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Multidisciplinary design optimization of a vehicle system in a scalable, high performance computing environment

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Abstract Multidisciplinary Design Optimization of a vehicle system for safety, NVH (noise, vibration and harshness) and weight, in a scalable HPC environment, is addressed. High performance computing, utilizing several hundred processors in conjunction with approximation methods, formal MDO strategies and engineering judgement are effectively used to obtain superior design solutions with significantly reduced elapsed computing times. The increased computational complexity in this MDO work is due to addressing multiple safety modes including frontal crash, offset crash, side impact and roof crush, in addition to the NVH discipline, all with detailed, high fidelity models and analysis tools. The reduction in large-scale MDO solution times through HPC is significant in that it now makes it possible for such technologies to impact the vehicle design cycle and improve the engineering productivity.

Key words multidisciplinary design optimization, high performance computing, crashworthiness, NVH, surrogate modeling and approximations

1 Introduction

The automotive industry today is grappling with a number of complex and often conflicting requirements. Automotive manufacturers need to:

- Compress vehicle design cycle time
- Lower the weight and cost of the vehicle
- Improve product performance, safety, quality, and reliability

To satisfy these requirements, the industry is increasingly relying on the use of more formal and structured approaches to design, analysis and optimization.

For automotive manufacturers, the vehicle design process has always involved intensive collaboration among teams with specialized disciplines, such as crash and safety, NVH, and computational fluid dynamics (CFD). Like practically all engineered and manufactured systems, automobiles experience interactions among various physical phenomena and between different components of the full system. Current processes require a trade-off between the disciplines to develop the final design. Traditionally, auto manufacturers have accomplished this by passing the designs back and forth between the teams working within these disciplines until the differences are minimized and a mutually acceptable solution is found.

Today this approach is too sequential and time consuming. The need to reduce time to market for new vehicles, coupled with the increased availability of affordable High Performance Computing (HPC) systems that can process hundreds of simulations concurrently has led to the increased adoption of structured techniques like MDO.

Once considered impractical due to economic and capability limitations, MDO methods are now much more feasible with the cost-effective turnaround of simulations on scalable platforms like the SGI Origin 3000 system. As an example, acrash simulation that took 27 hours and cost $5200 to run on a Cray Y-MP in 1993, runs in 1 hour today on an SGI Origin 3000 system and costs about $7. This dramatic cost/performance improvement is enabling new approaches like MDO to flourish.

The focus of this paper is on MDO of a vehicle system for safety, NVH, and weight, that is performed on a scalable, HPC environment. The application of MDO to automotive vehicle design for safety and NVH has been of significant interest over the last few years (Yang *et al.* 1994; Chargin and Miura 1999; Stander 1999;

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Schramm *et al.* 1999; Sobieszczanski-Sobieski *et al.* 2000). Sobieszczanski-Sobieski *et al.* (2000) report a very significant reduction in elapsed computing time for such large-scale MDO problems – from 9 months to 1 day – through the efficient use of shared memory multiprocessor systems. The present work is an extension of work reported by Sobieszczanski-Sobieski *et al.* (2000) with a substantial increase in computational complexity of the MDO problem. The increased computational complexity of the present work comes from addressing multiple safety failure modes including frontal crash, offset crash, side impact and roof crush, in addition to the NVH discipline.

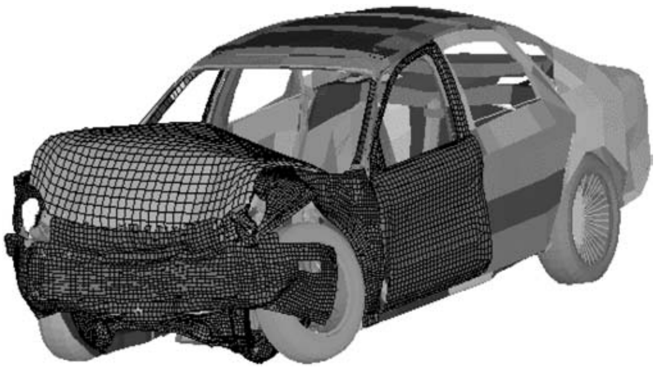

Fig. 1 Frontal crash model

2
MDO attributes where HPC environments would be useful

The design of complex structures and vehicles, such as in the automotive and aerospace industries, results in a simulation environment with the following characteristics:

