# Identification on Fatigue Failure of Impeller at Single Stage Feedwater Pumps During Commissioning Operation

# 단단 주 급수 펌프 임펠러에서 시운전 중 발생한 피로 절손에 관한 규명 연구

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**Key Words** : Impeller(임펠러), Pulsation(맥동), Vibration(진동), Alternating Stress(교번응력), Fatigue(피로), Failure(절손)

## ABSTRACT

This paper presents a case history on failures of impeller and shaft due to pressure pulsation at single stage feed water pumps in 700 MW nuclear power plant during commissioning operation. The pumps had been service and had run for approximately 40~50 hours. For the most part, the failures of impeller occurred with the presence of a number of fatigue cracks. All cracks were associated with the deleterious surface layer of impeller by visual and metallurgical examination. On-site testing and analytical approach was performed on the systems to diagnose the problem and develop a solution to reduce the effect of exciting sources. A major concern at high-energy centrifugal pump is the pressure pulsation created from trailing edge of the impeller blade, flow separation and recirculation at centrifugal pumps of partial load. Pressure pulsation due to the interaction generating between impeller and casing coincided with natural frequencies of the impeller and shaft system during low load operation. It was identified that dynamic stress exceeding the fatigue strength of the material at the thin shroud section due to the hydraulic instability at running condition below BEP.

## 요 약

이 논문은 건설이 완료된 700 MW급 발전소의 시운전 기간 중 주 급수펌프 임펠러에서 반복적으로 발생된 웨어링 이탈 및 고착, 슈라우드 손상 그리고 축 절단 등의 절손이 부분부하 조건에서 증폭되는 압력맥동과 연관이 있는 것으로 규명되었다.

## 1. Introduction

There are many flow induced pressure pulsation mechanisms and vibration that can introduce catastrophic failures in high pressure water system. For instance, flow instability can give rise to shocks in boiler feed water pump (BFP) system of nuclear power station. This paper presents a topic on the root cause of the

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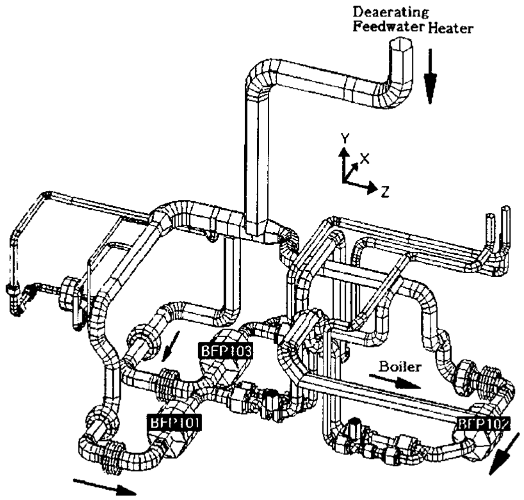



**Fig. 1** View of boiler feed water system layout

failures of impeller occurred at single-stage feed water pumps. Horizontal single-stage, double-suction, single discharge volute centrifugal pumps are in service at 3 units of 700 MW nuclear power station in Korea. This system shown in Fig. has been commissioned since 1997.

The impeller of a pump had failed after had run for approximately 50 hours on recirculation mode operation. A piece of shroud had become detached from the impeller and cracks were evident on a number of vanes and the vane tip/shroud intersection. Subsequent examination of the impeller from another pump, after 42 hours operation, also revealed cracks at the impeller vane tips. The impeller material was in accordance with the specified requirements of ASTM A747 CB 7Cu2 H1150M condition. So, the reduction of the diameter to meet the flow requirements was immediately undertaken to minimize working stress levels. The impeller material was changed to ASTM A743 CA-6NM alloy, which is improved ductility. However, the pump shaft instead of the impeller was broken during low load operation when was in service. The pump was manually stopped after a high vibration alarm went off.

**Fig. 2** View of impeller showing failed section at vane

## 2. Metallurgical Investigations

Figure 2 shows the failed section of pump impeller. The impeller was examined visually and the fractographic detail of the failed section was typical of a fatigue crack which had initiated at the vane tip. The impellers failed due to high cycle fatigue with significant cracks being initiated at impeller vane trailing edge tips at areas where the vane trip dressing had been blended into the "as cast" surface on the suction side of the vanes.

Metallurgical examination of the "as cast" surfaces revealed an abnormal surface layer with a coarse grain structure varying in thickness. The cause of the surface layer formation had been attributed to an unanticipated abnormality that occurred during the heat treatment. All cracks were associated with a deleterious surface layer which had been produced during the manufacture process. The pump was manually stopped after a high vibration alarm went off.

