Measurement and control system design for the assembly of stator can

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Abstract. Stator can assembly is one of difficult issues in the manufacturing of AP1000 nuclear reactor coolant pumps. A new measurement and control system is developed to ensure precise assembly of the ultrathin stator can with large length to thickness ratio on the stator core. The system includes three parts: hydraulic pressure measurement and control, deformation measurement of the can and displacement measurement of valve core. Since deformation of the can is hard to measure, a new method by measuring the bulge displacement of the can is proposed. With the help of the system, the loading path can be accurately controlled and the deformation can be precisely measured. The system provides possibility for the detailed study of assembly process. Finally, the feasibility of the system in the experiment rig of a reduced scale is verified.

1. Introduction

The AP1000 reactor coolant pump (RCP) is one of the key components in the primary loop of the third generation nuclear plant, which is a single-stage, hermetically sealed, high-inertia, centrifugal, canned motor pump. It provides power for the coolant to circulate in the nuclear island core, RCPs, heat leg main pipes, cold leg main pipes and steam generator[1, 2]. In order to avoid coil corrosion, the stator and rotor are encased in corrosion-resistant cans (made by Hastelloy C-276) [3, 4]. The clearance between the stator can and the rotor can is 4.83mm after assembly, which is the unique room for the coolant to pass. Length of stator core is over 2m with the inner diameter more than 500mm and the outer diameter more than 1175mm. Length of stator can is more than 3m with the thickness less than 0.5mm and the diameter over 500mm. The stator can is ultrathin can with large length to thickness ratio. There is a clearance between the stator can and the stator core after fitting them together, and methods should be used to eliminate this clearance.

Assembly methods currently available include: vacuum technique[5] and hydrostatic test[6]. For the first one, uneven deformation of the can will appear along the axial direction of the stator core and the load generated is too small to make the can deform to the expected profile. As for the second one, since the hydraulic pressure path corresponding to the time cannot be controlled step by step, we still cannot obtain the expected effects. Therefore, a new method based on the theory of tube hydroforming was presented by authors[7]. Pioneer work has been done [8, 9]. It is shown that the proposed method is feasible for the assembly of the stator can.

In this paper, an assembly experiment rig with reduced size was setup to study the assembly process at lower cost. Measurement and control methods were proposed, and the system were analyzed and designed. The stator assembly, hydraulic system and measurement and control system
were included in the experiment rig. Deformation of the stator can, hydraulic pressure and displacement of the overflow valve core are measured. At the same time, the location of relief valve core should be adjusted in order to precisely control the loading path. The effects of the system, such as, pressure-time curves, displacement-time curves, were verified by experiments. Finally, the assembly error of the displacement measurement equipment was discussed.

2. Measure & control methods for the assembly process

The experiment rig is shown in figure 1. Three components are included: hydraulic system, measurement & control system, and stator assembly. Parameters needed to be measured in the assembly process are the hydraulic pressure, displacement of the valve core and the radial displacement of the stator can.

![Figure 1. The experiment rig and measured points arrangement](image)

2.1. Hydraulic pressure measurement

Figure 2(a) shows cross section profile of the stator assembly. Figure 2(b) shows the actual stator assembly. Pressure measurement between the inner wall of stator can and the outer wall of supportive tube is hard to realize. A method by mounting a pressure transducer on the input pipe to measure the pressure indirectly is proposed, as shown in figure 1.

2.2. Deformation measurement of stator can

For proper installation of the ultrathin stator can, the can is required to deform uniformly and attached to stator core closely. Deformation measurement of the stator can is utterly important. Experiments combined with FEA method [8] are applied to study the assembly process. To simplify the structure, a reduced size is used in the axial direction, the coils and the slot groove are neglected in the radial direction, and only the components above the slot wedges are considered. Such simplification saves cost without reducing the assembly accuracy.