- A high number of design variables
- A substantial number of design subsystems and engineering disciplines
- Interdependency and interaction between the subsystems and disciplines
- Large, complex models across all engineering disciplines

These attributes are representative of an environment that would benefit from the use of MDO and HPC. Due to the level of complexity and dimensionality, high performance computing systems are critical for large scale MDO in order to impact the product development cycle. In addition, a heterogeneous mix of simulations is common with MDO. These various kinds of simulations put different strains on the computational systems. Some are I/O intensive, while others require fast CPUs with high CPU-to-memory bandwidth. Since all of these simulations need to be conducted simultaneously to impact the design cycle, the computing environment must be capable of effectively running the complete mix of simulations.

3
Car body models and analysis tools

3.1
Frontal crash

The full frontal car crash finite element model used in this study contains over 100 000 elements, and is shown in Fig. 1. It crashes into a rigid 90 degree fixed barrier with the speed of 35 MPH. The key safety performance measures in the full frontal crash include occupant Head Injury Criteria (HIC) and Chest G, which are calculated from the MADYMO analysis with the crash pulse imported from the RADIOSS crash analysis. The MADYMO code (TNO Automotive 2001) is multi-body occupant simulation software from TNO and the RADIOSS is an explicit, nonlinear finite element dynamic analysis software from Mecalog.

Full frontal crash is commonly used to design and validate the vehicle front structures. Federal Motor Vehicle Safety Standards 208 (FMVSS) clearly specifies the safety regulations and test configuration. The regulation states that the HIC and Chest G injury numbers have to be within 1000 and 60 g, respectively. RADIOSS is used to perform crash simulations throughout this study. The design targets for the full frontal impact in this study are not only to satisfy FMVSS 208 regulation but also to comply with corporate guidelines. In this paper, the occupant HIC and Chest G numbers are targeted to be less than 450 and 45 respectively. Note that the numbers may not be realistic, as they are solely used for proving the methodology. Another constraint is the New Car Assessment Program (NCAP) star-rating criterion, proposed by the National Highway Traffic Safety Administration (NHTSA) in 1994. The NCAP star-rating criterion is derived from the total injury probability criteria combining the occupant HIC and Chest G numbers. The total occupant probability of severe injury is given by:

$$P_{\text{total}} = 1 - (1 - P_{\text{head}})(1 - P_{\text{chest}})$$

where

$$P_{\text{head}} = \frac{1}{1 + e^{(5.02 - 0.0035\text{HIC})}}$$

$$P_{\text{chest}} = \frac{1}{1 + e^{(5.55 - 0.0693 ChestG)}}$$

$$\text{HIC} = \left(\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, \mathrm{d}t \right]^{2.5} (t_2 - t_1) \right)_{\max}$$

where:

a is a multiple of G's

t_1, t_2 is expressed in second and measured during impact

$(t_2 - t_1)$ is within 36 ms
If occupant P_{total} is less than 10%, it is graded as 5-star in the NCAP star-rating system

3.2
50% Frontal offset crash

The finite element model for 50% frontal offset impact, as shown in Fig. 2, is identical to the frontal crash model. The only difference is the barrier. In this model, the vehicle crashes into a 90-degree fixed rigid wall with 50% offset. The impact velocity is 40 mph. The RADIOSS code is used for the simulation. The key output from the frontal offset impact is the toe board intrusion. The design target for toe board intrusion is set to be less than 10 inches. The design variables used for 50% frontal offset crash are the same as those used for full frontal crash.