## 3. Fatigue Stress Analysis for Root Cause

The pump manufacturer undertook the fatigue

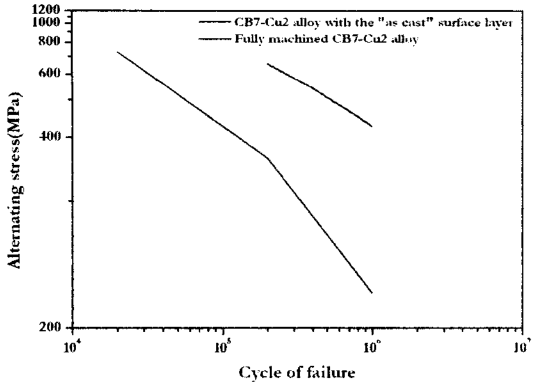



**Fig. 3** S-N curves of impeller materials

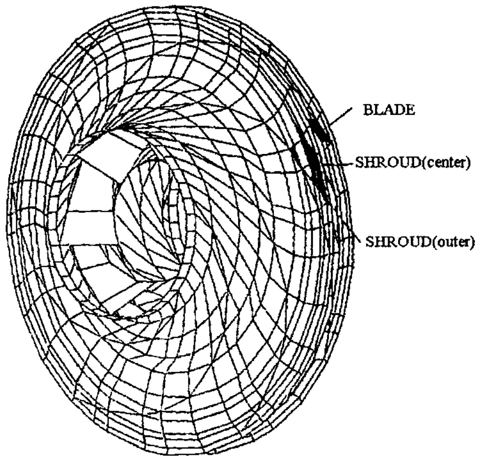



**Fig. 4** View of positions of maximum fatigue stress on impeller

testing of the samples of materials from the failed impellers with the "as cast" surface layer together with samples of fully machined CB7-Cu2 alloy. The results of the failed impellers samples were shown an order of magnitude lower than the fully machined CB7-Cu2 alloy in Fig. 3. Figure 3 shows that the fatigue limit reduced from 210 MPa to 170 MPa.

The pump impeller was subjected to worst pressure of 510 kPa and centrifugal loads of 3580 rpm, as steady state loading, and pulsation load applied to the blade outlet and adjacent shroud area. The pressure pulsation involves the interaction of the impeller pressure field with the stationary circumferential pressure field generated by a volute tongue. This is confirmed experimentally and is a function of tip gap and blade configuration. This value is indicative of the unsteady forces acting on the volute tongue. The magnitude of pulsation load is 375 kPa by the pump manufacturer. The mean and alternating stresses at each point of impeller was computed by finite element analysis method. Figure 4 shows the positions of maximum fatigue stress in the outer shroud, blade and central shroud.

The maximum dynamic stress was 129.0 MPa under pulsation loading. There was high stress at the blade tip where the pulsation is applied. The maximum mean stress is 179.0 MPa at mid radius adjacent to the blade.

The fatigue stress was a peak value of 199.8 MPa at blade tip of the failed impeller. This value was over 170.0 MPa, which is the fatigue limit of the impeller materials with the "as cast" surface layer in Fig. 3.

## 4. Natural Modal Test for Pump Impeller System

The measurement of natural vibration for pump impeller was required to diagnose the impeller failure problems and to specify counter-measures. Breakage of the impeller side plates due to dynamic loading of mostly associated with a resonance between a natural frequency of the impeller side plates and the exciting pressure pulsations(Florjancic, 1973). The impeller was investigated the possibility that impeller natural frequencies could have been excited. The inertance plot for the pump impeller is shown in Fig. 5. Modal test results are shown in Fig. 6. As can be seen from Fig. 6, the modes at 746 Hz, 130 kHz and 156 kHz are dominant modes for the impeller. In water all frequencies are reduced and become less responsive to the magnitude of the input force. In terms of

