SYSTEM DESIGN OF A VEHICLE STRUCTURE BY A NETWORK OF OPTIMIZATIONS

Jim He, PhD
Michigan Engineering Services, LLC
Ann Arbor, MI

Christopher G. Hart
University of Michigan
Ann Arbor, MI

Nickolas Vlahopoulos, PhD
University of Michigan
Ann Arbor, MI

ABSTRACT

Vehicle design is a complex process requiring interactions and exchange of information among multiple disciplines such as fatigue, strength, propulsion, survivability, safety, thermal management, stealth, maintenance, and manufacturing. Simulation models are employed for assessing and potentially improving a vehicle's performance in individual technical areas. The vehicle's characteristics influence the performance in all the different attributes. Challenges arise when designing a vehicle for improving mutually competing objectives, satisfying constraints from multiple engineering disciplines, and determining a single set of values for the vehicle's characteristics. It is of interest to engage simulation models from the various engineering disciplines in an organized and coordinated manner for determining a design configuration that provides the best possible performance in all disciplines. This paper presents an approach that conducts optimization analysis for a complex system by coordinating operations and exchange of data and information through a network of optimizations. The presented approach provides an organized and seamless environment that captures the implications of design changes from a particular discipline to all other disciplines. It is possible to share design variables among disciplines and thus identify the direction that design variables should follow based on objectives and constraints from multiple disciplines. A rotorcraft example that demonstrates the operation of this integrated design environment is presented. The mass of the gearbox support frame is minimized at the system level while at the same time the performance in structural dynamics and crashworthiness is optimized.

INTRODUCTION

In order to be effective and maximize the weight and cost savings when designing a vehicle, the efforts must be concurrent considering multiple engineering disciplines in parallel (i.e. durability, crashworthiness, etc.). In this manner, it is possible to account for the effects of structural changes across disciplines and improve the performance while the structure is being configured. A flexible Multi-discipline Design Optimization (MDO) capability must be available for driving simultaneously multiple separate optimization analyses, facilitating the exchange of data among the disciplines, and accounting for impact of changes introduced by a particular discipline to all others. The literature on MDO methods and applications is rich and representative references are [1-3]. The MDO term has been used for several different ways of considering multiple disciplines in an optimization process. In single objective optimizations it is used for indicating that the constraints are evaluated based on performance from different disciplines. In sequential optimizations (representative of a design spiral approach) it is used for reflecting that each optimization is associated with a different discipline. It is also used in multi-objective optimizations to indicate that multiple disciplines are considered when defining the cumulative single objective function which combines the performance metrics from the various disciplines. The Target Cascading (TC) method [4-8] differentiates itself by guiding in parallel a network of optimizations. It allows for solving simultaneously multiple individual optimizations for each discipline with separate objective functions and constraints, while at the same time pursuing an overall system level weight or cost objective. A general purpose implementation of this method has been employed in the past in a variety of engineering design areas (thermal protection system design for entry vehicles, aircraft wing design, undersea weapons design, submarine conceptual design, and aircraft design) [9-14]. In this paper the main mathematical background of the software implementation is discussed. An application associated with a rotorcraft vehicle application is presented. The mass of the gearbox support frame is minimized while the performances under crash landing and structural dynamic considerations are optimized in parallel.

MATHEMATICAL BACKGROUND

A flow chart that depicts the general outline of the optimization algorithm utilized in this work is presented in Figure 1. The essence of this approach is based on tracking the values of the objective functions O_i and the values of all the design variables DV_i from each discipline "$_i$" during the iterations of the top level optimization statement. The top level optimization has its own objective function O_T, design variables DV_T, and constraints. Within each iteration of the top level optimization a complete discipline level optimization is conducted. Different disciplines can share the same design variables. Each discipline level optimization determines separately the changes introduced in the design variables. This information is passed to the top level optimization. At the top level optimization additional constraints are introduced automatically, limiting the amount of change introduced in each discipline level objective function and in the design variables within each top level iteration. The extra constraints are expressed as:

