Unsteady Diffuser Vane Pressure and Impeller Wake Measurements in a Centrifugal Pump

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ABSTRACT

Unsteady surface pressure measurements on a vaned diffuser of a centrifugal pump, and wake measurements of the flow exiting a centrifugal impeller into a vaneless diffuser are presented. Frequency spectra and ensemble averages are given for the unsteady measurements. Two different impellers were used, the pump impeller of the HPOTP (High Pressure Oxygen Turbopump) of the SSME (Space Shuttle Main Engine) and a two-dimensional impeller. The magnitude of the unsteady total pressure measured in the stationary frame at the impeller exit was found to be of the same order of magnitude as the total pressure rise across the pump. The magnitude of the unsteady diffuser vane pressures was observed to be significantly different on suction and pressure side of the vane, attaining its largest value on the suction side near the leading edge while decreasing along the vane.

INTRODUCTION

The present study is the first part of an experimental program to investigate rotor-stator interaction in high performance centrifugal pumps with the aim to gain a better understanding of the unsteady pressures impeller blades and diffuser vanes are subjected to. Several intensive studies of flow development inside centrifugal impellers have been made by Eckardt[1], Inoue[2], and Krain[3]. In the present work averaged instantaneous total pressure measurements of the flow exiting an impeller into a vaneless volute, and averaged instantaneous vane pressure measurements on diffuser vanes will be reported. The experiments were conducted for two different radial gaps between the respective impeller trailing edge and the diffuser vane leading edge.

TEST FACILITY AND INSTRUMENTATION

The experiments were conducted in a recirculating water test loop. For the total pressure measurements, the test rig was equipped with either of the two test impellers and a vaneless diffuser of trapezoidal cross section, referred to as Volute D. For the vane pressure measurements, a specially manufactured vaned diffuser, referred to as Diffuser S, and either of the two test impellers were used.

The two test impellers are a two-dimensional research impeller, referred to as Impeller Z, and one side of the double suction pump impeller of the HPOTP of the SSME, referred to as Impeller R. Impeller Z is a five-bladed impeller, the blades being logarithmic spirals with a blade angle of 25 degrees. Impeller R has eight blades in total with four partial blades, and an inducer with four inducer blades. The blade angle for both the partial and the full blades at the trailing edge is about 36 degrees. The outer diameter of Impeller R had to be reduced slightly for the impeller to be run in the present test facility.

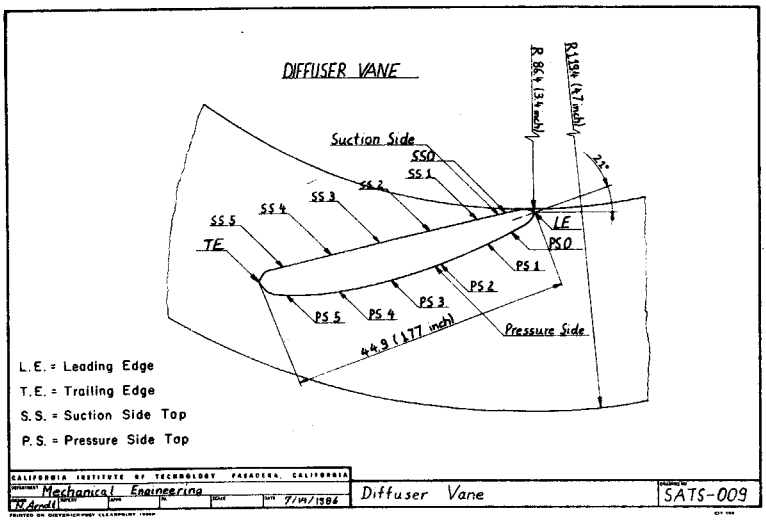


Fig. 1. Vane of Diffuser S

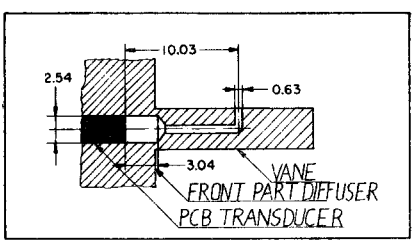
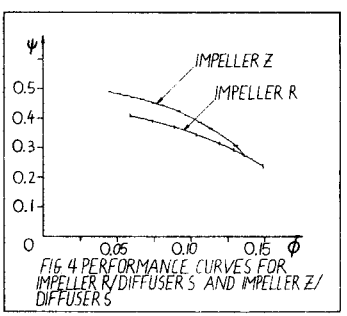


