Quantitative Measurement of the Geometric Anomaly in Steam Generator Tubes by an Advanced Eddy Current 3-D Profilometry

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1. Introduction

Most of the corrosive degradations in steam generator tubes are closely related to the residual stress existing on the region of geometric change, that is, expansion transition, u-bend, ding, dent, bulge, etc. Therefore, the accurate information on the geometric anomaly in the tube is prerequisite to the activity of non destructive inspection for the failure prevention during operation and the root cause analysis. In this paper, a newly developed eddy current technique of 3-dimensional profilometry is introduced and the proof for the applicability of the technique to the plant inspection is provided through the quantitative comparison of measured data for expansion anomalies in the steam generator mock-up tubes with those from the laser profilometry.

2. Experimental

2.1 Eddy Current 3-D Profilometry

P-MRPC probe is a brand-new, non-surface riding and rotary type eddy current coil probe, developed by KAERI [1]. It is used for measuring 3-dimensional profile of steam generator tubes and is compatible with the commercial eddy current test equipments being used for the in-service inspection of power plant. Compared to the other recently developed multi-coil array probe such as intelligent probe or x-probe [2], P-MRPC probe has a supreme advantage of measuring pure geometric changes on tube inner surface, excluding the noise from the tube outside by the use of test frequency higher than 400kHz. In this work, the profiles of the expansion mock-up tubes were measured with the test frequency of 700kHz using Zetec MIZ-70 digital data acquisition system, and the conditions of sampling rate, probe pulling speed, and probe rotating rate were adjusted so that each data could be obtained at distance intervals of about 1mm in both the axial and the circumferential direction of tube. The average impedance values from the free span and the expanded regions were calibrated to be 0 and 1.75 volts, respectively, considering the magnitudes of increase in the inner radius due to expansion in mock-up tubes were measured to be 0.175 $\pm$0.01 mm by the laser profilometry. Through this calibration process, the positive value of eddy current voltage can be set to stand for the magnitude of relative radial increase in mm with conversion factor of 0.1, and vice versa.

2.2 Laser 3-D Profilometry

Among the existing technology for measuring the profile of the tube inside, laser profilometry is regarded as the most advanced and precise one with the highest resolution. Therefore, the laser profilometry was also applied to the expansion mock-up tubes and the obtained results were counted as the reference standards for the comparison with those from the eddy current profilometry. LTC LP-2000 profilometry system, used for the measurement, has a rotary laser sensor with the spot size of 0.13mm and the resolution of 0.013mm. The data were obtained at the intervals of 1 degree in the circumferential direction and 0.4mm in the axial direction of the tube.

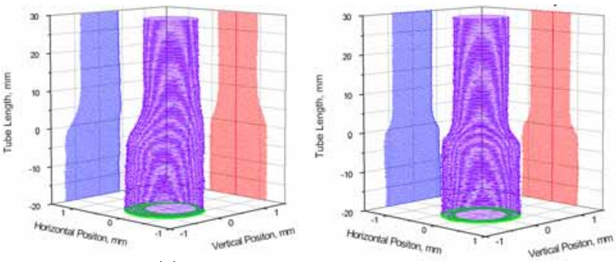
2.3 Expansion Mock-up Tubes

Two assemblies of steam generator tube to tube-sheet expansion mock-ups, one by explosive process and the other by hydraulic process, were used for the 3-dimensional profile measurement. In each assembly, 12 tubes of alloy 600 with the outer diameter of 19mm and the thickness of 1.07mm were expanded to the tube-sheet hole of 19.25mm in diameter and 300mm in length.

3. Results and Discussion

3.1 Expansion Anomaly in Mock-up Tubes

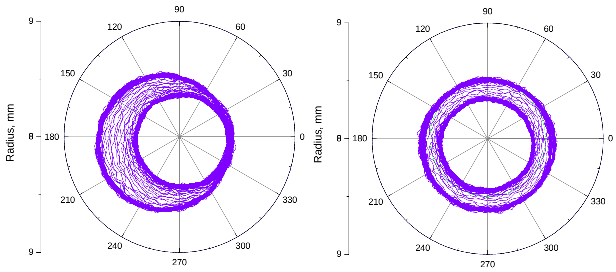
The results from the laser profile measurements of all the mock-up tubes showed a large difference in the uniformity of radial expansion around the tube circumference at the transition region between the two expansion methods. Relatively uniform increase in the radius was observed for the hydraulically expanded tubes, but the explosively expanded tubes showed a large variation in the magnitude of radial expansion with the location of the tube circumference. The 3-dimensional profiles typical of the explosive expansion and the hydraulic expansion were shown in Fig. 1. The projection images on the three orthogonal planes were also shown in the figure to support the understanding of 3-dimensional shape of the expansion, and the level corresponding to the top of tube sheet was set to zero in the z-axis. A large difference in the uniformity of radial expansion is evident for the two results, and even a slight and local protrusion (increase in the radius over the top of tube sheet) is observed in the explosively expanded tube.