$$\left\| O_i^{previous} - O_i^{current} \right\| \le d_i^O \qquad \left\| DV_i^{previous} - DV_i^{current} \right\| \le d_i^{DV} \tag{1}$$

where superscripts "^{previous}" and "^{current}" indicate the values for the objective functions and the design variables originating from the previous and the current step of the top level optimization; subscript "$_i$" indicates the ith discipline. The limits d_i^O, d_i^{DV} are not user prescribed limits, but instead they are variables that augment the top level optimization statement. Therefore, the overall top level optimization statement becomes:

$$\min_{DV_T, DV_i} \left(O_T + \sum_{i=1}^{N} d_i^O + \sum_{i=1}^{N} d_i^{DV}\right)$$

Subject to: Top level constraints

and
$$\left\| O_i^{previous} - O_i^{current} \right\| \le d_i^O$$
$$\left\| DV_i^{previous} - DV_i^{current} \right\| \le d_i^{DV} \tag{2}$$

In this manner the different values that may have returned for the design variables shared between the discipline level optimizations are consolidated at the top level and a new starting point is provided to all discipline level optimizations. This allows coordination of the multiple discipline optimizations by the top level. The TC process also provides the mechanism for passing information from one discipline to another in a form of a function F_i. In this manner any interaction between disciplines dictated by the physics of the design process (beyond the shared design variables) is facilitated through the system level optimization process.

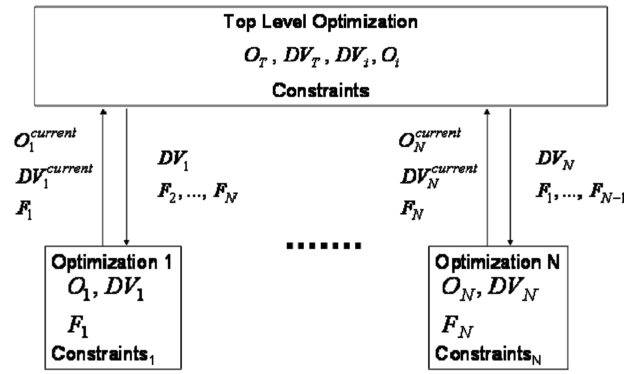

Figure 1. Flow Chart of the Optimization Approach for Guiding the Solution of a Network of Optimizations

The optimization algorithm presented in this Section has been implemented into general purpose optimization software. It allows the user to define the discipline level and the top system level optimization statements. The mathematical links between the network of optimization (Equations 1 and 2) and the exchange of information through the functions F_i are established automatically and without user interference. A user interface has also been developed for allowing the definition of the optimization statements through a sequence of action buttons and menus that the user can make selections from. Figure 2 presents the screen associated with the top level system definition of an optimization statement. The design variables, objective functions, and constraints for the top level optimization are defined along with the links between the top and the discipline level optimizations. For each one of the discipline optimizations a separate screen becomes available for defining the objective function, the design variables, and the constraints of the particular discipline level optimization. Figure 3 presents a representative screen for a discipline level optimization. All screens allow establishing links between design variables and entries in data files of simulation software that can be employed during the optimization process for function evaluations. They also allow for links between entries in the result files and variables that are used for evaluating objective functions and constraints. In this manner it is possible to engage any simulation software in the optimization processes for evaluating constraints or objective functions without the need of developing specialized translators for communicating information between the optimization process and the solvers.

