Ship Foundation Design using DDAM-coupled Optimization Methods

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Abstract— **The traditional design process for ship foundations often involves many iterations between the designer and the analyst. If the foundation is being designed to withstand specific shock conditions, the iterative process can be much more involved. Historically, design validation for structural integrity occurs near the end of the design lifecycle. By incorporating structural design that has been optimized for DDAM shock analysis, the iterative design cycle can be dramatically reduced.**

This paper presents a case study of a ship foundation optimized for DDAM early in the design phase to validate and optimize the structural integrity of a ship foundation subject to underwater shock conditions. The optimization and validation is performed using OptiStruct, a commercially available simulation software that not only validates structures using DDAM, but has unique built-in optimization capabilities for maximizing performance while reducing weight, cost, and design cycle times. Optimized results show an improvement in the structural performance of the part and will be compared to the baseline model.

Keywords—Optimization, DDAM, Performance Optimization, Weight Savings, Shock, OptiStruct, Validation, Topology Optimization, Shape and Size Optimization

I. INTRODUCTION

In naval applications, ship design must take into account environments considered harsh and atypical. Unlike most commercial ships, naval ships are often designed to withstand extreme conditions such as UNDEX (underwater explosion) events. To address the effects of shock loading on the equipment and machinery within surface ships and submarines, the Navy developed a series of analytical procedures known as DDAM (Dynamic Design Analysis Method). Developed by the Naval Research Lab (NRL) in the 1960's, DDAM is a methodology for qualifying shipboard equipment and supporting structures for survival of shock loading due to UNDEX for Navy ships. [1][3] At its core, DDAM is essentially a type of response spectrum analysis with the only difference being the selection of the participating modes and the calculation of the acceleration spectrum. Unlike a conventional response spectrum analysis, DDAM requires selecting the significant participating modes based off each mode's contribution to the total modal weight. From a normal modes analysis, the mode shapes and frequencies of each mode can be determined and used to solve the diagonal matrix of generalized masses for each mode. [1]

$$[K]-\omega^2[M]\{\Phi\}=0$$

Where;

$[K]$=stiffness
$\{\Phi\}$=mode shape
$[M]$=mass
ω=natural frequency

However, a normal modes analysis is solved such that the eigenvectors are independent of each other and are arbitrarily scaled. Until some type of loading is applied, it is unknown which modes are significant contributors in the analysis. One method of determining the significant modes is to use modal effective mass. In essence, a rigid body vector is assumed to be in the direction of the response of interest to generate a rigid body mass. The rigid body mass and generalized mass from each mode is then used to calculate the participation factor each mass contributes and can be calculated as follows: [1]

$$M_a^x = \frac{\Sigma_i M_i X_{ia}^2}{\Sigma_i M_i (X_{ia}^2 + Y_{ia}^2 + Z_{ia}^2)}$$

$$P_a^x = \frac{\Sigma_i M_i X_{ia}}{\Sigma_i M_i (X_{ia}^2 + Y_{ia}^2 + Z_{ia}^2)}$$

Where the modal mass and participation factor can be calculated in the x,y, and z direction. The modal effective weight then can be calculated as modal mass times the gravity. Once the modal participation is known, the shock response for each mode is computed as follows: [1]

$$\Gamma_{ia} = \S_{ia} P_a \frac{A_a}{\omega_a^2}$$

where:

ω_a=Natural frequency for a^{th} mode
P_a=Participation factor
A_a=Shock spectrum acceleration
$\S_{ia}$=i^{th} response for a^{th} mode
Γ_{ia}=Scaled response (stress, force, displacement)

The scaled response for shock is a function of the participation factor, acceleration spectrum, natural frequency, and response spectrum. The response spectrum, participation factor, and natural frequency can be derived from a normal modes analysis while the acceleration spectrum is calculated using the shock design values as specified in the NRL's DDAM documentation. Per NRL memo 1396, the acceleration spectrum can be calculated for surface ships with hull or shell mounted equipment as: [1]

$$V_0 = VF_i \frac{VA(VB+M)}{(VC+M)} \qquad A_0 = AF_i \frac{AA(AB+M)}{(AC+M)}$$

And all other ship types and mounting locations as:

$$V_0 = VF_i \frac{VA(VB+M)}{(VC+M)} \qquad A_0 = AF_i \frac{AA(AB+M)(AC+M)}{(AD+M)^2}$$