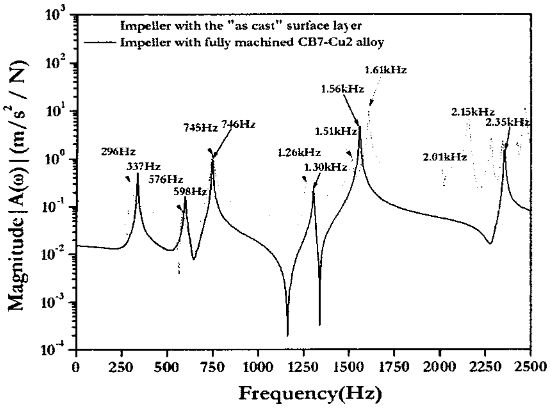



**Fig. 5** Plot of impeller inertance in air

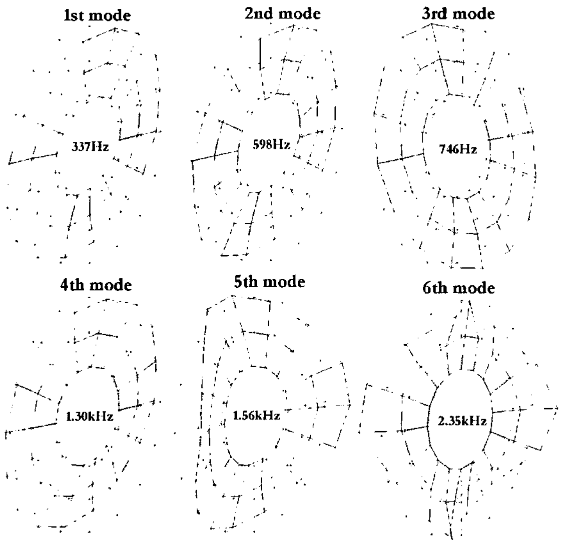
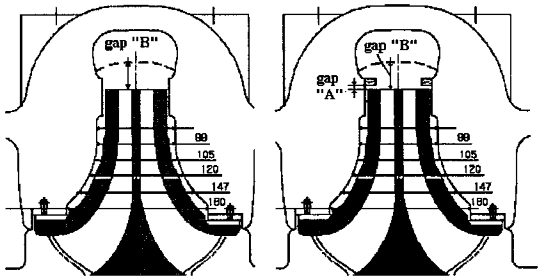



**Fig. 6** Views of natural mode shapes for impeller with fully machined CB7-Cu2 alloy in air

excitation possibilities of these modes within the pump, the six impeller vanes and two volute vanes would be expected to produce a pressure distribution which would excite only two nodal diameter modes. Generally, It is said that single diameter modes would tend not be exited by 6 and 2 blade combinations.

## 5. Main Exciting Source for Pump Impeller System

The measurements were made on all pumps in field as part of an investigation into the cause of damages. Normally the wake flow at the impeller outlet is the strongest source of pressure pulsation in a centrifugal pump. Broad band excitation forces are caused by large turbulence, flow separation, and flow recirculation. Recirculation between the impeller outlet and volute inlet with large eddies and strong velocity gradients always introduces additional dynamic loading forces on the rotor. Pressure pulsations were measured preferably by piezoelectric pressure transducers mounted in the suction and discharge branch of the pumps. The amount of pressure pulsations actually radiated into the piping system is only a small fraction of the variation of the total pressure at the impeller exit and depends on the acoustic radiation efficiency and the acoustic pipe impedance. Boiler feed water pump systems of two units have “type I” volute in nuclear power station and the pumps of other unit are “type II” as shown in Fig. 7. These tests were made in condition that the failed impeller be changed to new type impeller.




(a) Type I (b) Type II

**Fig. 7** View for comparison between two type volutes

### 5.1 Pressure pulsations due to “Type I”

The radial gap between the impeller vane outer diameter and volute tongues is considered the most important design parameter which affects the pressure pulsations at blade passing frequency. Pulsations can be influenced by the

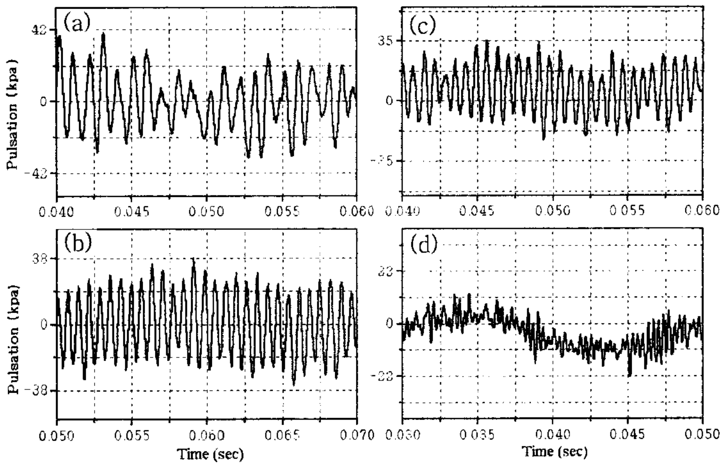


**Fig. 8** Pulsation waves measured at discharge pipe of "type I" volute pump; (a) 100 % recirculation flow, (b) 70 % recirculation flow, (c) 60 % recirculation flow and (d) <3 % recirculation flow

**Table 1** Pulsation frequencies obtained from recirculation conditions through the changeover operation for the pump with "Type I" volute

| Mode | 100 % | 70 % | 60 % | <3 % |
|---|---|---|---|---|
| 1st(Hz) | 712.5 | 762.5 | 806 | 825 |
| 2nd(Hz) | 1431 | 1525 | 1906 | 2038 |

shape of the impeller blade trailing edge. Fig. 8 is shown the pulsation waves obtained from recirculation operation tests for the pump system with "type I" volute.