Fig. 2. Pressure Tap



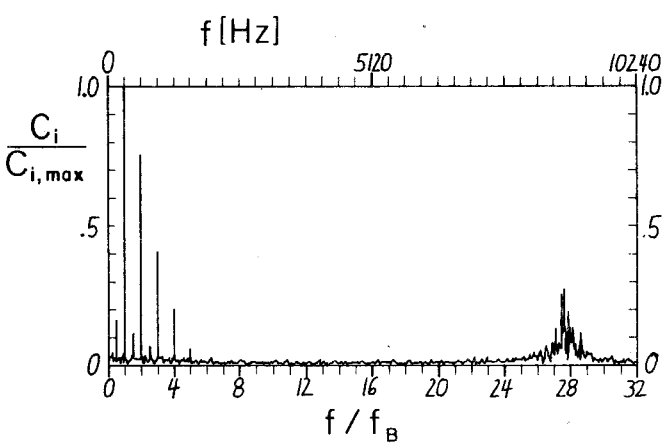


Fig. 3. Magnitude of normalized Fourier coefficients for instantaneous vane pressure measurements at suction side tap 1 (rpm=2400, ϕ=.15, R_3/R_2 = 1.046)

The impeller shaft runs on an eccentric orbit with respect to the volute or diffuser. By positioning the impeller on different locations on the eccentric orbit, different distances between the impeller trailing edge and the total pressure probe as well as the particular instrumented diffuser vane could be attained.

Diffuser S is a straight wall, constant width diffuser with nine vanes. The vanes do have the same shape as the vanes in the diffuser of the HPOTP of the SSME; however, the number of vanes was reduced to nine, and the vanes were spaced closer to the impeller trailing edge than they are currently in the SSME.

Piezoelectric PCB miniature pressure transducers were used for the pressure measurements.

Total pressure measurements were made by inserting a total pressure probe into Volute D . The diameter of the impact probe was reduced several times until no increase in the magnitude of the total pressure was observed. All data on total pressure reported herein were taken with a 0.63 mm inner diameter impact probe.

Diffuser vane pressures were measured at 20 different locations on the vanes, 14 of those located at the centerline of pressure and suction side, the remaining six being distributed axially between suction shroud and hub or back shroud at two different locations downstream of the leading edge on the suction side (Figs.1 and 2). A constraint on the geometry of the pressure tap was the frequency response; for the present geometry, the eigenfrequency was estimated, using a Helmholtz resonator model, to be 8000 Hz. The blade passage frequency at 2400 rpm, the highest speed at which tests were run, is 320 Hz for Impeller R. The spectrum of instantaneous vane pressure measurements (Fig. 3) taken at suction side tap 1 for Impeller R at 2400 rpm and ϕ = .15 shows that the model gave a reasonable estimate on the eigenfrequency of the pressure response.

The data were sampled and discretized in a 16 channel "data taker" made at Caltech. An encoder was used on the main shaft to trigger the data taker and to provide a clock for the data taker. The maximum sampling frequency of the data taker is 32 kHz; 1024 data per main shaft cycle were taken for speeds up to 1800 rpm, 512 for higher speeds. Since the signal contained some noise the discretized data were averaged. For Impeller Z the averaging was done over 512 main shaft cycles, for Impeller R over 2048 full and partial blade passages. However, the frequency spectrum presented was obtained by a Fast Fourier Transform on nonaveraged instantaneous data.

