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SNS mercury target design optimization

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Abstract. The mercury target at the Spallation Neutron Source (SNS) in Oak Ridge National Laboratory, Tennessee, works under a number of severe conditions: high temperature, radiation, mercury flow, and proton beam pulse pressures. Insufficient strength and durability of the target stainless steel vessel from beam pulse and thermal cyclic loads can lead to mercury leaks and premature target life termination. The parametric and non-parametric shape optimization tools (Isight, Tosca) from Dassault Systemes Extended Abaqus Package have been adopted at SNS to develop robust and reliable target designs. The durability evaluation with recognized leading Fe-Safe (structural fatigue) and Verity (weld fatigue) software is also included in optimization process. Design of Experiment (DOE) was performed to create the response surface for steel vessel structure. The response surfaces are used for design exploration on a basis of Abaqus and Fe-Safe different analyses results. The shape optimization of steel vessel filled with mercury was performed first time using Tosca optimization tool. Obtained complex results enable the consideration of possible trade-offs for the most feasible design.

1. Introduction

The Spallation Neutron Source facility at Oak Ridge National Laboratory will be expanded by developing the Second Target Station. In relation to it, the maximum power on the targets is planned to increase from 1.4 MW to 2.0 MW. The target steel vessel high cycle fatigue with higher power was analysed using Fe-Safe and is presented in the form of lifetime curves for different locations in figure 1. The total number of pulse cycles through the entire regular target service time is expected to be at least 600 million or higher.

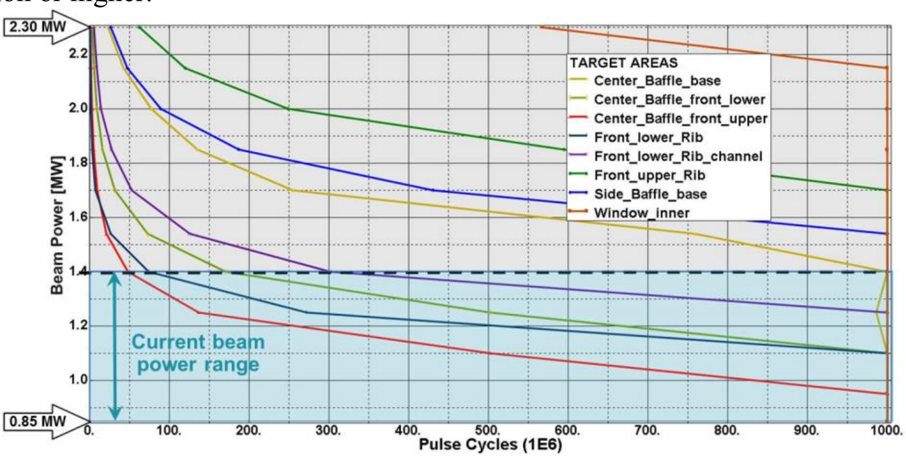

Figure 1. Target pulse fatigue life vs power at different locations.

Curves in figure 1 indicate the fatigue life reduction above 1.0 MW and significant reduction above 1.4 MW power in comparison with required target service time. That leads to the necessity of vessel optimization to address the demands of reliable operation. Two tools from Abaqus Extended Package are being used for target steel vessel optimization – Isight for parametric optimization and TOSCA for non-parametric optimization.

2. Parametric optimization of the target

The one case of parametric optimization is the search for optimal speed of mercury pump. Nominally pump provides the flow of mercury at 2 m/s but also can be run at different speeds. Higher speed provides better cooling of steel vessel and reduces the thermal stress. However, at the same time it leads to higher pressure from mercury what increases the stresses at vessel walls. Those factors are in contradiction with respect to fatigue life and actually represent the multi-objective optimization problem. The Isight capabilities were used to perform Design of Experiment (DOE) and generate the response surface for fatigue life on a basis of Abaqus and Fe-Safe simulation results. Obtained response surface is presented in figure 2 and clearly indicates the optimal point for maximal target life before the appearance of damages from fatigue.