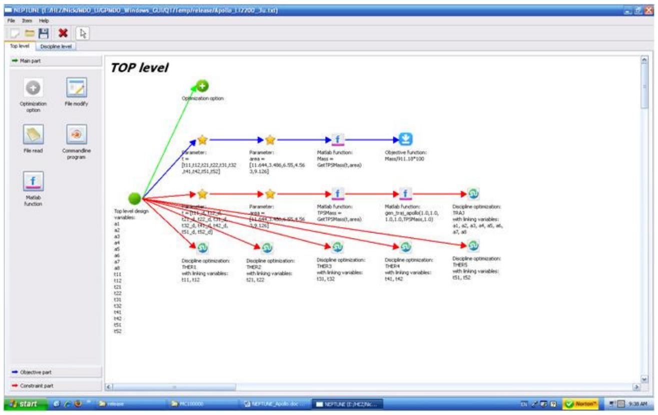

Figure 2. User Interface Screen for System Level Optimization Definition

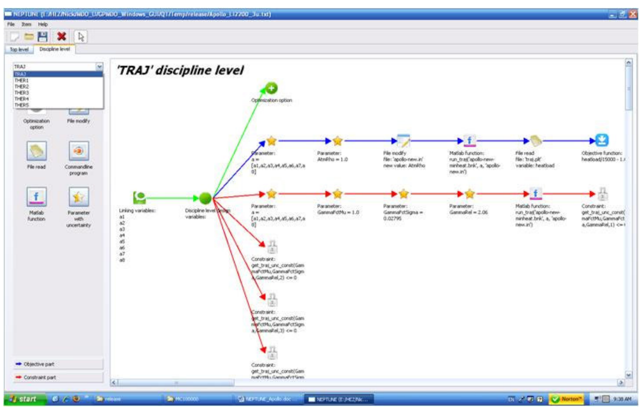

Figure 3. User Interface Screen for Discipline level Optimization Definition

ROTORCRAFT OPTIMIZATION

In order to demonstrate the functionality provided by the network of optimizations capability in designing the structure of a vehicle under multiple disciplines, an optimization analysis for a rotorcraft structure is presented. The base support structure of the gearbox in the rotorcraft fuselage presented in Figure 4 is optimized under structural dynamic and crash landing considerations. The frame structure of the fuselage is presented in Figure 5, and the titanium gearbox base which is optimized is highlighted with light blue color.

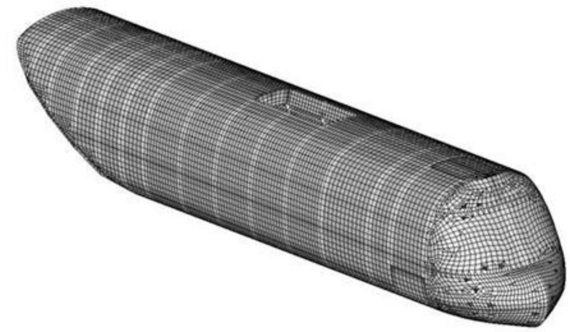

Figure 4. Finite Element Model of Rotorcraft Fuselage used in the Optimization Analysis

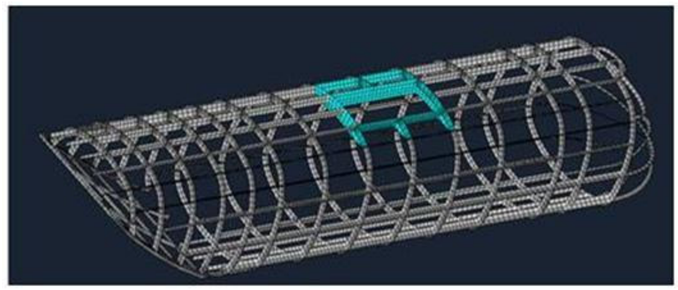

Figure 5. Frame of Rotorcraft Fuselage used in Optimization Analysis

Minimizing the weight of the titanium base where the gearbox is mounted comprises the top level objective. Two discipline optimizations are solved in parallel based on guidance and organization provided by the top level optimization. The two disciplines are associated with crashworthiness performance and with structural dynamic considerations, respectively. Figure 6 presents the flow chart of the multi-discipline optimization analysis performed in this Task. Six design variables are considered in the optimization, each associated with the thickness of a section of the titanium base. The six design variables are highlighted with different colors at the top level optimization in Figure 6. They are:

t1: thickness of front panel (deep blue)
t2: thickness of rear panel (light blue)
t3: thickness of outside panel (green)
t4: thickness of cross stiffener panel (red)
t5: thickness of inner-front panel (yellow)
t6: thickness of inner-rear panel (orange)