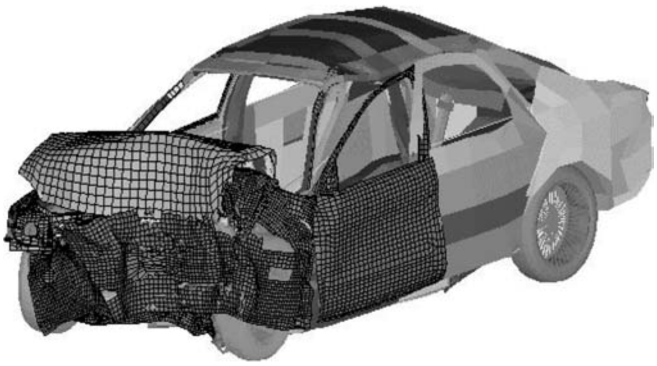

Fig. 2 50% frontal offset crash model

3.3
Roof crush

Vehicle roof crush is a federal mandatory requirement intended to enhance passenger protection during a rollover event. The test procedure is defined in FMVSS 216. The finite element roof crush model for this study is converted from a NVH model, as shown in Fig. 3.

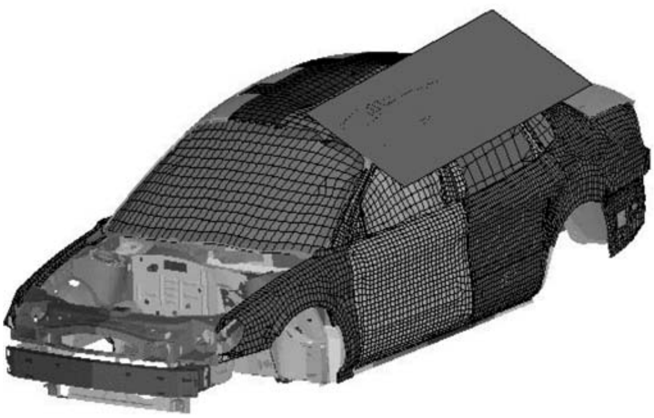

Fig. 3 Roof crush model

The RADIOSS software is used for crush simulation. Unnecessary parts in the NVH model are deleted and some missing parts are added in the roof crush model; for example, very detailed side doors are added and the glasses are refined. The total number of elements for roof crush is about 120 000. A 72 inches by 30 inches rectangular ram is added to perform the roof crush as specified by the FMVSS 216. The longitudinal axis of the ram (see Fig. 3) is at a forward angle (side view) of five degrees below the horizontal, and is parallel to the vertical plane through the vehicle's longitudinal centerline. The lateral axis is at a lateral outboard angle, in the front view projection, of 25 degrees below the horizontal. The lower surface is tangential to the surface of the vehicle and the initial contact point is on the longitudinal centerline of the lower surface of the ram and 10 inches from the forward-most point of the centerline. In roof crush simulation, the ram normal speed is set to be 7.5 MPH.

As described in the FMVSS 216, the force generated by vehicle resistance must be greater than 5000 lbs. (22 240 N) or 1.5 times the vehicle weight (whichever is less) through five inches of ram displacement. In this study, the roof crush resistant force is set to be 6000 lbs. The door thickness and material yield stresses are chosen as the design variables.

