The Analysis of Flow-Induced Vibration and Design Improvement in KSNP Steam Generators of UCN #5, 6

Sang-Nyung Kim*, Yeon-Sik Cho
Department of Nuclear Engineering, Kyunghee University, Seocheon-ri #1, Kiheung-up, Youngin-city, Kyung-gi-do 449-701, Korea.

The KSNP Steam Generators (Youngkwang Unit 3 and 4, Ulchin Unit 3 and 4) have a problem of U-tube fretting wear due to Flow Induced Vibration (FIV). In particular, the wear is localized and concentrated in a small area of upper part of U-bend in the Central Cavity region. The region has some conditions susceptible to the FIV, which are high flow velocity, high void fraction, and long unsupported span. Even though the FIV could be occurred by many mechanisms, the main mechanism would be fluid-elastic instability, or turbulent excitation. To remedy the problem, Eggcrate Flow Distribution Plate (EFDP) was installed in the Central Cavity region of Ulchin Unit 5 and 6 steam generators, so that it reduces the flow velocity in the region to a certain level. However, the cause of the FIV and the effectiveness of the EFDP was not thoroughly studied and checked. In this study, therefore the Stability Ratio (SR), which is the ratio of the actual velocity to the critical velocity, was compared between the value before the installation of EFDP and that after. Also the possibility of fluid-elastic instability of KSNP steam generator and the effectiveness of EFDP were checked based on the ATHOS3 code calculation and the Pettigrew's experimental results. The calculated results were plotted in a fluid-elastic instability criteria-diagram (Pettigrew, 1998, Fig. 9). The plotted result showed that KSNP steam generator with EFDP had the margin of Fluid-Elastic Instability by almost 25%.

Key Words: Flow-Induced Vibration (FIV), Eggcrate Flow Distribution Plates (EFDP), Stability Ratio (SR) Fluid-Elastic Instability, Critical Velocity, Korea Standard Nuclear Plant (KSNP)

Nomenclature

D : Outside diameter of tube
De : Equivalent diameter of flow boundary
f_n, f : Natural frequency
K : Instability constant
m_k : Hydraulic(Added) mass
m_o : Effective mass of tube
P : Pitch of tube array
V_{crit} : Critical velocity
V_{eff} : Effective velocity
V_p : Gap velocity
V(x) : Cross flow velocity spanwise variation
x : Spanwise coordinate measured along tube axis
P/D : Pith to diameter ratio

Greeks

α : Void fraction
δ_0 : Logarithmic decrement($=2\pi\zeta$)
$\phi(x)$: Spanwise variation in normalized modal displacement
ρ_0 : Secondary fluid density(average)
$\rho(x)$: Secondary fluid density spanwise variation
ρ_{TP} : Two phase density
ζ : Damping ratio

* Corresponding Author,
E-mail : snkim@khu.ac.kr
TEL : +82-31-201-2561; **FAX** : +82-31-202-1541
Department of Nuclear Engineering, Kyunghee University, Seocheon-ri #1, Kiheung-up, Youngin-city, Kyung- gi-do 449-701, Korea. (Manuscript **Received** February 4, 2003; **Revised** September 29, 2003)

ζ_{fD}	: Film dynamic damping
ζ_S	: Structural damping
ζ_{TP}	: Two-phase damping
ζ_V	: Viscous damping
ν_f	: Kinetic viscosity of liquid
ν_g	: Kinetic viscosity of gas

Abbreviations

DSHIC	: Doo San Heavy Industry Company
EFDP	: Eggcrate Flow Distribution Plate
KSNP	: Korea Standard Nuclear Plant
SR	: Stability Ratio
WEC LLC	: Westinghouse Electric Company Limited Liability Company

1. Introduction

A steam generator(S/G) has two points of significance from the aspect of safety. The first one is the contamination of the secondary system by radioactive materials due to the breakage of the pressure boundary between the primary system and the secondary system. The contaminated primary cooling water flows into the secondary system and then the contaminated secondary water might discharge into the air through the steam generator valve(s). The other is the possibility of the so-called LOCA accident whereby the amount of primary cooling water will be decreased because the primary system cooling water flows into the secondary system due to the pressure difference between them. The decreased primary water inventory causes a lot of problems such as inadequacy of fuel cooling, departure of nucleate boiling, core melting, etc. Besides the safety problems, the excessive wear of the tube causes a sudden stoppage of operation in the nuclear plant and requires frequent inspections for the tube plugging. Also, it results in diverse economic losses such as labor costs due to the tube plugging and its inspection, irradiation of workers, and long time operation outage, etc.