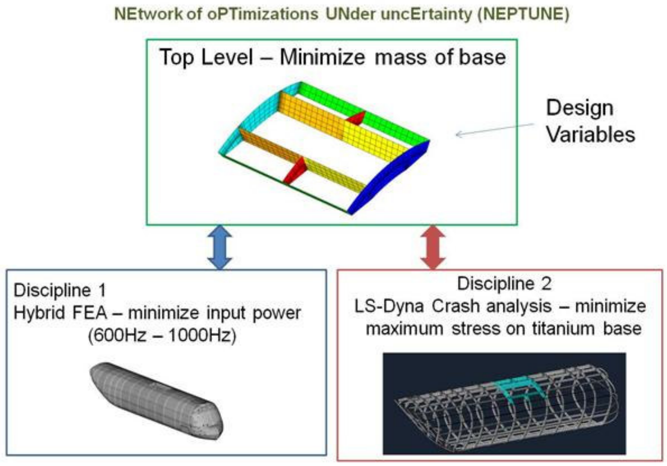

Figure 6. Flow chart of multi-discipline optimization analysis

The discipline associated with the rotorcraft structural vibration analysis is using as a simulation driver a Hybrid FEA method [15-17]. The helicopter model is excited by unit harmonic forces in x/y/z directions applied at 4 locations where the gearbox is mounted on the titanium base (Figure 7). The forces at one node have 90 degree phase shift from the forces at its neighboring node. The objective is to minimize the input power to the helicopter structure under the prescribed excitation in the frequency range of 700Hz to 1,000Hz. This type of structural dynamic objective is associated with fatigue considerations, structural vibration and interior noise concerns associated with passenger comfort.

The discipline associated with the crashworthiness is using LS-Dyna as the simulation driver. It simulates the helicopter being dropped to a rigid ground with impact velocity of 30m/s. The objective is to minimize the maximum dynamic stress observed at the titanium base structure during the crash analysis. This objective ensures that the frame will not brake and the gearbox will not penetrate into the cabin during crash landing.

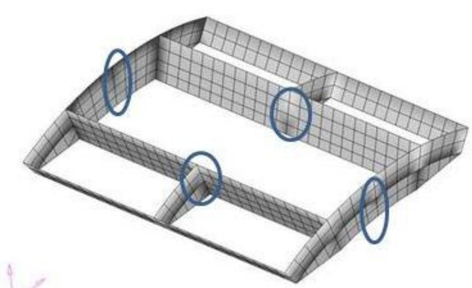

Figure 7. Locations on the titanium gearbox base where the gearbox excitation is applied

In all optimizations the six thickness parameters are ranging between 70% and 130% of their initial values. In the two discipline optimization a constraint is also imposed limiting the increase in the total mass of the base allowed by the discipline level optimizations. Within each iteration of the top level optimization, each discipline optimization is solved completely (i.e. minimizing the input power and minimizing the maximum dynamic stress) and the results are passed to the top level. The top level optimization consolidates the answers and at the same time drives the design in a direction that improves its own objective (i.e. minimizing the mass). The network of optimizations analysis provides the following results for the six design variables and for the objective functions of the top level and the two discipline level optimizations:

	Normalized Thickness					
	t1	t2	t3	t4	t5	t6
Initial	1.0	1.0	1.0	1.0	1.0	1.0
Optimal	1.2997	1.2997	0.7003	0.97216	0.7465	0.7003

Table 1. Summary of the design variables from the network of optimizations analysis

	Top obj (mass)	D1 obj (input power)	D2 obj (max stress)
Initial	133.17	0.0132	6.185E8
Optimal	120.03 (-9.87%)	0.0112 (-15.2%)	4.810E8 (-22.2%)

Table 2. Summary of the Objective Functions at the Optimal Configuration

For an easier interpretation of the results, the thicknesses that correspond to the optimal configuration are presented in Figure 8. The results are presented in a non-dimensional scale (1 indicates no change from initial values, values smaller than 1 indicate a decrease, and values larger than one indicate an increase). As it can be observed from Table 2 the mass of the titanium base of the gearbox is reduced by ~10%, while at the same time the vibrational input power is reduced by ~15%, and the maximum stress is reduced by ~22% from the initial configuration.