3.4
Side impact

For side impact protection, the vehicle design should meet the requirements for the National Highway Traffic Safety Administration (NHTSA) side impact procedure (Federal Motor Vehicle Safety Standards 214) or European Enhanced Vehicle-Safety Committee (EEVC) side impact procedure. In our study, the EEVC side impact test configuration is used. The dummy performance is the main concern in side impact, which includes head injury criterion (HIC), chest V*C's (viscous criterion) and rib deflections (upper, middle and lower). These dummy responses must at least meet EEVC requirements. The finite element vehicle model along with moving deformable barrier model is shown in Fig. 4. A finite element dummy model is also employed for prediction. Other concerns in side impact design are the velocity of B-Pillar at middle

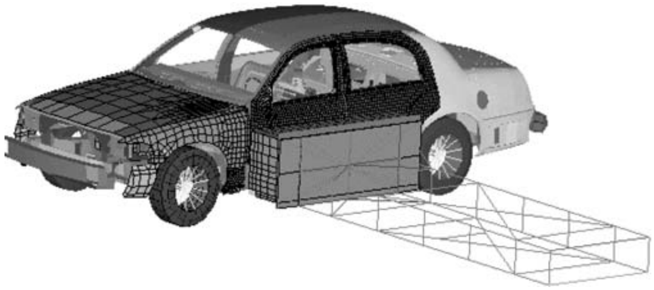

Fig. 4 Side impact model

point and the velocity of front door at B-Pillar. The total number of elements in this model is about 100 000.

The moving deformable barrier position is defined in the EEVC side impact procedure. All nodes of the moving barrier are assigned an initial velocity equal to 50 km/h. For side impact, the increase of gage design variables tends to yield a better dummy performance. However, it also increases vehicle weight, which is undesirable. Therefore, a balance must be sought between weight reduction and safety concerns. The objective is to reduce the weight while imposing safety constraints on the dummy. The dummy safety performance is usually measured by EEVC side impact safety rating score. In the EEVC side impact safety rating system, the safety rating score depends on four measurements of the dummy: HIC, abdomen load, rib deflection or V*C, and pubic symphysis force. In this study, the dummy chest V*C and rib deflection are used to measure the safety performance.

3.5 NVH

In the car product development process, different NVH models are used for different purposes so that the quality of the NVH is high and the cost is minimized. A car body called Body-In-Prime (BIP) is used for this study. The BIP is a trimmed body without all the closures (door, hood, deck lid) and other sub-systems (steering column, fuel tank, and seats) and trim items (carpeting, battery, and so on). A trimmed body structure may be thought of as a vehicle without the suspension and power train subsystems. The BIP can also be thought of as the "Body-In-White" with glass. The BIP plays an important role in determining the dynamic characteristics of the vehicle.

The BIP normal modes, static bending and static torsion analyses were conducted using the MSC/NASTRAN. The full scale NVH finite element model is shown in Fig. 5. The total number of shell elements is close to 68 000. The total number of nodes is about 69 000. The normal modes were calculated under the free-free condition. The static bending analysis was conducted with the boundary condition of front (yz and z) and rear (xz and xyz) shock towers constrained, while for the static torsion analysis rear shock tower supports (xz and xyz) and a middle point of the lower radiator support (z) were constrained for boundary conditions. The bending stiffness calculated using a load applied at the front rocker locations was 4551 N/mm while the torsion stiffness calculated using a torque applied at the front shock tower locations was 8726 Nm/deg. The free-free normal mode analysis showed that the overall torsion was 26.5 Hz and overall bending was 38.9 Hz.

Fig. 5 NVH model

The torsion frequency for the BIP free-free normal mode is set to increase by 5% from 26.5 to 27.8 Hz. The upper bounds for static torsion and static bending displacements are chosen as 3.4 mm and 0.9 mm, respectively (10% improvement from the initial design).

4 Elapsed computing times for safety and NVH analysis

The elapsed computing time for single analysis of the various safety and NVH systems is provided in Table 1. The RADIOSS code shared memory parallel version, RADIOSS v4.1h, is used for this benchmark. For NVH, MSC/Nastran v70.2, Solution Sequence 200 is used.

SGI Origin 3800 HPC server was used for all of the computations. The Origin 3800 is a cache-coherent non-uniform access multiprocessor (ccNUMA) architecture where the memory is physically distributed among the nodes but is globally addressable to all the processors through the interconnection network. The Origin 3800 configuration used in this study involves 128 400 MHz IP35 processors, with MIPS R12000 processor chip and main memory size of 131 Gbytes.

