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CONCEPTUAL DESIGN AND INITIAL SHAPE PREDICTION OF AUTOMOTIVE STRUCTURE USING INTEGRATED CAE APPROACH

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ABSTRACT

Conceptual design of automotive structures has received substantial research attention in recent years in order to speed up vehicle development and innovation. Although several structural optimization methods have been employed in concept design, there still exists lack of efficient design tools to produce initial design shapes with less problem dependency, less computation-intensive analysis and more design flexibility. In this paper, an innovative Computer Aided Engineering (CAE) approach based on an integrated Genetic Algorithms(GA) and Finite Element (FE) optimization system has been studied and implemented for efficient conceptual design of automotive suspension system related structural part. Integration of GA provides the method a great amount of design flexibility and robustness that increases possibility of finding more efficient and innovative design shapes of the structure.

INTRODUCTION

Automotive industry today is facing a consistent growth in global competition to introduce rapid improvement in product performance and quality. Industries are becoming increasingly dependent on Computer Aided Engineering (CAE) tools particularly for conceptual design purpose to shorten product development cycle and thus reduce cost. Therefore, CAE has evolved as an indispensible tool of automotive part design and development process. It is intensively used in early design phase for concept decisions. However, most of the current CAE methods are based on very sophisticated virtual models, specifically, Finite Element (FE) models whose generation is substantially complicated and their analysis is computation-intensive. That is why, usually, a limited number of variants only is investigated and optimum structural concepts are obtained more or less by chance. Thus, innovative CAE concept tools are required to efficiently assist vehicle development in its early phases.

FE based structural design optimization can be considered as a two steps design process [1]. First, a topology optimization is performed to investigate initial design with optimal load paths. Next, the suggested configuration is analyzed in detail with real design requirements. The success of this design methodology is largely dependent on first step of finding good initial design. It is believed that major weight reduction is achieved during the selection of initial configuration not during detailed design optimization. Because the emphasis of early design phase is on rapid evaluation of various design concepts [2].In this context, an innovative CAE integrated concept design method has been investigated in this paper. The primary objective is to find the idea of promising initial designs that can be the basis for next detailed design. But the additional requirement is that the method should achieve concept designs with less computational time and cost than topology optimization approach.

The proposed methodology is based on a coupled Genetic Algorithms(GA) and Finite Element (FE) optimization system which has been implemented for efficient conceptual design of automotive suspension system related structural part. The method does not incorporate traditional ground structure or sophisticated FE models. The original structure is approximated by a linear elastic FE model of beam elements that evolves through successive iterations of optimization algorithm. GA continuously searches initial structure configurations to minimize structure weight while satisfying imposed static stiffness constraints. The detailed methodology and optimization results for automotive suspension part's conceptual design have been discussed in later sections of this paper.

Conceptual Design Methodology

The proposed methodology defines the physical design space as a discretized space of points or nodes. Inspired by the First Order Analysis (FOA) [3], discrete structural element (beam) are used to represent part structure. Thus, the original structure can be approximated as a linear elastic FE model by connecting the nodes with beam elements. Nodal locations are set as design variables and the GA based optimization algorithm is guided in a intelligent manner to change the nodal locations for the evolution of various structural configurations. GA continuously searches optimum structural configurations to minimize structure weight while satisfying imposed design constraints. The evolved structure can have any shape within the discretized design space with following important features-

1. Total number of nodes and beams are fixed. Only nodal locations will be varied during the design process to generate structure shapes. The nodal points can take any position within the design space with bounds on nodal coordinates.

2. It is possible to put constrain on how locations of some specified nodes will be varied during optimization process. This may be required to meet some special design requirement like fitting up requirement with other components. Also, some nodes can be set as partially fixed or fixed i.e. to represent mounting points.

3. The structure will be generated by layers. First, the nodal positions in two adjacent layers will be specified and then the layers will be connected by beams. The number of beams connecting two layers can be specified. Usually, the design should have more beams in critical sections of the structure.

4. The structure can be subjected to static or dynamic, single or multiple loads. It can include structure self-weight or any other type of loading required for robust design.