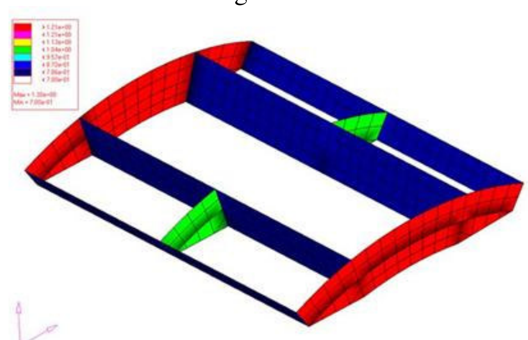

Figure 8. Optimal distribution of thicknesses for titanium gearbox base (non-dimensional)

The optimal design increases the thicknesses at the front and aft panels, retains the cross stiffeners at the same levels with the original design and reduces the thicknesses in all of the longitudinal panels. Figure 9 depicts the input power into the rotorcraft structure for the original and for the optimal configurations. It can be observed that the optimal design has a significantly reduced peak around 950Hz. To better understand the effect of the changes induced by the multi-discipline optimization analysis the vibration levels at 952Hz for the base are plotted in Figures 10 and 11 for the original and the optimal configurations, respectively. The frequency of 952Hz is selected since it exhibits the highest response in the frequency sweep presented in Figure 9. It is clear that the optimal design has reduced vibration levels at the four excitation locations and therefore, reduced input power to the rotorcraft structure.

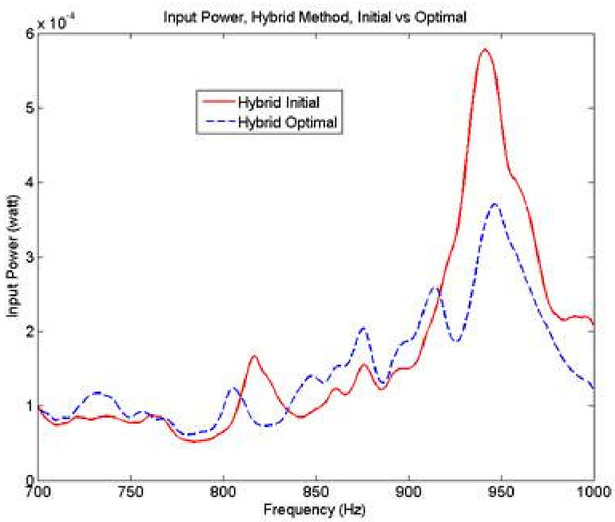

Figure 9. Input power for the 700Hz-1,000Hz range for the initial and the optimal designs