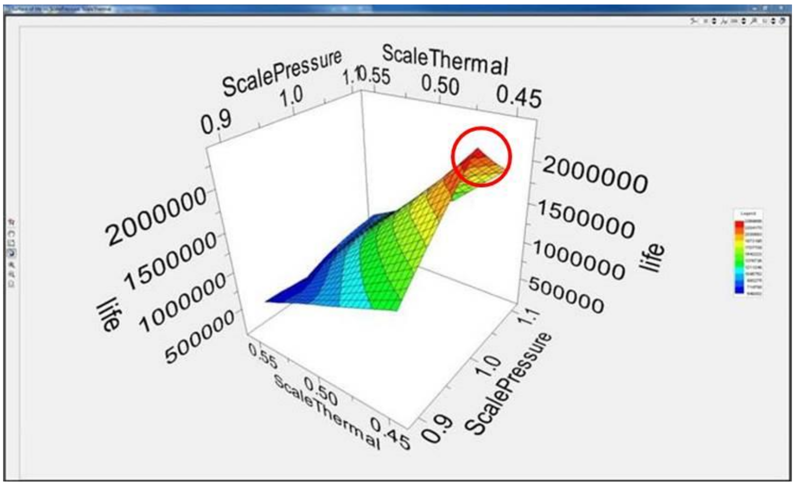

Figure 2. Response surface of vessel fatigue life vs pump speed factors.

3. Overall optimization of the target

Target overall optimization is an interactive process and is illustrated as general flowchart in figure 3. As an optimization problem it can be formulated in the following way:

Minimize: $\mathbf{f_g}\ (\sigma_1^{\mathbf{max}}, \sigma_2^{\mathbf{max}}, \ldots, \sigma_n^{\mathbf{max}})$ (1)

Subject to: $P_j^{min} \leq P_j \leq P_j^{max}$ (2)

Where: $\mathbf{f_g}$ – aggregate function of max stresses $\sigma_i^{\mathbf{max}}$

$\sigma_i^{\mathbf{max}}$ – max stress at $\mathbf{i}^{\mathbf{th}}$ stress concentration

P_j – parametrized design features (geometric, etc.)

No any efficient method exists to solve the problem (1), (2) for the mercury target with its highly complicated operational loadings and constraints. Only interactive, task by task approach there is possible as shown in figure 3.

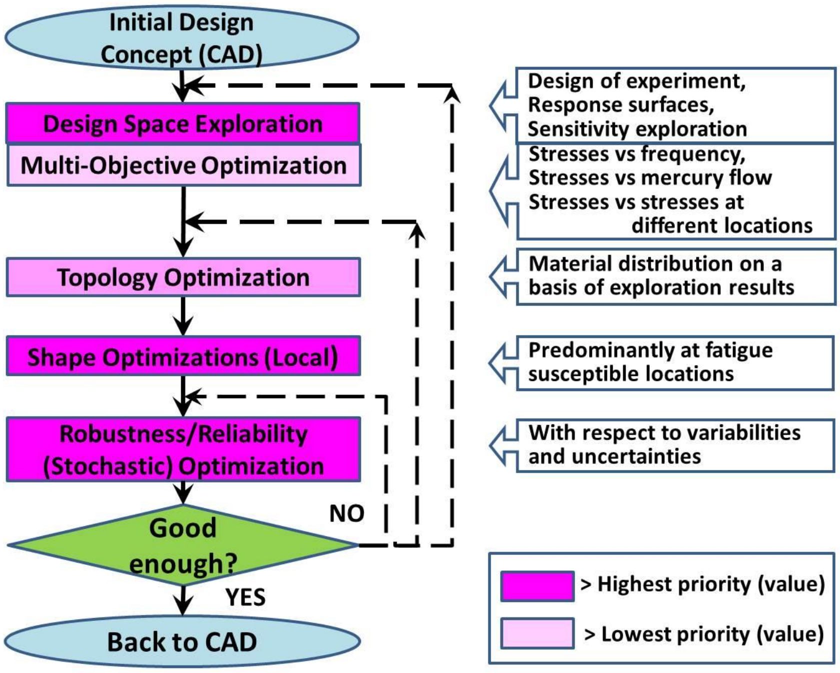

Figure 3. Target overall optimization flowchart.

4. Target steel vessel shape optimization

To minimize fatigue damage and extend the target life there is very important to reduce the stresses in local concentration areas. The TOSCA shape optimization capabilities had been efficiently employed for that purpose. Optimization problem here can be formulated as follows:

Minimize: σ_i^{max} (3)

Subject to: $p_j^{min} \le p_j \le p_j^{max}$ (4)

Where: σ_i^{max} – max stress at i^{th} stress concentration

p_j – local geometry features (nodal coordinates)

Direct application of problem (3), (4) for target steel vessel inner baffle shape optimization is illustrated in figure 4. The TOSCA optimizer successfully reduced local stress by 45% in 5 iterations. However, it appeared that the connection between mercury and steel finite element surfaces had been lost when the steel surface shape was undergoing modification in optimization process. Consequently, the pulse pressure induced in mercury had not been entirely transferred to steel resulting in unjustified reduction of stress.