In the current steam generators of the Korea Standard Nuclear Power Plant, fretting wear due to the Fluid-Induced Vibration has occurred commonly and is concentrated especially in the upper part of the U-Bend above the central cavity. This region is the upper part of the stay-cylinder which is one of the features of the WEC LLC steam generator. The region has only horizontal portion of the tube. The velocity of this region is faster than that of the other region because of less flow resistance. Also the region has longer unsupported span than the other region. These conditions can cause the Fluid-Elastic Instability at lower fluid velocity than expected. Therefore, for the Ulchin #5 and #6 steam generators, two Eggcrate Flow Distribution Plates (EFDP) were installed in the central cavity area in order to prevent Fluid-Induced Vibration by suppressing the fluid velocity in this area (Park, 2002).

2. Improvement in Design

The governing parameters of FIV is the damping, fluid velocity, fluid density and the tube array geometry (Kim, 2001 ; 2000). However the most practical and simple design modification of S/G to prevent the FIV is to reduce the local velocity below the critical one. To reduce the local velocity the EFDP was proposed by the CE (WEC LLC).

The EFDPs, installed in the full Eggcrate #4 and #5 of Ulchin #5 and #6 steam generators to prevent fretting wear, intend to prevent the horizontal upper part of the tube from the direct-impact shock by the high velocity flow in the central cavity.

In the design of the plates, a lot of considerations were given to the problems such as thermal expansion, flow resistance, and fixing method. The expected thermal expansion problem was removed in advance with the use of SA240, Type 405 materials that have the same coefficient of thermal expansion as the Full Eggcrate (SA176, Type 409). Moreover, bolt clamping was employed rather than welding for the fixation. To prevent the bolt from loosening, after the bolt was clamped, a lock washer was attached and welded instead of using direct welding. The features of the Ulchin #5 and #6 steam generator in which the Eggcrate Flow Distribution Plates were installed are presented in Fig. 1.

Also to exclude the possibility of excessive non-

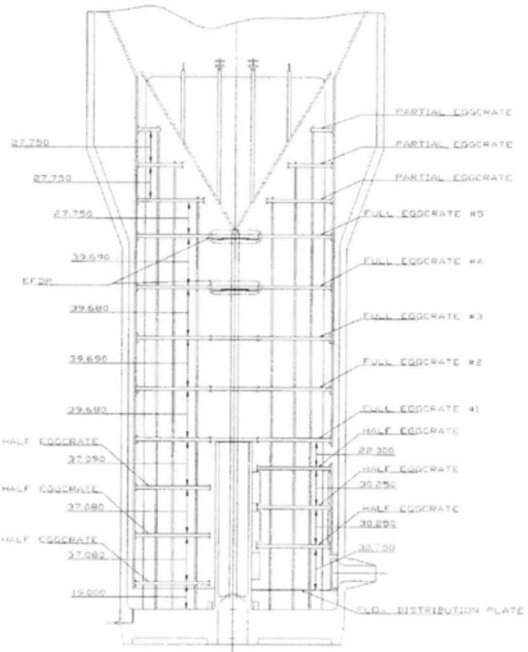


Fig. 1 Tube support arrangement for Ulchin #5, 6 Steam Generator

uniformity of flow, the size and number of hole in the plates were determined so that the flow resistances through the plates are same as that through the vertical tube outside of the cavity.

3. Thermal Hydraulic Effects on the Secondary System by the Installation of EFDP

The steam generator secondary side was modeled for a flow distribution analysis using ATHOS3 code. The Code, World widely used, have been developed by CHAM of North America, Inc. for three-dimensional, steady-state and transient analyses of PWR steam generators (Singhal et al, 1990).