Several steps are involved in study of the assembly process: Step 1, numerical simulations have been conducted for the assembly process to obtain an ideal assembly process, and the strain and stress of the stator can were analyzed[7]. Step 2, assembly experiments have been conducted according to the loading path determined in Step 1, and the deformation and stress are measured by the designed measurement & control system. Step 3, FEA model established described in[10] is revised based on analyzing the difference between experiment data and simulation data, then numerical simulation was conducted again. A reliable FEA model and the best assembly process will be obtained by conducting the above steps repeatedly. Eventually, assembly processes of full size stator can deduced by numerical simulations will be reliable.
The stress, strain, thickness of the stator can need to be known in the assembly process study. However, the stator can is enclosed in the cavity formed by the supportive tube and the stator: the room between the stator can and the supportive tube is filled with high pressure oil. The other room between the stator can and the stator core is needed to be eliminated. After assembling, the stator can is attached to inside of the stator core closely. It is difficult to measure the deformation of the stator can. If strain gauges are mounted on the inner wall which is filled with high pressure oil, the strain gauges are hard to be fixed and the wire is not easy to be connected to the outside equipment. On the other hand, if strain gauges are mounted on the outer wall which will be attached on stator core, the gauges are easily to be damaged.

Based on the difficulties discussed above, a method for measuring the stator can’s deformation by measuring bulge amount of the stator can in the radial direction is proposed. The new method is shown in figure 2(a) in detail. Four holes are bored in the stator core around the circumferential direction and the displacement sensors are mounted in the holes to measure the deformation in real-time. Other deformations can be deduced from the bulging amounts. The curves of pressure-time, displacement-time can be obtained through the post-processing of the computer.

![Figure 2](image)

Figure 2. The stator assembly and the illustrations of the control & measurement methods

2.3. Displacement measurement for proportional relief valve
In the assembly process, the proportional relief valve is used to increase the pressure increasing rate. Given a signal by electromagnet, the valve core will move and adjust the opening size of the nozzle, which will change the pressure increasing rate of the valve. It is thus necessary to measure and control the displacement of the valve core accurately so as to precisely control the loading path. The pressure increasing rate can be calculated by analyzing the displacement of the valve core. The movement of the valve core can be controlled by the computer through comparing the pressure measured with the input. The displacement sensor is used to measure the displacement. The feedback control of the pressure is realized by using the digital module of the PLC.

3. Design of the measure & control system
3.1. Functional requirements of the system
The requirements of the designed system are as follows:

1. Functional requirements. Displacement of the stator can in radial direction and pressure in the stator core should be measured in precision real-
time tracking. Location of the valve core should be measured precisely. The curves of pressure-time, displacement-time and displacement-pressure can be shown with the post-processing progress. Six variables are needed to be measured. Five displacement sensors and one pressure transducer are required. It is important that the values are collected synchronously to avoid errors.

(2) Precision requirements. Clearance between the stator can and surface of slot wedge of the stator core is 2mm, which is the maximum displacement of the stator can in the assembly process. The maximum allowable pressure of hydraulic system is 25MPa. The requirements for the sensors are shown in table 1.

| Types                      | Precision requirements       |
|----------------------------|-----------------------------|
| Displacement measurement   |                             |
| Test precision             | The sensitivity is 0.01mm   |
| Resolution                 | 0.001mm                     |
| Dynamic frequency          | 200HZ                       |
| Measuring range            | 0-3mm                       |
| Pressure measurement       |                             |
| Test precision             | The sensitivity is 0.01MPa  |
| Measuring range            | 0-30MPa                     |

3.2. System design

![Figure 3. The design of the system](image)

Figure 3 shows the structure of the system. Two measurement subsystems and one measuring-feedback control subsystem are included. The experiment rig is shown at the bottom. The hardware for collecting information (namely sensors) which is used to convert the non-electrical variables into...
electrical signals is shown in the middle. The controlling and processing system of the computer which is used to convert the analog quantity into digital quantity is shown on the top. Adding the designed control-measurement system on the hydraulic system (previous work) is shown in figure 4. Every component is composed of signal generator, signal detection and conditioning circuit[11, 12], data acquisition card[13], network card. In the post-processing phase, the data processing software collects data and exports the relationships of displacement-time, liquid pressure-time in the form of curves and tabular[14].