Where M is the modal weight and V and A are the velocity and acceleration shock design coefficients. Once Vo and Ao are calculated, Vo must be converted to an equivalent acceleration:

$$A_{eq} = \frac{V * \text{Modal Frequency (rad/s)}}{g}$$

Where g is the gravitational constant. Aeq is then compared to Ao such that the acceleration used for that particular mode is the smaller of the two. The acceleration values calculated for each significant mode then constitute the input acceleration spectrum. The scaled responses can then be summed using the NRL summation method which estimates the peak response by taking the mode exhibiting the largest response and adding the square root of the squares of the responses from the other modes: [2]

$$\Gamma_{iNRL} = |\Gamma_{iMAX}| + \sqrt{\Gamma^2_{iRSS} - \Gamma^2_{iMAX}}$$

where:

$$\Gamma_{iRSS} = \sqrt{\Sigma_a \Gamma_{ia}^2}$$
$$\Gamma_{iMAX} = \textit{Maximum of } \Gamma_{ia}$$
$$\Gamma_{ia} = i^{th} \textit{ scaled shock response } a^{th} \textit{ mode}$$

II. Design Optimization

The goal of this case study is to generate an optimal ship foundation design for structural performance while also trying to reduce the weight. The existing design, as shown in Figure 1, is a simple ship foundation supporting a wash basin, represented as a point mass.

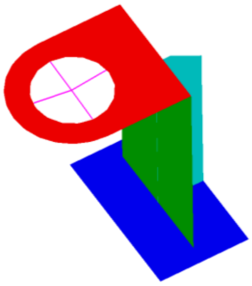

Figure 1: Baseline ship foundation design

A. DDAM Setup

As a baseline comparison, the existing design is first analyzed to generate the displacement response to the DDAM-generated shock spectrum. The baseline foundation weighs 8.33 lbs and the wash basin weighs 9.65 lbs while the base of the foundation is fixed at the bottom. The FEA model consists of 2D elements that are 0.5" thick throughout the part. To begin the DDAM setup, the FEA model is subject to a normal modes analysis to determine the modal weight of each mode. This is done by adding PARAM, EFFMASS to the input deck. Using the built-in DDAM utility in HyperMesh automatically selects the significant modes that consist up to 80% of the total modal weight. For the purposes of determining which Navy coefficients to use for calculating the shock spectrum, the ship foundation can be categorized as being mounted on the hull of a submarine and is subject to elastic deformation. The generated acceleration spectrum can be seen in Figure 2 and is used to perform a response spectrum analysis on the ship foundation.

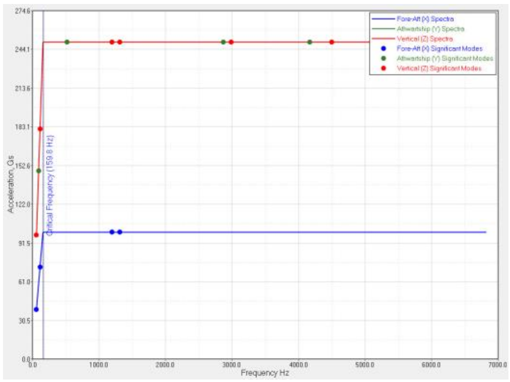

Figure 2: DDAM generated acceleration spectrum on baseline ship foundation

Upon applying the DDAM shock spectrum, the baseline dynamic response of the total displacement of the wash basin to the X, Y, and Z shock spectrum is as follows:

Table 1. Baseline ship foundation displacement response of wash basin

Baseline Model	Displacement (in.)			Mass (lb)
	x-rspec	y-rspec	z-rspec	
	0.096	0.161	0.302	17.98

B. Topology Optimization

To begin the ship foundation optimization, topology optimization is used to generate a broad concept level design for the ship foundation. Essentially, topology optimization is an optimization method that removes and redistributes material in a design space based on the load path. In order to give OptiStruct adequate flexibility in determining a new design, a solid block of material consisting of solid elements is added in place of the stiffener in the baseline ship foundation.

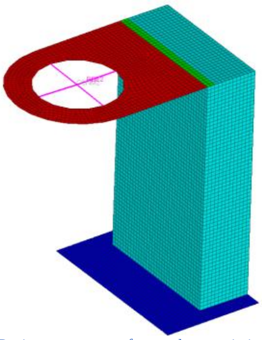

Figure 3: Design space set up for topology optimization

The added block of material is designated as the design space, meaning that OptiStruct had free reign to redistribute material specifically in that portion of the model while the rest of the foundation remains untouched. Since the purpose of the optimization is to generate a design that has an improved performance over the original foundation design, the optimization objective is to increase the overall stiffness of the part while removing at least 50% of the design space. The model with the added design space is set up for DDAM using the same procedure in the baseline FEA model to generate a new acceleration spectrum.