3.1 Vertical velocity distribution in the central cavity

The upper region of the hot-leg in the current KSNP steam generator is an area where large amounts of steam are produced by high heat transfer rate to the secondary system. The fluid

Table 1 Comparisons of the density, axial velocity, mass velocity, and dynamic pressure before and after the installation of EFDP

	Installation of EFDP		Increase Rate (%)
	Before	After	
Density (kg/m^3)	360.0	300.0	-16.67
Axial velocity (m/sec)	1.372	1.120	-18.4
Mass flux (kg/m^2-sec)	471.6	334.65	-29.0
Dynamic pressure (Pa)	2.245	1.30	-42.0

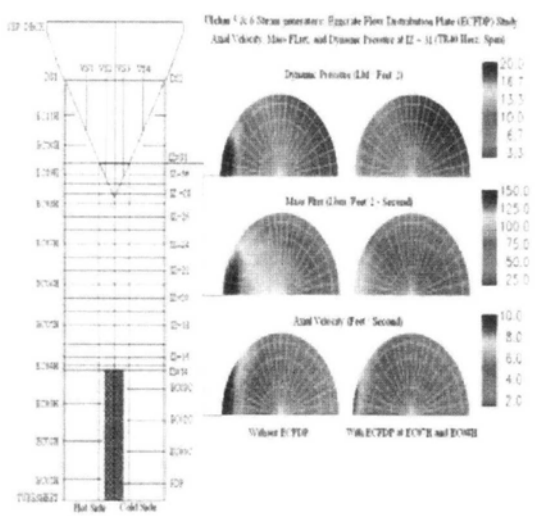


Fig. 2 The analysis results of the dynamic pressure, mass velocity, and axial velocity in the central cavity before and after the installation of the EFDP

resistance of the central cavity is relatively small due to less flow resistance. Thus a large amount of inflow is expected.

Using the ATHOS3 code, a axial velocity was analyzed to examine the velocity change before and after the installation of EFDP at the location of row 41 (IZ=31, Z=8. 645 m from tube sheet) which is the upper area of the central cavity and supposed to be most susceptible to FIV due to long unsupported span, high local velocity. After the installation of EFDP, the axial velocity of hot-leg within the central cavity displayed a significant drop from 1.4 m/sec to 1.1 m/sec (Refer to Fig. 2). It also caused the density to decrease from 360.0 kg/m^3 to 300.0 kg/m^3. The analysis results of the dynamic pressure, the mass velocity, and the axial velocity in the central cavity before and after the installation of EFDP are shown in Fig. 2. The Calculation results of these important parameters to FIV were summarized in Table 1.

3.2 Radial velocity within the central cavity

An analysis on the change of the radial velocity within the central cavity before and after the installation of the EFDP was carried out from IZ=19 (where the second support is located from the top of the central cylinder) to IZ=32 (the inner area of the upper part of the central cavity).

The results in Fig. 3. show that the inflow and outflow of radial velocity within the central cavity dropped in most areas excluding the areas IZ=28, 29, and 30, which compose the upper area of the full Eggcrate #5. However, because the areas where the radial velocity increased have highly rigid tube compared to other areas and have narrower gaps between the tubes, these areas will hardly be affected by an little increase in radial velocity. The high rigidity of the tube in the area comes from the short supported span.

3.3 Quality and void fraction in the central cavity

In order to examine the installation effect of the EFDP on the areas contiguous to the central cavity, an analysis of the quality and void fraction of the areas was carried out by using the ATHOS3 code. The results show that without the installation, the maximum void fraction and quality of the area displayed 0.9269 and 0.4082, respectively. However, with the installation, these figures increased slightly to 0.9355 and 0.4412, respectively (Refer to Fig. 4 and Table 2).

Both quality and void fraction affect the average speed, density of the fluid and ultimately dynamic pressure in the two-phase flow. But, in terms of fluid-induced vibration occurring in this area, the minute change in quality and void fraction does not affect significantly the wear and vibration of the tube because the amount of the

Table 2 Comparisons of the maximum void fraction and quality before and after the installation of EFDP

	Installation of EFDP		Increase of Rate (%)
	Without	With	
Max. void fraction	0.9269	0.9355	0.93
Max. quality	0.4082	0.4412	8.08