Table 1 Elapsed computing time on SGI Origin 3800 server

System	Model size and impact simulation time	Elapsed time using 8 processors per analysis
Frontal Crash	101 709 elements, 100 ms	7:06:09 hrs
Offset Crash	101 709 elements, 120 ms	8:40:29 hrs
Roof Crush	124 688 elements, 40 ms	3:26:30 hrs
Side Impact	97 100 elements, 80 ms	5:04:55 hrs
NVH (statics, modal, & design sensitivity analysis)	350 000+ degrees of freedom	0:25:00 hrs on asingle processor

5 Multidisciplinary Design Optimization – problem definition and solution

Multidisciplinary Design Optimization (MDO) has evolved as a new discipline (Sobieszczanski-Sobieski

1995) that provides a body of methods and techniques (Kodiyalam and Sobieszczanski-Sobieski 2001) to assist engineers in moving engineering system design closer to optimum. Formal MDO methods are intended for the synthesis of generic, multidisciplinary engineering systems, such as an aircraft or automotive, whose design is governed by multiple disciplines. The key concept in these MDO methods is a decomposition of the design task into subtasks performed independently in each of the modules, and a system-level or coordination task, to account for the interactions between the subtasks. An important benefit from the decomposition is granting autonomy to the groups of engineers responsible for each particular subtask in choosing their methods and tools for the subtask solution. As an additional advantage, the concurrent execution of the subtasks fits well the technology of massively concurrent processing that is now increasingly available.

The general system optimization problem is stated in the following form:

Given a set of design variables, $\mathbf{X}$,

Find: $\Delta\mathbf{X}$

Minimize : $F(X,Y(X))$

Satisfy: $G(X,Y(X))$

Bounds on X. (1)

In the problem defined by (1), $Y(X)$ represents the behavior (state) variables, F represents the design objective function and G represents the design constraints.

The above optimization problem can be specifically stated as a multidisciplinary problem involving the "disciplines" of NVH and Safety:

Given the set of system ($\mathbf{Z}$) and local ($\mathbf{X}$) design variables,

Find: $\Delta\mathbf{X}$ and $\Delta\mathbf{Z}$

Minimize: Weight of the vehicle system structure

Satisfy: NVH:

Static torsion & bending displacements
Frequency (Mode3) $26.65 < w3 < 29.32$ Hz
Frontal Crash:
Dummy HIC (Head Injury Criterion)
Dummy Chest G
Probability of severe injury
50% Frontal Offset Crash:
Intrusion at several key locations
Roof Crush:
Maximum resistance force
Side Impact:
Displacements at several key locations
Viscous Criterion
Bounds on the design variables, $\mathbf{X}$ and $\mathbf{Z}$

In this MDO task, the NVH discipline has 19 local design variables, while the safety disciplines combined have 25 local design variables. In addition, 10 system design variables (Z) are common to both the NVH and crash disciplines. The design variables are primarily sizing (thickness) variables and spring stiffness.

The above MDO problem is solved using a variation of the OMDAA (Optimization by a Mix of Dissimilar Analysis and Approximations) method (Sobieszczanski-Sobieski *et al.* 2000). It involves using multiple approximation models, a sensitivity-based approximation model for NVH responses (Starnes and Haftka 1979) and Kriging metamodels for the Safety discipline responses. A SQP optimizer is used to solve the numerical optimization problem. The MDO procedure is as follows:

1. Sampling of the design space using Latin Hypercube procedure centered at the baseline or current optimal design point;
2. Analysis of the sample points concurrently on the multiprocessor machine. Evaluation of design objectives and constraints;
3. Construction of metamodels for design responses using Kriging approximation method;
4. MDO solution using numerical optimization strategies and Kriging metamodels;
5. Verification analyses of the optimal design point from Step 4. Evaluation of design objectives and constraints;
6. Engineer's judgement/interface to study the solution and make problem modifications as required;
7. Check for convergence of the solution. If not converged, refine design variable limits, and repeat cycle from Step 1.