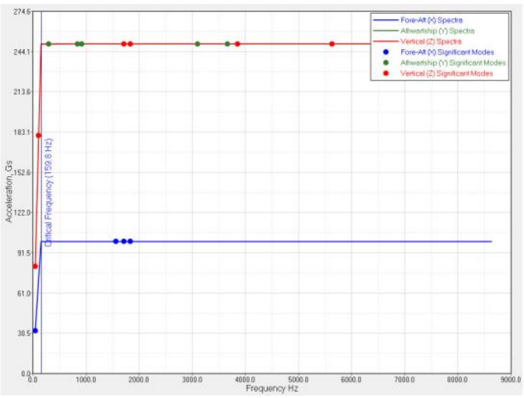

Figure 4: DDAM generated acceleration spectrum for optimization setup

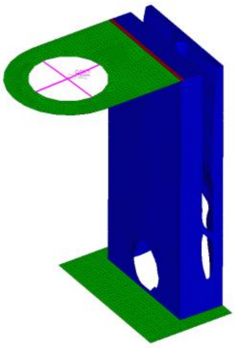

Figure 5: Topology optimized foundation design

Performing topology optimization results in the design seen in Figure 5. The topology optimized design shows a marked improvement in the displacement response of up to 55% as compared to the baseline model.

Table 2. Topology optimized ship foundation displacement response of wash basin

Topology	Displacement (in.)			Mass (lb)
	x-rspec	y-rspec	z-rspec	
Baseline Model	0.096	0.161	0.302	17.976
Topology Optimized Model	0.085	0.071	0.270	20.535
% Difference	-11.00	-55.83	-10.58	14.24

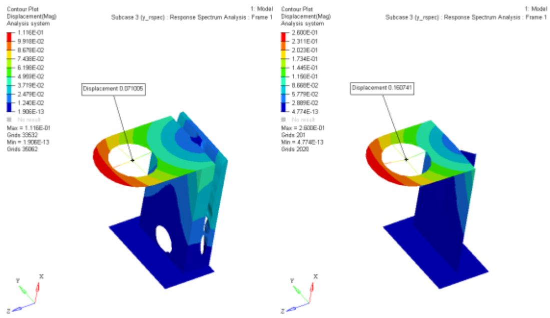

Figure 6: Displacement contours comparing optimized foundation to baseline design

While the dynamic response of the total displacement for the optimized model shows improvement, the topology optimized design still weighs more than the baseline model. Further optimization methods are explored to further tweak the design of the optimized foundation to generate an improved structure.

C. Size and Shape Optimization

Shape optimization is introduced to manipulate the shape of the topology optimized foundation design to reduce the weight of the part while still retaining the improved structural performance. OptiStruct shape optimization takes user-prescribed mesh shapes and optimizes the structure to the best configuration or combination of those shapes. 6 different shapes are generated as design variables to be used in shape optimization.

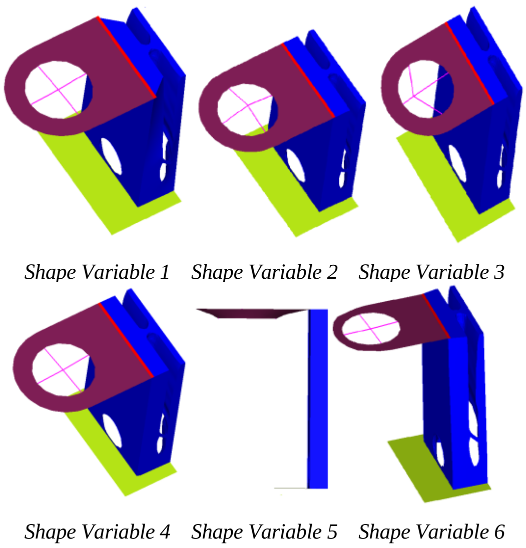

Figure 7: Shape design variables for shape optimization

To further supplement the shape optimization process, size optimization is introduced as a means to optimize the thickness values of the plates supporting the wash basin and the foundation base. Size optimization allows OptiStruct to optimize any parameter defined in the property deck such as plate element thicknesses. The size optimization design variable is set to allow OptiStruct to optimize the plate thicknesses between 0.1" to 1.5". Once the design variables for shape and size optimization are defined, the optimization constraints is set to match the topology optimization total displacement responses to the X, Y, and Z acceleration spectrum:

Table 3. Constraint setup of wash basin displacement for shape and size optimization

	Wash Basin	
	Baseline	Constraint
X Dir	0.096	0.09
Y Dir	0.161	0.08
Z Dir	0.302	0.3

The optimization objective is then set to minimize the total volume of the ship foundation.

