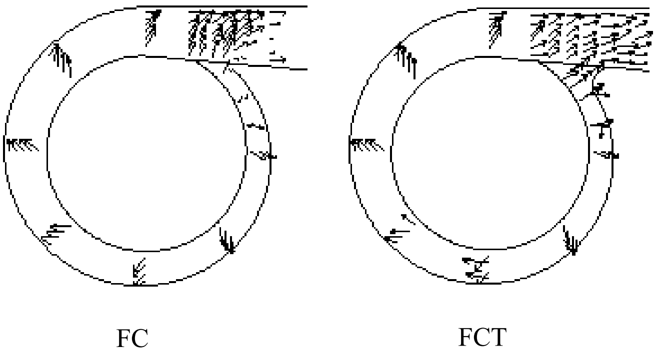

Fig.11 Distribution of r-θ component of velocity (φ=0.67)