To implement the proposed concept(?) design strategy, a coupled GA-FE design optimization system has been developed. It consists of four computer programs- (1) optimization program, (2) FE simulation program, (3) simulation input generation program and (4) simulation output evaluation program. The structure of the system is illustrated in Fig.1. The four programs are integrated sequentially in a closed loop to establish an automatic and iterative optimization system. The first program is the optimization program which is the main controlling program of the system. It runs GA to produce new population of design variables based on the simulation results of previously evaluated models. It also takes important decision of stopping the analysis by checking the stopping criteria in each iteration. MATLAB®[4] GA toolbox is used as the optimization tool. The MATLAB® GA solver supports algorithm customization. A customized GA variant is developed by varying different default solver properties to meet the problem-specific requirements.

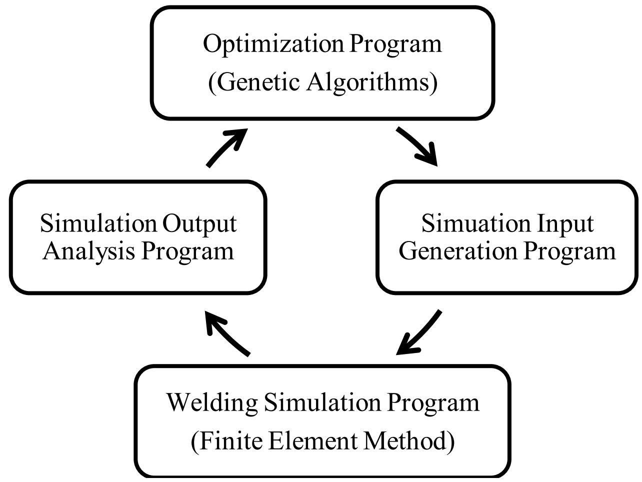

Figure 1: Framework of design optimization system.

In this work, the functional relationship between design variables (selection of nodal locations) and objective function (structure weight) to be optimized is implicit. Therefore, conversion of the original FE model and its responses into standard mathematic function values recognizable by the fundamental optimization algorithm is necessary. For this purpose, two computer programs are developed in the MATLAB® programming environment and embedded inside the design optimization framework. Simulation input program is a simple input-output function. It takes new values of design variables as input, inserts those values into the FEM input file and passes the updated input file to the FE simulation program as output. FE simulation program used in this work is a commercial finite element solver named MSC Nastran[5]. It executes the FE simulations based on input file to investigate static and dynamic responses of the structure. The last program is the simulation output evaluation program which reads the output result files of FE simulations, extracts the specified results and feedbacks the optimization program with those extracted results. The optimization program uses the extracted results to produce new population and in this way the analysis loop repeats until the best solution does not change over pre-specified number of iterations.

Test Problem Description and Formulation

The conceptual design approach described in preceding section has been implemented for initial shape prediction of an automotive suspension component called subframe. A subframe is a structural component of a vehicle, that supports the suspension system.

