Static, Dynamic, and Fatigue Analysis of the Mechanical System of Ultrasonic Scanner for Inservice Inspection of Research Reactors

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Abstract. This analysis is conducted to determine the effects of static and dynamic loads of the structure of mechanical system of Ultrasonic Scanner i.e., arm, column, and connection systems for in-service inspection of research reactors. The analysis is performed using the finite element method with 520 N static load. The correction factor of dynamic loads used is the Gerber mean stress correction (stress life). The results of the analysis show that the value of maximum equivalent von Mises stress is 1.3698E8 Pa for static loading and value of the maximum equivalent alternating stress is 1.4758E7 Pa for dynamic loading. These values are below the upper limit allowed according to ASTM A240 standards i.e. 2.05E8 Pa. The result analysis of fatigue life cycle are at least 1E6 cycle, so it can be concluded that the structure is in the high life cycle category.

Keywords: Ultrasonic Scanner, Research Reactor, Mechanical System, Fatigue, Static.

1. Introduction

The ultrasonic scanner is one of the tools that comprise the sensors for ultrasonic testing (UT) used to inspect the reactor pool walls. The UT inspection system can be used to detect aging and the various types of degradation of a research reactor system, structure and components (SSCs). Presently, all existing research reactors in Indonesia are experienced an aging of their structures; therefore, it is necessary to examine their SSCs. Our research team has designed the mechanical system an ultrasonic scanner for in-service inspection of research reactor and needs to analyze the mechanical safety of the design before constructing and testing it in reactor pool.

A mechanical systems design for the ultrasonic scanner for research reactors has been analyzed. The analysis includes static, dynamic, and fatigue life analyses on the structure of the mechanical systems. The mechanical system analyzed consists of arm, column, and connection systems. The analysis used the finite element method (FEM) because this analysis method is commonly used for performing structural and static load structure evaluation as well as determination of the fatigue life of the structure. Here, FEM was used to test the effects of static and dynamic loads on the stress distribution of arm structures and column connections.

The purpose of this analysis to find the fatigue life of the structure used the Gerber correction factor because this correction factor is suitable for ductile materials [1]. The ductile materials used in
the mechanical system for research reactor ultrasonic scanner are 6061 aluminium alloy (Al 6061) and 304 stainless steel (SS304) [2].

2. Theory

2.1. Finite Element Modeling (FEM)

Finite element modeling is required for analysis with FEM. To create the model, the CAD geometric model (as shown in Figure 7.) is discretized into smaller and simpler elements, with the result shown in Figure 1. [3]. The meshing of the elements is performed for various sizes, from relatively large to the smallest, to ensure the convergence of the analysis results.

![Finite Element Model of an ultrasonic scanner mechanical system](image)

In this modeling, the mechanical properties of the materials used are also inputs of the analysis. They can be seen in Table 1.

| Material             | Young's modulus (Pa) | Poisson's Ratio (ν) | Yield Strength (Pa) |
|----------------------|----------------------|---------------------|---------------------|
| 6061 Aluminium       | 69E9                 | 0.33                | 1.2408E8            |
| 304 Stainless Steel  | 190E9                | 0.29                | 2.05E8              |
2.2. Loading Conditions
Static and dynamic analysis of the ultrasonic scanner mechanical system for in-service inspection of a research reactor should be carried out to ascertain the safety of the design. In this case, the load and constraints provided shall be in accordance with the loading conditions at the time of operation. The load is in the form of static and dynamic load within a certain period of time. From the load, the fatigue life can also be known. The dynamic load effect is calculated because it will add about 8-77% of the load that can cause fracture or fatigue which can lead to structural failure [7]. To do so, the effects of static and dynamic load on the ultrasonic scanner mechanical system need to be determined. Thus, the system's safety can be ascertained, as the age at which the structure experiences fatigue is known.