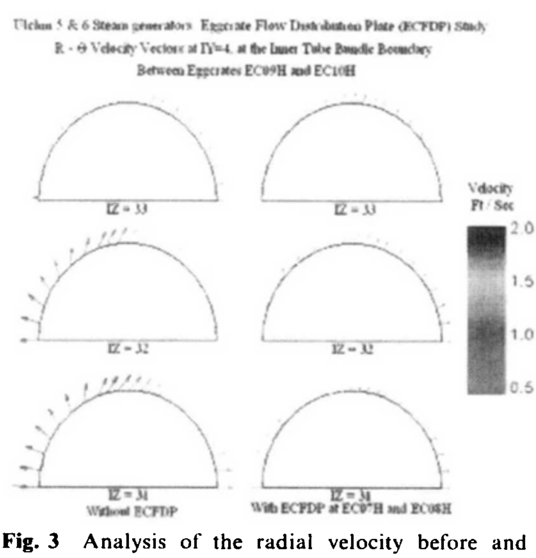


Fig. 3 Analysis of the radial velocity before and after the installation of the EFDP

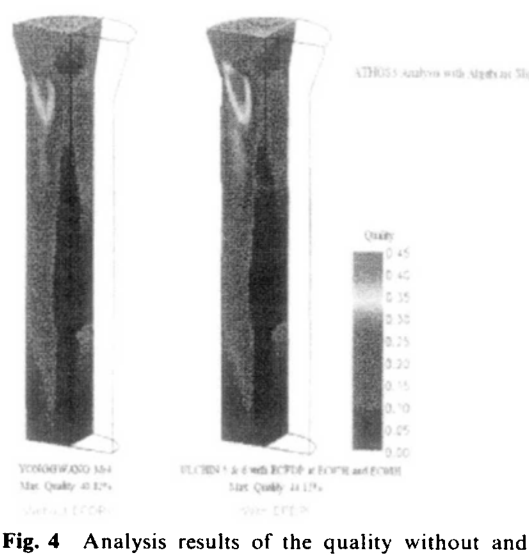


Fig. 4 Analysis results of the quality without and with the installation of EFDP

velocity decrease in the upper area of the central cavity is more dominant.

4. Flow-induced Vibration Analysis

The analysis on the change of flow-induced vibration without and with the installation of EFDP was carried out for the tube in row 41 within the central cavity because the tube has the longest horizontal span among the tubes that were not supported vertically by the first partial eggcrate. Thus, it was expected that it would be most susceptible to flow-induced vibration. A mode frequency analysis subroutine of Structural Routine of ANSYS, was used to carry out the analysis of the natural frequency and relative amplitude of the tube. Also in the calculation for the straight and horizonal tube elastic straight pipe element model was used and for the curve pipe the elastic curved pipe element model. The model used and results of calculation of the natural frequency and relative amplitude are shown in Fig. 6(a), (b). In order to calculate the stabi-

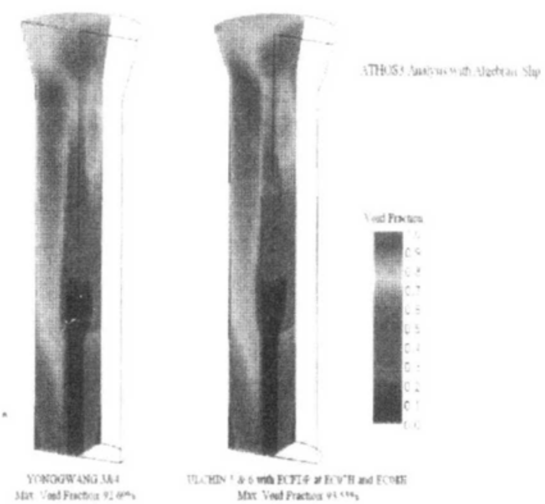
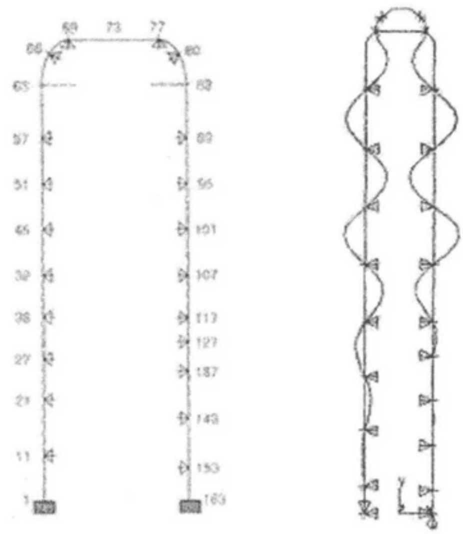
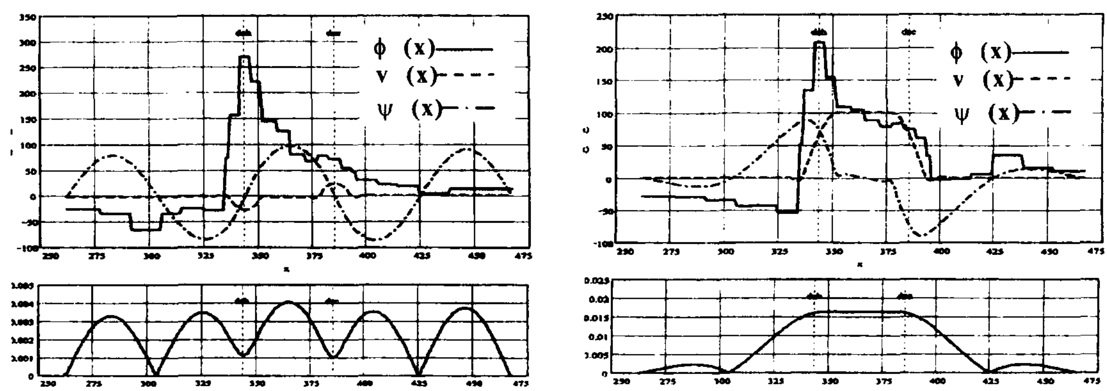