5.1 Kriging metamodel-based approximations

The mathematics of Kriging includes a combination of a global model of the design space as well as local deviations so that the Kriging interpolates the sampled data points (Guinta, *et al.* 1998; Simpson *et al.* 1998). The principal difference between the references and this work is in the implementation, specifically; the optimization algorithm used for solving the n-dimensional unconstrained optimal fitting problem outlined below. With Kriging, a spatial correlation metamodel is chosen of the form:

$$y(x) = f(x) + Z(x)$$

where the first term $f(x)$ represents the global model characterized by a standard polynomial response surface model or an artificial neural network, and the second term $Z(x)$ is the localized deviations and the departure from the standard polynomial RSM.

Some key characteristics of the Kriging approximations include:

1. Capable of modeling responses that are difficult to approximate using a quadratic polynomial response surface model;
2. It is an exact fit for the given sample points;
3. Provides for sufficiently accurate approximations in the neighborhood of the sample points;
4. Requires significantly higher computational effort compared to the polynomial RSM, as the number of sample points increase.

6 Vehicle system MDO results

The MDO problem results are provided in Table 2 for the two cycles of the OMDAA process. The initial design is an infeasible design with NVH and Safety constraint violations of over 10% from the target. The final design is feasible without any adverse impact on the system objective, weight of the car body.

In a typical engineering system optimization such as this MDO problem, many different criteria are involved and the designers and disciplinary experts would like to have trade-off information available for deciding how best to balance the various criteria to arrive at the most desirable design. Certain trade-off analyses are performed for the system objective with respect to the active design constraints, and the results are used in constructing Pareto optimal curves and surfaces. The Kriging approximation models are used in conjunction with the Pareto trade-off analyses to achieve the desired computational efficiency.

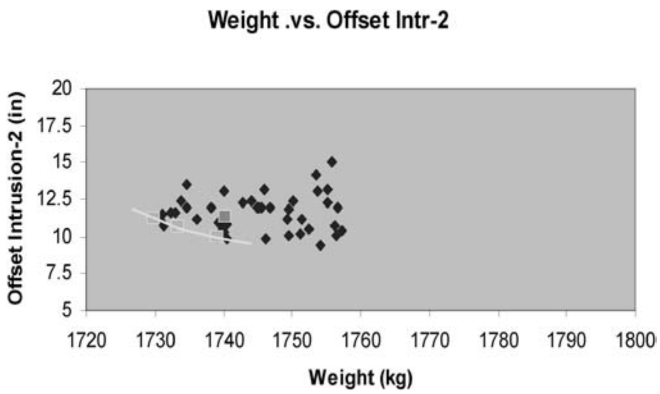

Fig. 6 Pareto optimal trade-off curve between weight and offset system response (Intrusion 2)

Figure 6 shows the trade-off between the vehicle weight and offset crash response-intrusion that is an active constraint in the MDO problem. The dots represent the sample set of design points using the Latin Hypercube sampling method.

7 Computational performance

In this work, very high fidelity analysis models and tools are used. These in turn contribute to computationally ex-