2.3. Fatigue Analysis
A design for the mechanical system of an ultrasonic scanner for in-service inspection of a research reactor shall either satisfy the minimum limit of fatigue life or design for infinite life. This can only be confirmed by physical tests or fatigue analysis. In this analysis, the fatigue life of the ultrasonic scanner mechanical system on the finite element stress analysis is predicted using computer code from ANSYS Workbench. Fatigue calculations are performed for materials SS 304 and Al 6061 based on the S-N curves of the materials. The S-N curve shown in Figure 2. and Figure 3. used as the reference for SS 304 and Al 6061 materials.

Fatigue analysis can be performed after static analysis showed that the safety factor criteria were fulfilled i.e., value is 1 – 10. In the fatigue analysis, the load factor given is 1 so that the von Mises stress found from the static analysis represents the maximum stress ($\sigma_{max}$) occurring in the structure. The maximum stress is formulated as [10]:

$$\sigma_{max} = \sigma_{ym} = \sigma_{m} + \sigma_{a}$$  \hspace{1cm} (1)

Here, $\sigma_{m}$ is the average stress in units Pa. and $\sigma_{a}$ is the alternating stress in the unit of Pa. The assumption given is that the amplitude of the alternating stress $\sigma_{a}$ is 10% of the average stress $\sigma_{m}$, so the maximum stress $\sigma_{max} = \sigma_{m} + 0.1\sigma_{m}$ = $1.1\sigma_{m}$, meaning that a given load is 10% greater than the static load. The stress ratio (R) is defined as [10]:

$$R = \sigma_{min}/\sigma_{max}$$  \hspace{1cm} (2)
Where \( \sigma_{\text{min}} \) is the average stress minus the alternating stress amplitude in Pa. \( \sigma_{\text{min}} = \sigma_m - \sigma_a \). The alternating stress is assumed to have constant period constant amplitude; it is illustrated in Figure 4.

\[
\frac{\sigma_a}{S_u} + \left( \frac{\sigma_m}{S_u} \right)^2 = 1
\]

Where \( S_u \) is ultimate tensile strength of the SS 304 and the Al 6061. The \( \sigma_a \text{ effective} \) resulting from interpolation was then used as the reference parameter on the S-N curve to determine the fatigue life. The diagram of stress limit versus metal fatigue is shown in Figure 5.
3. Methodology

The static, dynamic, and fatigue analysis of the mechanical system for the ultrasonic scanner for in-situ inspection research reactor using FEM using software package followed the methodology presented on Figure 6:

![Figure 6. Analysis flow diagram](image)

The 3-D model of the ultrasonic scanner mechanical system consists of the guide for the movement of the column retaining arm, columns, column shafts, and connections system used in this analysis. The curved column is restrained by a column guard, allowing movement with a radius of 2950 mm. The hollow, curved column is made of SS 304 with a size of 40 mm × 80 mm, 1.20 mm thick, as shown in Figure 7. The system was designed for the radial data retrieval process on the research reactor pool wall. The column holder is made of SS 304 also, with the same cross-section of 40 mm width, 80 mm height, and a column thickness of 1.20 mm thickness, while the ultrasonic handle's cross-section has a width of 20 mm, height of 40 mm, a thickness of 1.20 mm. The handle is connected with a wire sling. The column is made of Al 6061 profile with a cross-section size of 80 mm × 80 mm. The design was intended to facilitate the vertical movement on the research reactor pool wall [2]. The 3-D modeling of the mechanical system was performed with the Solidworks 2015 CAD software package. The model is shown in Figure 7.
The geometric model for FEM consisted of 419998 four tetrahedron element nodes and 758497 nodes and with quality of mesh is fine. The loads in this mechanical system were 200 N, representing the load of the ultrasonic sensor holder and the weights located on the top of the column holder, and 320 N, representing the load of the aluminum profile column located at the bottom of the column holder [2]. Aluminum column loads are assumed not to be submerged in reactor pool water. The constraint in this analysis is to use the fixed support that is placed on the stand guide column of the column retaining arm. The boundary conditions of FEM are shown in Figure 8.
For dynamic loads, it was assumed that repeated loading occurred for 45 minutes with 60 cycles at 1 Hz lasting for one minute, with loading tolerance of ±10%. that is, the amplitude of the dynamic or alternating loads is 10% of the static load magnitude. The correction theory used was the Gerber mean stress theory because this correction theory is suitable with material used i.e. SS 304 and Al 6061. This is equivalent to 2700 cycles per day or 1E6 cycles per year. The ambient temperature is assumed to be uniform 22 °C. The ratio, frequency, and correction of dynamic loading can be seen in Figure 9.