Fig. 5 Analysis results of the void fraction before and after the installation of EFDP



(a) Tube model in ANSYS calculation (b) The results of ANSYS

Fig. 6 Finite element model and analysis result of U-Tube at Row 41



(a) Before the installation of EFDP (b) After the installation of EFDP

Fig. 7 The analysis results of the critical velocity and vertical displacement before and after the installation of EFDP

Table 3 Comparisons of the critical velocity, effective velocity, stability ratio before and after the installation of EFDP

Installation of the EFDP	Critical velocity	Effective velocity	Stability ratio
Before	3.647m/sec	1.455m/sec	0.399
After	3.647m/sec	1.120m/sec	0.31

lity ratio of Fluid-Elastic Instability which is a kind of Flow-Induced Vibration, the critical velocity and vertical displacement were examined at a natural frequency of 31.07 Hz. The frequency was chosen due to the lowest one of row 41. The results are shown in Fig. 7.

Using the analysis result by ANSYS code, the stability ratio (SR=Veff/Vcrit) can be calculated by the following equations.

The critical velocity, is defined as the cross flow gap velocity at which fluid elastic instability initiates for single span tube array subjected to uniform cross flow, is given by the equation(1).

$$V_{crit}=f_n K\sqrt{\frac{m_0\delta_0}{\rho_0}} \quad (1)$$

The effective velocity, V_{eff}, is the equivalent single span velocity for a tube with multiple spans or with non-uniform cross flow.

$$V_{eff}^2=\frac{\int \frac{\rho(x)}{\rho_0} V(x)^2\phi(x)^2dx}{\int \frac{m(x)}{m_0}\phi(x)^2dx} \quad (2)$$

The calculation was performed by the computing code CALSR developed by the Thermal Hydraulic Laboratory in Department of Nuclear Engineering of Kyung Hee University. The calculation results are as follows.

The reduction of stability from 0.399 to 0.31 by installation of EFDP shows enough conservativeness compared to the WEC LLC standard of flow elastic stability ratio 0.75.

Also, calculating results of $2\pi\zeta m_0/\rho D^2$ and V_{eff}/fD in order to apply them to the results of Pettigrew's experiment for fluid-elastic instability are follows (Pettigrew, 1998, Fig. 9).

$$2\pi\zeta m_0/\rho_0 D^2=\frac{0.126\times 0.8393kg/m}{332.16kg/m^3\times(0.019m)^2}=0.88 \quad (3)$$