Table 2 Vehicle system MDO results

System	Attribute	Baseline	Target	CYCLE 1 Solution	CYCLE 2 Solution
NVH	Frequency- Mode3 (Hz)	26.5	$27.8 \leq f3 \leq 29.3$	27.8	27.9
	Torsion disp1(mm)	3.8	≤ 3.4	3.39	3.38
	Torsion disp2(mm)	−3.8	≥ -3.4	−3.41	−3.40
	Bending disp(mm)	−0.97	≥ -0.9	−0.90	−0.90
FRONTAL CRASH	HIC	500	≤ 450	378	426
	Chest G	42	≤ 45	35.9	36.9
	Ptotal (%)	10	≤ 10	6.8	7.5
OFFSET CRASH	Intrusion 1 (in.)	11.2	≤ 10	8.9	9.0
	Intrusion 2 (in.)	10.8	≤ 10	9.9	10.0
	Intrusion 3 (in.)	10.9	≤ 10	9.6	9.5
	Intrusion 4 (in.)	10.1	≤ 10	8.7	8.7
	Intrusion 5 (in.)	10.5	≤ 10	9.1	8.8
ROOF CRUSH	Resistance Force (kN)	34.7	≥ 27	35.2	32.8
SIDE IMPACT	VC 1	0.48	≤ 0.54	0.48	0.47
	VC 2	0.51	≤ 0.54	0.53	0.52
	VC 2	0.54	≤ 0.54	0.55	0.54
	Disp2 (mm)	26.3	≤ 27.2	25.9	25.8
	Disp3 (mm)	27.2	≤ 27.2	26.7	26.6
SYSTEM	Weight (kg)	1740.5	Minimize	1740.8	1739.1

Table 3 Computational details for safety disciplines

System	Number of design variables (N)	Number of RADIOSS simulations	Total elapsed time on (using 8 CPU/simulation) Origin 3800 machine
Frontal Crash	10 (system)+ 5 (local)	3N + 1 (baseline)+ 2 (validation) = 48	340.8 hrs
Offset Crash	10 (system)+ 5 (local)	3N + 1 (baseline)+ 2 (validation) = 48	416.8 hrs
Roof Crush	10 (system)+ 10 (local)	L24 + 1 (baseline)+ 2 (validation) = 27	93.15 hrs
Side Impact	10 (system)+ 5 (local)	3*N + 1 (baseline)+ 2 (validation) = 48	244.0 hrs

pensive analyses and in addition these expensive analyses are repeatedly performed during the optimization search, making the MDO process very long, if not prohibitive, with respect to impacting the design cycle.

The primary computational cost is in performing the RADIOSS finite element analysis for the sample set of design points corresponding to each of four safety systems. The sampling methods that are used in generating a linearly independent set of design points in the design variable space (X and Z) include: (i) the Latin Hypercube sampling for frontal crash, offset crash and side impact, and (ii) multilevel orthogonal arrays for roof crush. The computational details of the number of sample points and the elapsed computational times are provided in Table 3. It is important to note that the RADIOSS analysis for the baseline and sample set (3N) designs can be performed concurrently on a multiprocessor machine, thereby reducing the elapsed time. The two validation analyses correspond to the verification analyses on the optimal design point obtained at the end of each OMDAA cycle.

In Sobieszczanski-Sobieski (1995), a similar MDO problem, involving NVH and a single safety system (roof crush) required 257 days of elapsed computing time for a complete solution on a single processor of an Origin 2000 server. SGI has recently introduced the Origin 3000 class of servers that provides for target bandwidth improvement of double that of Origin 2000, as well as target latency reduction of 50% over Origin 2000. On the Origin 3800 server, using 256 processors and a combination of fine and coarse grain modes of parallelism, the elapsed computing time is compressed to less than 2 days, enabling high fidelity MDO solutions to impact the vehicle design cycle.

8 Summary

This work explores automotive system optimization for multidisciplinary design requirements including safety, NVH and weight. The system optimization problem is highly computationally intensive, involving high fidelity finite element models and analyses for both NVH and safety subsystems. It is shown that MDO methods, in conjunction with HPC, can provide for superior solutions along with solution turnaround times that can impact the design cycle. For the MDO problem of interest, a significant reduction in computational effort is obtained through effective use of concurrent processing on a distributed-shared memory computing system. Based on the present trends in HPC, it is clear that computationally intensive and powerful methodologies like MDO will become increasingly used within the manufacturing industry.

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