OVERALL PERFORMANCE

Performance curves were taken for Impeller R/Diffuser S and Impeller Z/Diffuser S. The results are shown in Fig. 4. Impeller R achieves a higher flow coefficient; however, the head coefficient attained by Impeller Z is considerably higher.

DISCUSSION OF EXPERIMENTAL RESULTS

Averaged Instantaneous Total Pressure Measurements.- For Impeller R, averaged instantaneous total pressure measurements made at the centerline of Volute D at 1200 rpm and ϕ = .12 with two different radial gaps between impeller trailing edge and impact probe are presented in Fig. 5a (r_3/R_2=1.02) and b (r_3/R_2=1.05). The fluctuations are of the same order of magnitude as the total pressure rise across the pump. They are strongly decreasing with increasing (r_3/R_2). For r_3/R_2=1.02 it is

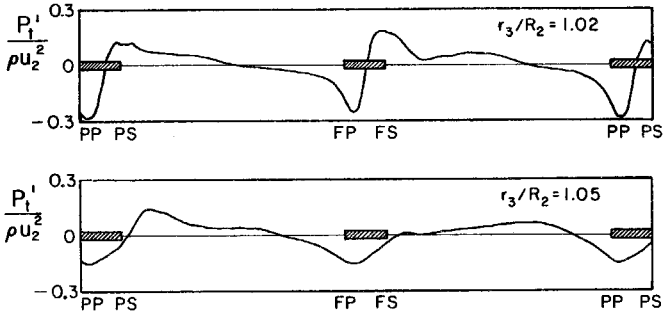


Fig. 5a and 5b. Averaged instantaneous total pressure measurements for Impeller R at centerline of Volute D for r_3/R_2=1.02 (top) and r_3/R_2=1.05 (bottom). RPM = 1200, ϕ=.12, the cross-hatching indicates the blade trailing edge. FP=full blade pressure side, FS=full blade suction side, PP=partial blade pressure side, PS=partial blade suction side

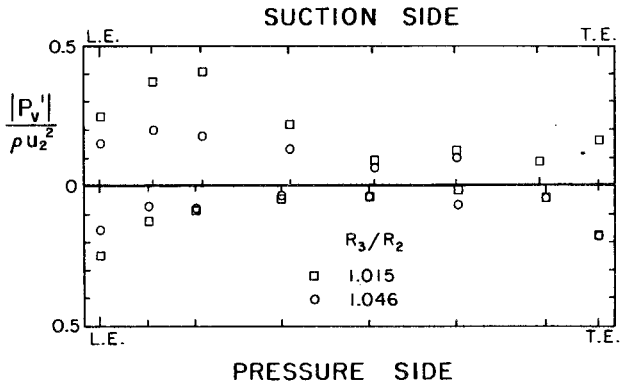


Fig. 6 Averaged instantaneous vane pressure measurements for Impeller R at vane centerline. RPM=1800, ϕ=.12, R_3/R_2=1.015 and 1.046

evident that the wake is located on the suction side of the blades. There is, however, a difference in the flow along full and partial blades. This becomes particularly obvious for r_3/R_2=1.05. It therefore appears that the mixing process may be different for the different blades.

Averaged Instantaneous Diffuser Vane Pressure Measurements. -As the main purpose of this experiment was the investigation of the instantaneous vane pressures, vane pressure measurements were taken for both impellers at several flow coefficients and two different ratios of R_3/R_2. All data presented were, if not otherwise mentioned, taken at shaft speeds of 1800 rpm for Impeller R and 1200 rpm for Impeller Z. Figure 3 shows the spectrum of instantaneous vane pressure measurements taken at suction side tap 1 for Impeller R at 2400 rpm and ϕ=.15. It is evident that the fluctuations are periodic with blade passage frequency. Furthermore, the difference in a partial or full impeller blade passing by the vane is evident from the half blade passage frequency seen in Fig. 3.