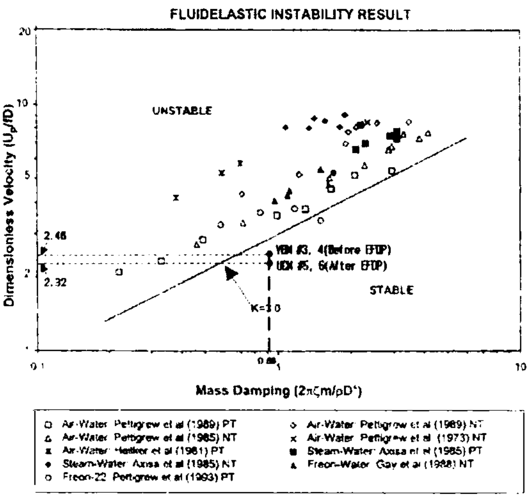


Fig. 8 Comparison of the fluid elastic instability before and after the installation of EFDP

$$V_{eff}/f_n D=\frac{1.372m/sec}{(31.07/sec)\times(0.019m)}=2.32 \quad (4)$$

The variables used in the above equations are based on the materials stated in the References and the Report on Vibration and Structure Analysis of Heat Transfer Tubes of the Ulchin #5 and #6 Steam Generators. Fig. 8 shows the comparison with Pettigrew's experiment after applying the calculation result above.

5. Discussions

The analysis results show that the design modification can reduce the possibility of the fluid-elastic instability drastically. However, the flow condition of the area is highly two phase flow, that is, the void fraction of the region is between 63% and 90%. In that condition, the validity of parameters used in the analysis should be checked. In particular, in two phase flow, fluid density, hydrodynamic mass (added mass) and the damping parameter depend on the void fraction. The density can be calculated by the homogeneous flow model. However, the two other parameter are quite complicated.

The practical recommended correlations for the hydraulic mass in two-phase flow can be expressed as follow.

$$m_h = \left(\frac{\pi}{4}\rho_{TP} D^2\right)\left[\frac{(D_e/D)^2+1}{(D_e/D)^2-1}\right] \tag{5}$$

But for the damping parameter more discussions are necessary.

The parameter can be divided into many factors as follow.

$$\zeta_T = \zeta_S + \zeta_V + \zeta_{fD} + \zeta_{TP} \tag{6}$$

According to many related research result (Pettigrew, 1994), the ζ_{fD} is negligible compared to total damping. Also the ζ_{TP} is also only few percent of total damping in the high void fraction (above 70~80%) condition. Furthermore since damping acts as the suppression of vibration, the underestimation would be more conservative in the view of the vibration. Therefore only important factor in two phase flow would be ζ_S and ζ_V.

The viscous damping is suggested as follow by Pettigrew (1994).

$$\zeta_V = \frac{\pi}{\sqrt{8}} \frac{\rho_{TP} D^2}{m} \left(\frac{2\nu_{TP}}{\pi f D^2}\right)^{1/2} \frac{[1+(D/D_e)^3]}{[1-(D/D_e)^2]^2} \tag{7}$$

$$\nu_{TP} = \frac{\nu_f}{1+\alpha(\nu_f/\nu_g - 1)} \tag{8}$$

However, it is quite difficult and complicate to specifically determine the viscous damping and the structural damping since there two factors in two phase flow are dependent on the various two phase parameters such as void fraction, flow pattern, configuration (P/D), and so on. But without the specific knowledge of the damping, another method to evaluate the fluid-elastic instability in the two phase flow was suggested by Remy and Bai (1982). The method consisted of regrouping Conors' equation and replotted the experimental data in terms of reduced velocity (V_{eff}/fD) and mass flux ($m_t/\rho_{TP}D^2$). Then it was found that the data was reasonably collapsed well and Pettigrew also recommended the method. Therefore in these study, to avoid the damping issue and the non-uniform velocity and void fraction, the method was adapted to confirm the validity of the EFDP installation. As shown in the Fig. 9, the modification guarantees the safe operation of S/G without FEI.

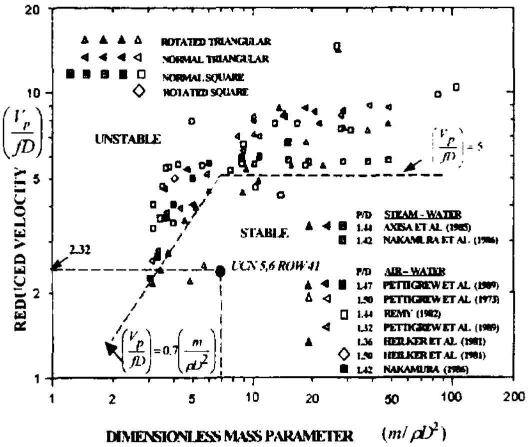


Fig. 9 Fluidelastic instability data presented in terms of mass parameter ($m/\rho D^2$)

6. Conclusions and Suggestions

Through the study of FIV problem and calculation of stability ratio, the following conclusion and suggestions were drawn.