Detailed of test which summarized in Fig. 8 are given in Table 1. During the changeover from one pump to the standby pump it was obtained pulsation frequencies shifted at recirculation conditions at type I volute pump system.

The 1st mode frequency of pulsation was shifted from 712.5 Hz to 825 Hz. The 2nd mode frequency of pulsation was shifted from 1431 Hz to 2038 Hz. These data show the possibility that the impeller's natural modes, 3rd, 4th, 5th could have been coincide with the 1st frequency or the 2nd frequency of pressure pulsations

### 5.2 Pressure pulsations due to "Type II"

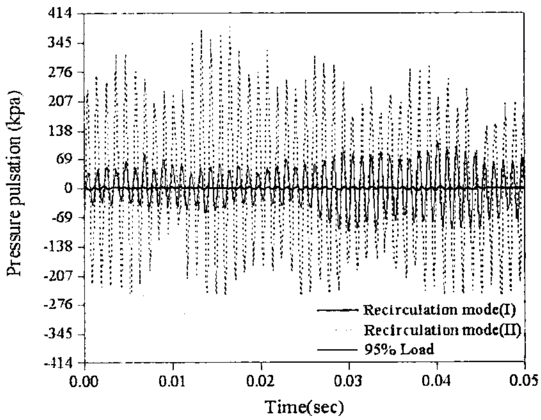


**Fig. 9** Pulsation waves measured at discharge pipe of "type II" volute pump; mode (I) : >60 % recirculation flow, mode (II) : <60 % recirculation flow

The pressure pulsation measured depends strongly on the characteristics of the pump system. Part load recirculation at the impeller outlet leads to an increase of the pressure pulsation at distinct frequencies as well as broad band pulsations. Figure 9 shows the pulsation waves which were measured by piezoelectric pressure transducers installed at discharge pipe for "Type II" in Fig. 7.

Figure 10 shows the pulsation spectra measured at discharge pipe of "type II" volute

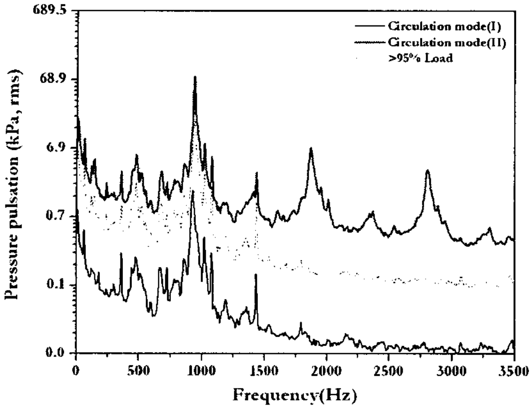



**Fig. 10** Pulsation spectra measured at discharge pipe of "type II" volute pump; mode(I) : > 60 % recirculation flow, mode(II) : <60 % recirculation flow

pump. The acoustic resonance phenomena were occurred when the magnitude of the pressure pulsation wave suddenly increased at part load recirculation condition in the impeller outlet pipe. 8× rotation frequency's harmonics and 928 Hz's harmonics were amplified 100 times as many as these of recirculation (I). These results show the possibility that the impeller had been failed by amplified pulsation. It is assumed that maximum pressure pulsation amplitude in impeller could be increased more than that of the pulsation in the discharge pipe. It could be assumed that the real magnitude of pulsation load at impeller was not less than 375 kPa of the pump manufacturer.

## 6. Conclusion

Based on the tests on two type volute pumps as follows :

- Many cracks had been found at the failed impeller. Because of the fatigue strength reduction due to the "as cast" surface layer, the impeller exceeds the fatigue limit.
- The wake flow at the impeller outlet is the strongest source of pressure pulsation in the centrifugal pump.
- The test results on the pump with no gap "A" show the possibility that the impeller's natural modes coincide with the pressure pulsation.
- The test results with gap "A" show that the magnitude of the pressure pulsation wave is suddenly magnified at part load of recirculation condition in the impeller outlet pipe. Especially, Part load recirculation at the impeller outlet leads to an increase of the pressure pulsation at distinct frequencies.
- Therefore, it could be assumed that root cause of the impeller failure is resonance between the impeller and the frequencies of the pressure pulsation waves at "Type I" and is the acoustic amplification of pressure pulsation wave at "Type II".

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