Figures 5 to 8 show the magnitude of the fluctuating vane pressure along the vane centerline . In Fig. 6 measurements are presented for Impeller R, one flow coefficient (ϕ=.12) and two ratios R_3/R_2; whereas in Fig. 7 and 8 measurements are presented for Impeller R and Impeller Z and one ratio R_3/R_2 (1.046 and 1.052, respectively) but two different flow coefficients (ϕ=.15 and .09 for Impeller R, and ϕ=.14 and .10 for Impeller Z). The fluctuations are in all of the cases presented largest on the front part of the suction side of the vane, and in that region they attain values comparable to the total pressure rise aross the pump. The location of the largest fluctuation in this region seems to depend on flow coefficient. Moving downstream along the suction side of the vane, the fluctuations decrease, but it appears that they attain a rather small relative maximum on the rear part of the vane. On the pressure side, the fluctuations are generally smaller than on the suction side and they are largest in the vicinity of the leading edge and decrease downstream along the vane. It appears that they, at least for Impeller R, also attain a relative maximum on the rear half of the vane. The authors as yet do not have an explanation for the large fluctuations at the trailing edge that were measured when Impeller R was used as test impeller.

The fluctuations decrease, especially on the front half of the vane, significantly with increasing R_3/R_2 (Fig. 6).

For both test impellers, the fluctuations on the front half of the suction side are smaller for the lower flow coefficient (Figs. 7 and 8). For Impeller R the fluctuations continue to be smaller on the rear part of the vane; however , for Impeller Z they are approximately equal.

In order to investigate to which extent the instantaneous vane pressures vary across the span of the vane, four taps were spaced on the suction side at two different locations from the leading edge. Due to the limited number of vanes a similar investigation could not be done on the pressure side. The magnitude of the instantaneous vane pressures for Impeller R was found to vary significantly across the span, being largest near the hub and decreasing strongly towards the shroud (Fig. 9). These variations are still noticeable further downstream at the second measurement location. The differences in magnitude of the fluctuating vane pressure across the span for Impeller Z are smaller at both measuring locations (Fig. 9).

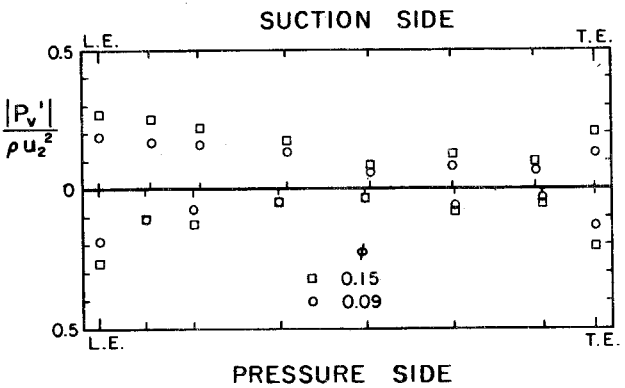


Fig. 7. Averaged instantaneous vane pressure measurements for Impeller R at vane centerline. RPM=1800, ϕ=.15 and .09, R_3/R_2=1.046

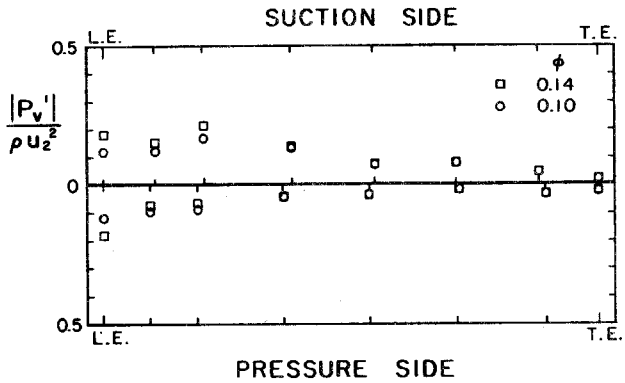


Fig. 8. Averaged instantaneous vane pressure measurements for Impeller Z at vane centerline. RPM=1200, ϕ=.14 and .10, R_3/R_2=1.052