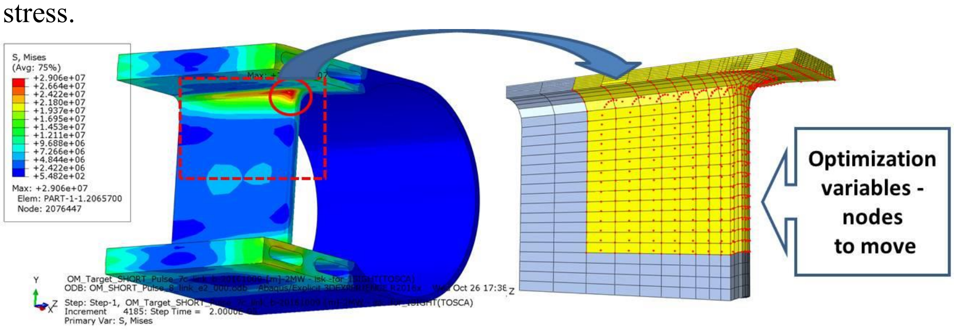

Figure 4. Local shape optimization at inner baffle area.

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Problem was resolved by artificially pulling the mercury surface to the corresponding surface of steel after each consecutive optimization iteration as it is illustrated in figure 5. The stresses at the best, 2nd optimization iteration, are presented in figure 6.

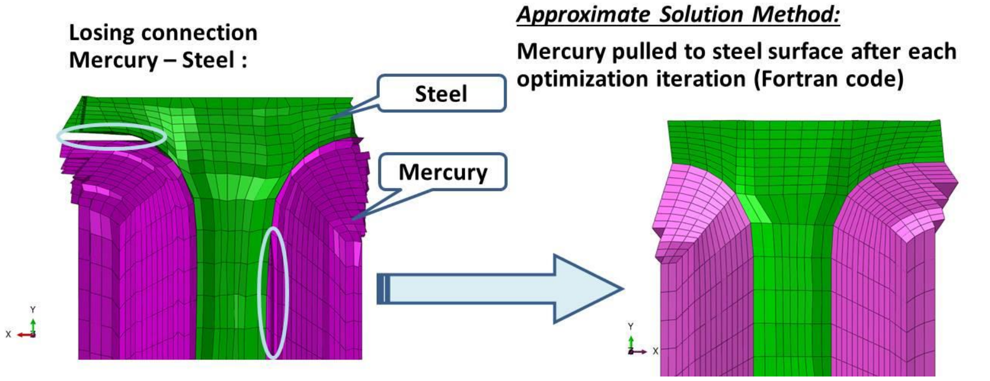

Figure 5. Steel – mercury detachment during shape optimization.

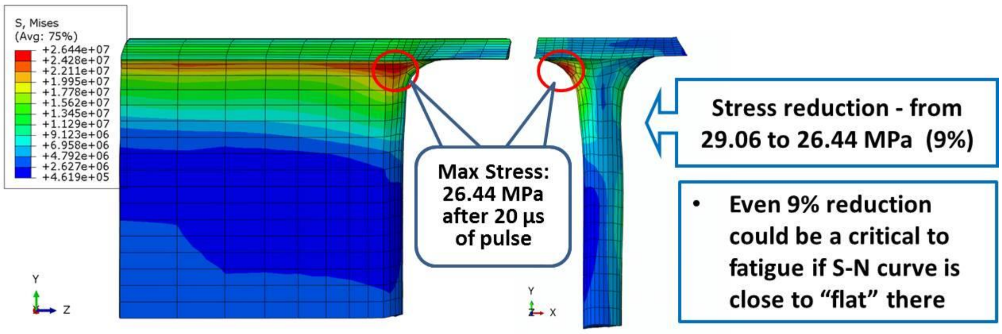

Figure 6. Stress contours after shape optimization.

It has to be noticed the complicacy of the problem. On one hand, the proton beam pulse wave passing through the target is changing the levels and locations of maximum stresses at steel. On the other hand, intervention into optimization process between iterations disorients the optimizer in its searches for direction to the optimal solution. It creates the jumps in objective function history. The best iteration with minimal stress may not be the last one in such case.

5. Conclusions

- Harsh operating conditions of SNS mercury target and increasing levels of power require to achieve the high robustness and reliability of the mercury steel vessel.
- Traditional "Design-Analysis-Evaluation" path is not sufficient to achieve the required design characteristics.
- Design Exploration and Optimization technics are necessary and capable to provide the best possible design and address the increasing demands.

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