The final stage of the process is to output the fatigue life cycle, safety factor, and equivalent alternating stress on a form in the finite element software display.

4. Result And Discussion

The result of static loading analysis using equivalent (von Mises) stress showed that the minimum stress was 4.9298 Pa and the maximum stress was 1.3698E8 Pa, occurring in the part of the structure made from SS 304. The results show that the stress occurring in the structure is still below the material limit of SS304 maximum yield strength of 2.05E8 Pa. Therefore, the process of analysis continued with fatigue loading analysis by giving the load parameters repeatedly with frequency of 1 Hz. The results of Dynamic loading analysis using equivalent Alternating Stress was the minimum stress 0.49298 Pa and the maximum stress value of 1.4758E7 Pa. The result of static loading analysis can be seen in Figure 10. and the result of dynamic loading analysis can be seen in Figure 11.
The result of the security factor analysis shows that the minimum security value of the structure due to static loading was 1.8251 and occurring on the column support bolt. The value is allowed by the design recommendations because the minimum limit of the security factor for static loading is 1. The result of security factor the structural analysis due to dynamic loading was minimum 2.7856 and the value is likewise allowed by the design recommendations because the minimum limit of the security factor for dynamic loading is 2. The maximum value of the security factor of the structure of the ultrasonic scanner mechanical system based on the static and dynamic analysis of the finite element software was 15 which means that the security factor was high. The results of security factor analysis due to static loading can be seen in Figure 12. and the results of security factor analysis due to dynamic loading can be seen in Figure 13.

![Figure 12. Results of safety factor analysis for static loading.](image)

![Figure 13. Results of safety factor analysis for dynamic loading.](image)

The result of fatigue life cycle analysis was performed with load described in Figure 9., namely a 1-Hz load of ±10% of 520 N, and using the Gerber mean stress theory as correction. It was found that minimum or shortest fatigue life cycle occurring on any part of the system was 1E6 life cycles and the maximum or longest was 1E10 life cycles. The parts of the system with the shortest fatigue life were the column retaining bolt and the ultrasonic scanner holder connection, so the solution to lengthen the life cycle would be by strengthening the welding on each connection and enlarging the column support bolts. Based on the results obtained, the design of mechanical structure was found suitable for the design requirements of mechanical structure design having to fulfill the high life cycle number or the minimum limit of life cycle being 1E6 Thus, the safety of the operation is ensured. The results of the fatigue life cycle analysis can be seen in Figure 14.
5. Conclusion
A reseach on the static, dynamic, and fatigue lifes of the mechanical system of the ultrasonic scanner for inservice inspection of research reactor has been conducted. The results of the analysis can be summarized as follows: the maximum equivalent von Mises stress for static loading analysis is $1.3698 \times 10^8$ Pa and its minimum is $4.9298$ Pa. The result of the equivalent alternating stress for dynamic loading analysis which its maximum is $1.4758 \times 10^7$ Pa and its minimum is $0.49298$ Pa in the SS 304 structure. Analysis result of safety factor for mechanical structure found a maximum value of 15 and a minimum of 1.8251 for static loading and a minimum of 2.7856 for dynamic loading, both of which fulfilled the criteria of structure safety of 1-10 for static loads and 2-10 for dynamic loads. The design of ultrasonic scanner mechanical system fulfills the high life cycle category that is at least $1E6$ life cycles. Its maximum fatigue life is $1E10$ cycles. As these results are still bellow of stress limit according to ASTM A240 standards is $2.05E8$ Pa for SS 304, so the structure of the ultrasonic scanner mechanical system can be used safely.

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