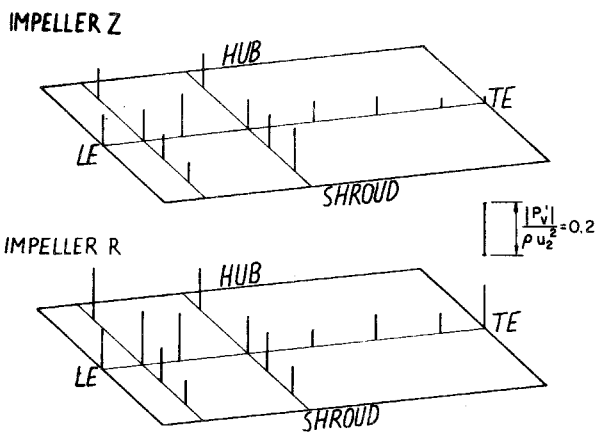


Fig. 9 Averaged instantaneous pressure measurements on the suction side of the diffuser vane for Impeller R (RPM=1800, ϕ=.12, R_3/R_2=1.046) and Impeller Z (RPM=1200, ϕ=.10, R_3/R_2=1.052)

CONCLUSION

Instantaneous total pressure measurements and instantaneous vane pressure measurements were taken for two different impellers operating in a vaneless volute and a vaned diffuser, respectively. As for the total pressure, for Impeller R

* the fluctuations are of about the same magnitude as the total pressure rise
* the fluctuations decrease strongly with increasing distance to the impeller
* the wakes are mostly located on the suction side of the blade

As for the vane pressures, for both impellers

* the fluctuations were largest on the suction side in the vicinity of the leading edge
* the fluctuations were larger on the suction side than on the pressure side
* the fluctuations especially on the front half of the vane decreased significantly when the distance from the impeller trailing edge to the vane leading edge was increased.

For the pump impeller of the HPOTP of the SSME

* the fluctuations were significantly larger near the hub than near the shroud

For the two-dimensional impeller

* the differences in fluctuation between hub and shroud were small.

The present study has shown that the diffuser vanes in a centrifugal compressor stage are subject to considerable pressure fluctuations. For the three-dimensional centrifugal impeller of the HPOTP of the SSME the vane pressure fluctuations vary over the span as well as along the vane.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A_2 =impeller discharge area
b_2 =impeller discharge width
c_i =magnitude of i'th Fourier coefficient
$c^{i,max}$ =magnitude of largest Fourier coefficient
f =frequency
f_b =impeller blade passage frequency
p_t =total pressure
p_{t1} =upstream total pressure
p_{t2} =downstream total pressure
p_v =vane pressure
Q =flow rate
R_2 =impeller discharge radius (83.82 mm for Impeller R
80.92 mm for Impeller Z)
R_3 =shortest distance between diffuser vane and center of impeller rotation
r_3 =distance from impact probe to center of impeller rotation
u_2 =impeller tip speed ($u_2=2R_2\pi f$)
ρ =density of water
ϕ =flow coefficient ($\phi =Q/(u_2A_2)$)

ψ =total head coefficient ($\psi = (p_{t2}-p_{t1})/(u_2^2\rho)$)

SUPERSCRIPT

' = averaged instantaneous values

ABBREVIATIONS

FP	pressure side of full impeller blade
FS	suction side of full impeller blade
HPOTP	High Pressure Oxygen Turbopump
Hz	hertz
LE	diffuser vane leading edge
PCB	PCB PIEZOTRONICS, INC. DEPEW, NEW YORK 14043
PP	pressure side of partial impeller blade
PS	suction side of partial impeller blade
PS0-PS5	pressure measurement taps on pressure side of diffuser vane
rpm	revolutions per minute
SS0-SS5	pressure measurement taps on suction side of diffuser vane
SSME	Space Shuttle Main Engine
TE	diffuser vane trailing edge

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