(a) (b)

Figure 1. 3-D laser profile; typical of (a) explosively and (b) hydraulically expanded mock-up tube.

The degree of expansion uniformity is more clearly recognized by the 2-dimensioal profile on the plane normal to tube length, as shown in Fig.2. It can be seen from this figures that the explosively expanded tube is characterized by the eccentric shape in the transition region and the hydraulically expanded tube by the concentric shape.



(a) (b)

Figure 2. 2-D laser profile; typical of (a) explosively and (b) hydraulically expanded mock-up tube.

The variation in the eccentricity among mock-up tubes and between expansion methods can be quantified by measuring the value of the maximum increase in the radius. That is, because the average magnitude of the radial expansion is 0.175mm, the deviation of the maximum value from the average directly reflect the degree of eccentricity in the individual mock-up tube, as shown in Fig. 3. Larger deviations are observed for all the explosively expanded tubes and the hydraulically expanded tubes show values near concentric expansion.

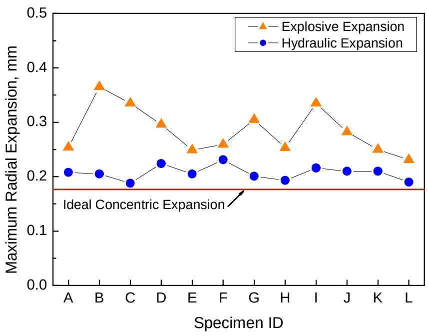
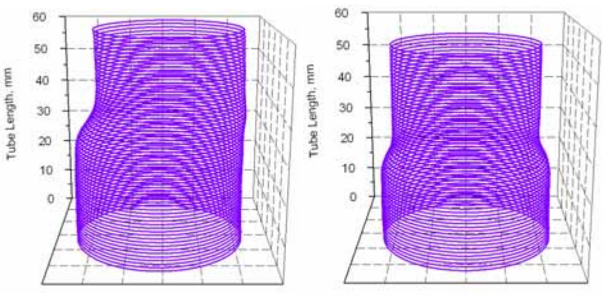


Figure 3. Variations in the maximum radial expansion among mock-up tubes and between expansion methods.

3.2 Quantitative Eddy Current 3-D Profilometry

The results of eddy current 3-dimensional profile for the same mock-up tubes of Fig. 1 are shown in Fig. 4. By comparison with Fig.1 of the laser profilometry, almost identical 3-dimensional profiles are observed for both tubes with different expansion method.



(a) (b)

Figure 4. 3-D eddy current (P-MRPC) profile; typical of (a) explosively and (b) hydraulically expanded mock-up tubes.

In order to confirm the accuracy and also to verify the applicability of the quantitative profile measurement by P-MRPC probe, the values of the maximum increase in the radius obtained by laser and P-MRPC probes were directly compared for the mock-up tubes with various eccentricities. As shown in Fig. 5, a linear correlation within the error range of ±10% was observed.

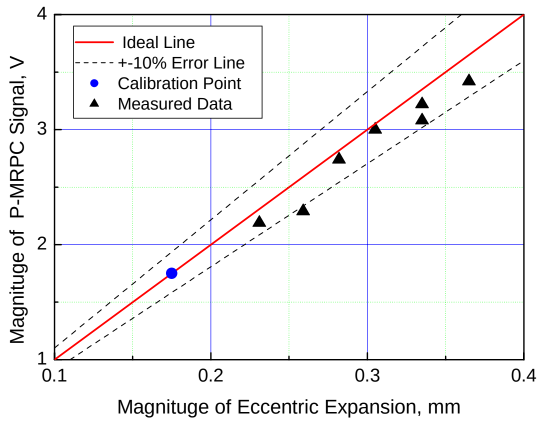


Figure 5. Comparison of quantitative profile data by laser and eddy current probes.

4. Conclusion

A newly developed eddy current technique of 3-dimensional profilometry has a measuring accuracy comparable to that of the laser profilometry, and the applicability of the technique to the plant inspection has been verified.

REFERENCES

[1] D.H. Hur et al, Patent Application No.6391, KAERI, 2004.
[2] J. Kang, X-probe Experience at Diablo Canyon, 22nd EPRI SG NDE Workshop, Hilton Head, USA, 2003.