(1) After the EFDP was installed, the effective velocity is low enough to the critical velocity by Pettigrew.

(2) Due to the installation of the EFDP, the velocity and dynamic pressure in the central cavity area are reduced about 18% and 42%, respectively. This fact also indicates that the SR of the outside central cavity area is more less than that of the central cavity area.

It is evaluated that the installation of the Eggcrate Flow Distribution Plates would improve the problems of fretting wear in the steam generator tubes by Fluid-induced Vibration through a decrease in velocity in the upper part of the central cavity area. Even though this design modification still a lot attention should be paid to through the monitoring of tube wear and the evaluation, and data reduction technique of Eddy Current Test.

Also, by the installation of EFDP, the problems such as heat transfer characteristic change, chemical corrosion, the vibration of EFDP itself so minor that it would not be troublesome.

Acknowledgment

This study was supported by Doo San Heavy Industries and Construction Company, Electrical Engineering and Science Research Institute, and Nuclear Power Plant Technology Research Center.

References

Au-Yang, M. K., 1987, "Development of Stabilizers for Steam Generator Tube Repair," *Journal Nuclear Engineering and Design*, Vol. 122, pp. 189~197.

Axiasa, F., 1986, "Flow Induced Vibration of Steam Generator Tubes," *Electric Power Research Institute Report EPRI NP-4559.*

Chen, S. S., 1985, "Flow Induced Vibration of Circular Cylindrical Structures," *Report No. ANL-85-51.*

Jo, J. C., 1992, "A Study on the Thermal-hydraulic and Flow-induced Tube Vibration Analysis of Nuclear Steam Generators," *KINS/AR-198.*

Kim, S. N., 1998, "Fluid-elastic Vibration in a Rod Bundle," *Ministry of Science and Technology* (MOST), Korea.

Kim, S. N., 2000, "Critical Velocity of Fluidelastic Vibration in a Nuclear Fuel Bundle," *KSME International Journal*, Vol. 14, pp, 816~822.

Kim, S. N. and Sin, C, 2001, "The Experimental of Flow Induced Vibration in PWR RCCAs," *KSME International Journal*, Vol. 15, pp. 291~299

Lee, C. H., 1991, "Vibration & Structural Analysis of The Tubes & Tube supports," *ABB-CENP.*

Lee, L. S., 1971, "Vibration of U-Bend Segments of Heat Exchanger Tubes," *Atomic Energy of Canada Limited, AECL 3735.*

Pettigrew, M. J. , Taylor, C. E., Fisher, N. J., Yetisir, M. and Smith, B. A. W., 1998, "Flow-induced Vibration : Recent Findings and Open Questions," *Journal Nuclear Engineering and Design*, Vol. 185, pp. 249~276.

"Palo Verde Steam Generator Tube Degradation and YGN3 and 4 Steam Generator Design," *ABB-CENP Report*

Pettigrew, M. J. and Taylor, C. E., 1994, "Two-Phase Flow-Induced Vibration", *ASEM*, Vol. 116, pp. 233~252.

Pettigrew, M. J., Taylor, C. E. and Kim, B. S., 1989, "Vibration of Tube Bundles in Two-Phase Cross Flow : Part1 Hydrodynamic Mass and Damping," *Journal of Pressure Vessel Technology Trans. of the ASME*, Vol. 3, pp. 466~477.

Singhal, A. K. and Keeton, L. W., 1990, "ATHOS3 Mod-01 : A Computer Program for Thermal-Hydraulic Analysis of Steam Generators," *EPRI NP-4604-CCML*, Vol. 1-3.

Singhal, A. K. and Srikantiah, G., 1991, "A Review of Thermal Hydraulic Analysis Methodology for PWR Steam Generators and ATHOS3 Code Applications," *Progress in Nuclear Energy*, Vol. 25, No. 1, pp. 7~70.

Slack, D. G., 2001, "Vibration and Structural Analysis of the Tubes and Tube supports (UE-211SS-302)," *WEC LLC.*