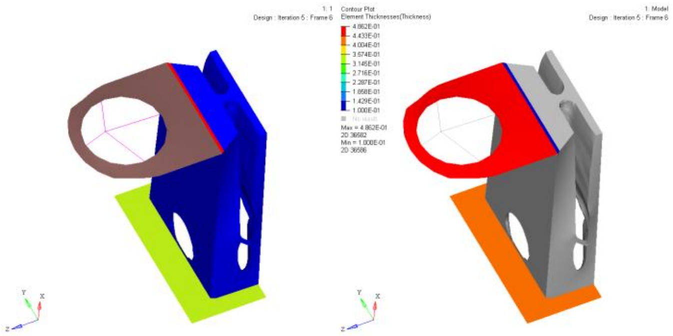

Figure 8: Shape and size optimization result

Size optimization changes the wash basin plate thickness from 0.5" to 0.48" and the base plate thickness from 0.5" to 0.43". Shape optimization determines the optimal combination of shapes as a configuration of shape variable 1, 2, 3, and 6.

Table 4. Size and shape displacement results of wash basin

Size and Shape	Displacement (in.)			Mass (lb)
	x-rspec	y-rspec	z-rspec	
Baseline Model	0.096	0.161	0.302	17.976
Size and Shape Optimized Model	0.090	0.073	0.231	17.528
% Difference	-5.92	-54.79	-23.67	-2.49

The results of the shape and size optimization result in a decreased weight slightly below the original ship foundation weight yet retaining the structural performance of the topology optimized results.

III. Validation

To validate the optimized ship foundation design, the optimized design is subject to an updated DDAM acceleration spectrum. The updated acceleration spectrum is as follows:

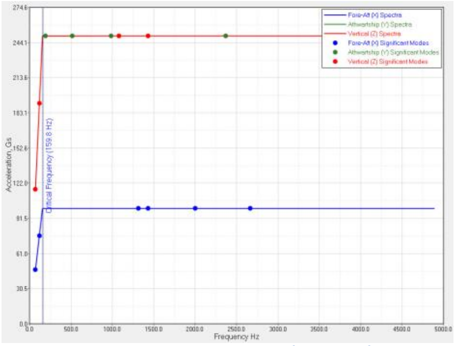

Figure 9: Updated acceleration spectrum of optimized foundation

Re-running the response spectrum analysis with the updated DDAM results in the following displacement contour and total displacement response results:

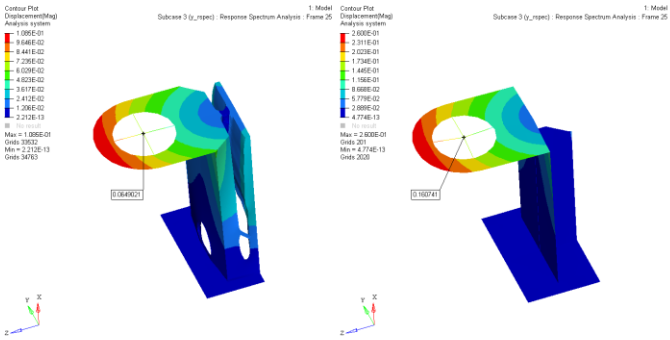

Figure 10: Optimized design versus baseline design displacement contour

Table 5. Optimized results with updated DDAM acceleration spectrum

Size and Shape	Displacement (in.)			Mass (lb)
	x-rspec	y-rspec	z-rspec	
Baseline Model	0.096	0.161	0.302	17.976
Size and Shape Optimized Model	0.082	0.065	0.273	17.528
% Difference	-14.36	-59.62	-9.62	-2.49

The results indicate a negligible difference between the updated spectrum results and the results shown in the shape and size optimization meaning that the final optimized design shows a concrete improvement over the original baseline design.

IV. CONCLUSION

This paper presented a successful case study showing the design optimization of ship foundation model subject to shock loading conditions and DDAM criteria. DDAM-coupled topology optimization generated a conceptual design for the ship foundation that resulted in as much as a 55% improvement in the displacement response of the wash basin. Shape and size optimization further retained the structural improvement of the part while further reducing the weight of the optimized design to make it lighter than the original foundation design. The optimized design is validated through the update of the acceleration spectrum to ensure the structural improvement of the design over the original baseline design. In conclusion, coupling optimization with ship foundation design allows the engineers to account for shock loading early in the design phase to generate structures that can aid the structural performance and/or improve the weight savings.

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