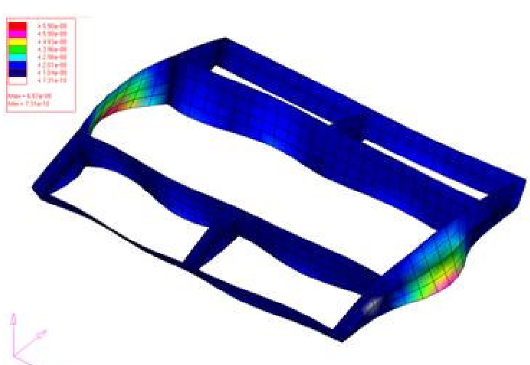

Figure 10. Vibration levels at base for initial design at 952Hz

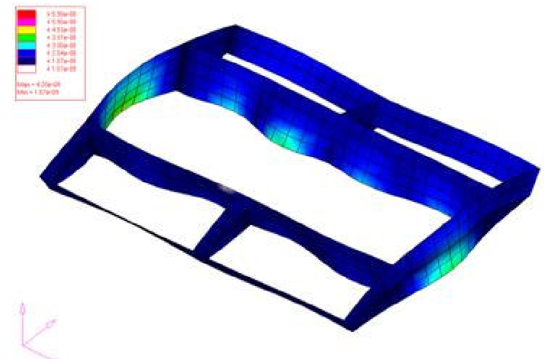

Figure 11. Vibration levels at base for the optimal design at 952Hz

For the crash analysis, the contour plots of the dynamic Von Mises stress are plotted in Figures 12 and 13 for the time step that exhibits the maximum dynamic stress in the initial and optimal configurations, respectively. The same color scale is used in Figures 12 and 13. The time steps that the maximum stress is encountered are not the same between the two design configurations. It can be observed that considerably lower dynamic stresses are observed in the optimal configuration.

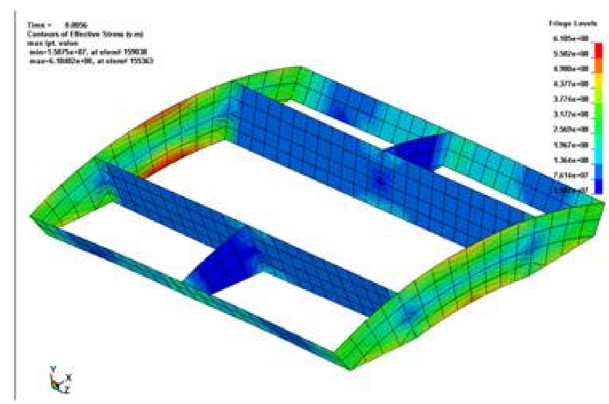

Figure 12. Stress distribution at the base during the time step when the maximum dynamic stress is encountered, initial design

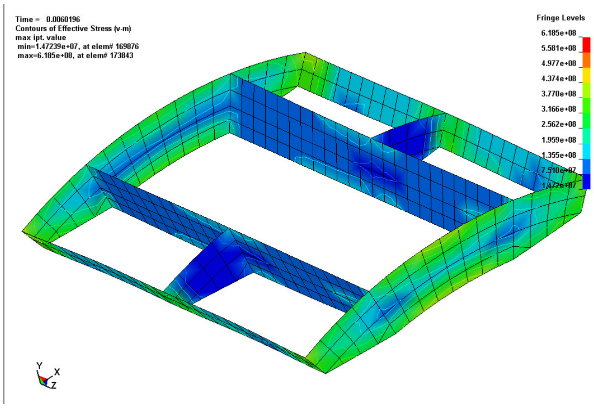

Figure 13. Stress distribution at the base during the time step when the maximum dynamic stress is encountered, optimal design

Overall it is demonstrated that the multi-discipline analysis conducted using the network of optimizations capability captures the interactions among multiple disciplines, and guides the design to an optimal point that improves the system level objective while simultaneously improving the performance at all disciplines.

SUMMARY

This paper presents the main mathematical formulation for coordinating a network of optimizations. The interaction between a system level and the discipline level optimizations is automated through a general purpose code that conducts the network of optimization analysis. A vehicle application is presented for optimizing a system level and multiple discipline level objectives. The mass of the main support structure of a rotorcraft fuselage is minimized while improving performances associated with structural dynamic and crash landing objectives.

AKNOWLEDGEMENTS

The rotorcraft analysis was conducted as part of the NASA Phase I SBIR contract NNX09CF14P (TPOC: Noah Schiller).

REFERENCES

[1] Frank, P. D., A. J. Booker, et al. (1992). "A comparison of optimization and search methods for multidisciplinary design." AIAA Paper: 92-4827.