4. Test result analysis

4.1. Analysis of pressure test results

The maximum pressure of the hydraulic system was firstly set 20MPa with the holding time of 600s and the pressure increasing rate is 0.2MPa/s. Then it is unloaded. The testing pressure curve is shown in figure 5. The points A, B, C, D represent 0.87MPa (t=0.1s), 20.00MPa (t=98.3s), 20.2MPa
(t=691.8s), 0.74MPa (t=702.8s), respectively. Analysis of the points and every phase’ errors (loading phase, holding phase, unloading phase) are shown in table 2: (1) Loading phase error is defined as the percentage ratio of the absolute difference of the pressure increasing rate between the input and test to the input. Then the percentage is 2.6% and considered to be within the allowable error range. (2) Holding phase error is defined as the percentage ratio of the absolute difference of the holding time between the input and test to the input. Then the percent is 1.08%, which is also considered to be within the allowable error range. (3) Unloading phase error is defined as the percentage ratio of the absolute difference of the pressure decreasing rate between the input and the test to the input. Then the percentage is 54.1% and the deviancy is significant. Many reasons account for this, i.e. large setting for the unloading rate as 4MPa/s, the low sensitivity of the system. As the system becomes complicated, the more lag as the rate increases. Compared to the loading rate of 0.2MPa/s, it can be concluded that the precision of the system increases with the decrease of loading rate.

From figure 5 and table 1, it could be observed that measurement-control system meets our precision control requirements in certain rate range. Under the circumstance, the loading and unloading velocity will be linearly increased and decreased steadily. It is found that the start point is not at the origin and this is attributed to the sensitivity and error of the system. But it will be back to the point which has the same pressure value as the start point after unloading. The start point will be considered as the origin point. Then it indicates that the designed system is steady.

Table 2. Testing errors analysis

|                  | Loading phase | Holding phase | Unloading phase |
|------------------|---------------|---------------|----------------|
| Testing results  | 0.1s, 0.87MPa| 98.3s, 20.00MPa| 691.8s, 691.8s, 702.8s, 0.74MPa |
| Theory results   | 0.0s, 0.00MPa | 100.0s, 20.00MPa | 700.0s, 700.0s, 705.0s, 0.00MPa |
| Error analysis   | $E_{\text{load}} = \frac{|V_{\text{test}} - V_{\text{input}}|}{V_{\text{input}}} \times 100\% = 2.6\%$ | $E_{\text{hold}} = \frac{|T_{\text{test}} - T_{\text{input}}|}{T_{\text{input}}} \times 100\% = 1.08\%$ | $E_{\text{unload}} = \frac{|V_{\text{test}} - V_{\text{input}}|}{V_{\text{input}}} \times 100\% = 54.1\%$ |

4.2. Assembly results

Figure 6 shows the assembly results obtained by the designed system under maximum pressure of 20MPa, the pressure increasing rate of 0.2MPa/s and the holding time of 600s. It is found that the stator can was already attached inside of the stator core closely. It is indicated that the system can meet the requirements of precise measuring and controlling of the assembly process.

Figure 6. Assembly results  
Figure 7. Error analysis for measuring
5. **Precision analysis of the deformation measurement**

Figure 7 is the detailed enlarging picture at the position of displacement sensor 1 shown in figure 3. The sensor is mounted in the hole which is drilled in the stator wall and the sensor head is contacted with the outer wall of the stator can. The bulging of the stator can push the sensor bar which will cause the change of the electric current. The errors of drilling the hole and mounting the sensors may occur which are shown with the type of skew (axis of the sensor bar isn’t vertical to the surface of the stator can). There may be a skew angle \( \theta \) between two axis of the sensors caused by manufacturing error or assembly error, shown in figure 7. Displacement measured will be not accurate due to this angle. The error increases with the increase of the deflection angle and the displacement measured is larger than the theoretical one. The error is analyzed by equation \( L = D \sin \theta \) and \( \varepsilon = D(1 - \sin \theta) / \sin \theta \).

Measures must be taken to eliminate testing errors. The finish machining of the hole is necessary. As to reducing the mounting errors, several sensors can be mounted around the circumferential direction of the stator core and the displacement curve values can be obtained by calculating the average values of sensors. The measurement error will be minimized by these improved methods.

6. **Conclusion**

A new measurement and control system used in the precision assembly of the stator can is proposed based on the presented assembly method. Due to the difficulties in the measurement of the stator can, an indirect method by measuring the bulge amount in the radial direction of the stator can is proposed. The reliability of the designed system was verified by testing results: the loading path can be controlled precisely and the loading rate can be set in a broad range. The loading rate and unloading rate must be set at a small rate in order to obtain an accurate loading path. Also, the reasons of the displacement measuring errors are discussed and the improving methods are presented. In the future work, the experiments will be performed to study on the best assembly process of the stator can, and the deformation mechanism of the stator can effected by the pressure will also be investigated.

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