[2] Alexandrov, N. M. and M. Y. Hussaini (1997). *Multidisciplinary Design Optimization: State of the Art*, Society for Industrial & Applied Mathematics.

[3] Yi, S. I., J. K. Shin, et al. (2008). "Comparison of MDO methods with mathematical examples." Structural and Multidisciplinary Optimization 35(5): 391-402.

[4] H.M. Kim, "Target Cascading in Optimal System Design," Ph.D. Thesis, University of Michigan, Ann Arbor, 2001.

[5] N. Michelena, L. Louca, M. Kokkolaras, C.C. Lin, D. Jung, Z. Filipi, D. Assanis, P. Papalambros, H. Peng, J. Stein, M. Feury, "Design of an Advanced Heavy Tactical Truck: A Target Cascading Case Study," SAE Paper 2001-01-2793.

[6] H.M. Kim, M. Kokkolaras, L.S. Louca, G.J. Delagrammatikas, N.F. Michielena, Z.S. Filipi, P.Y. Papalambros, J.L. Stein, and D.N. Assanis, "Target Cascading in Vehicle Redesign: A Class VI Truck Design," Int. J. of Vehicle Design, vol.29, No.3, 2002, pp.1-27.

[7] H.M. Kim, N.F. Michielena, P.Y. Papalambros, I. Jiang, "Target Cascading in Optimal System Design," Transactions of ASME, Journal of Mechanical Design, September 2003, vol.125, pp.474-480.

[8] N.F. Michielena, H.A. Park, P.Y. Papalambros, "Convergence Properties of Analytical Target Cascading," Proceedings of the 9th AIAA/ISSMO Symposium On Multidisciplinary Analysis and Optimization, AIAA-2002-5506, Atlanta, GA.

[9] C. G. Hart, N. Vlahopoulos, "An integrated multidisciplinary particle swarm optimization approach to conceptual ship design," accepted for publication by Structural and Multidisciplinary Optimization.

[10] J. He, G. Zhang, N. Vlahopoulos, "Uncertainty propagation in Multi-Disciplinary Design Optimization of Undersea Vehicles," 2008 SAE Congress, SAE Int. J. Mater. Manuf. Vol1, No.1, pp. 70 – 79, 2008.

[11] G. Zhang, A. Wang, N. Vlahopoulos, "Engaging Energy based Structural-Acoustic Simulations in Multi-Discipline Design," SAE Paper 2009-01-2198, 2009 SAE Noise and Vibration Conference, May 2009.

[12] C. G. Hart, and N. Vlahopoulos, "Relating affordability and performance metrics in a multidisciplinary conceptual submarine design optimization," 2009 ASNE Day, April 2009.

[13] J. He, N. Vlahopoulos, "Utilization of Response Surface Methodologies in the Multi-discipline Design Optimization of an Aircraft Wing," SAE Paper 2009-01-0344, 2009 SAE Congress.

[14] J. Sun, G. Zhang, N. Vlahopoulos, S-B. Hong, "Multi-disciplinary design optimization under uncertainty for thermal protection system applications," 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, September 2006, Portsmouth, Virginia, AIAA Paper 2006-7002.

[15] S.B. Hong, A. Wang, N. Vlahopoulos, "A Hybrid Finite Element Formulation for a beam plate system," *Journal of Sound and Vibration,* Vol. 298, 2006, pp. 233 – 256.

[16] N. Vlahopoulos, S. Li, M.Viktorovitch, D. Caprioli, "Validation of a Hybrid Finite Element Formulation for Mid-Frequency Analysis of Vehicle Structures," SAE Paper 2007-01-2303, 2007 SAE Noise and Vibration Conference.

[17] R. Sbragio, A. Wang, N. Vlahopoulos, D. Caprioli, C. Bertolini, "Structure-borne Vehicle Analysis using a Hybrid Finite Element Method," SAE Paper 2009-01-2196, 2009 SAE Noise and Vibration Conference