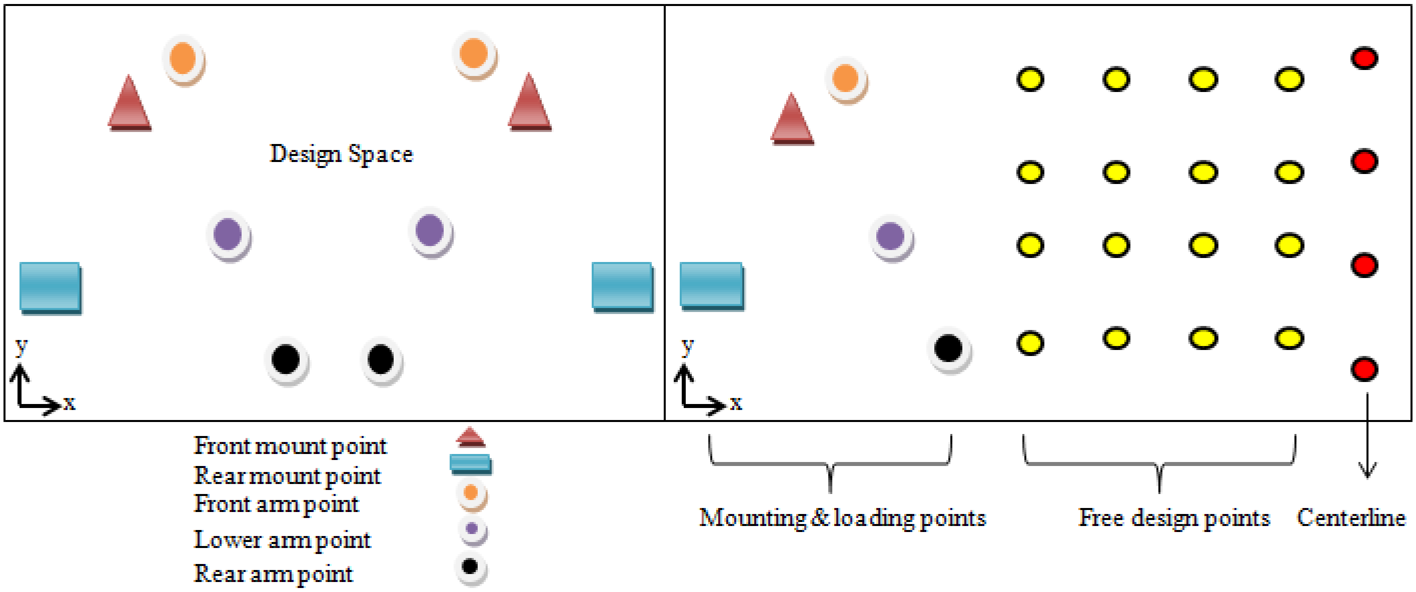

Figure 2 : Approximated design space and discretized half design space considering symmetry condition

Based on manufacturer's information, fixed mounting and loading (arm) point coordinates of the structure and the bound of design space were confirmed. . Accordingly, the design space has been approximated using the provided points as boundary points as shown in Fig. 2. The requirement is that the structure configuration should be confined within this design space. The design space is subsequently discretized into an array of 50 nodes. Considering the symmetry of the space, the design space can be reduced to 25 nodes as shown in Fig. 2 (right box). To facilitate the visualization, top view of the design space has been shown. The figure is also not drawn to scale. The yellow dots are the free design nodes and red dots represent the centerline points to ensure symmetry. Only free and centerline points will be allowed to change position for the evolution of structure. However, centerline point movement is constrained in x-y plane to ensure symmetry condition. Mounting and loading points will be treated as fixed points.

Next, the fixed points are to be connected to the centerline points through free design points. Since the connection can be established in numerous ways, a predefined guideline is followed. Connecting between fixed points and first layer of free design points will be established by two beams from one loading point to two design points. But the rest of the layers has been connected by one-to-one beam. After connecting all the layers, the half structure will have 29 fixed beams and 25 nodes as shown in Fig. 3. The red lines represent fixed beams and the black lines represent variable beams whose connecting nodes will change position during optimization process. Under this guideline, the optimization algorithm by GA will change the free design point locations in successive iterations to find out the optimum configuration.

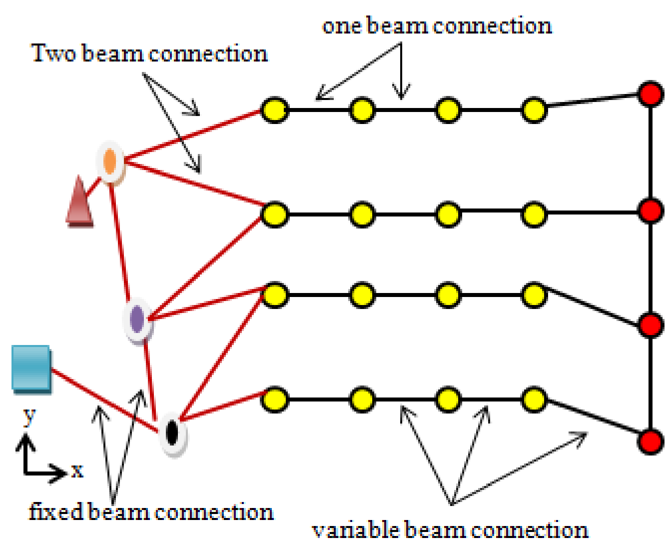

Figure 3 : Arbitrary shape of the approximated structure

Genetic Algorithms Based Conceptual Design

GA can be considered as a controlled random walk, they efficiently exploit information from previous configurations to generate new configurations with improved performances expected [6]. It starts search with an initial set of random solutions called population. Each individual in the population is a solution to the optimization problem. The individuals evolve through successive iterations, called generations, mimicking the process of natural evolution. Through this evolution process, the algorithm actually searches for better solutions. During each generation, the individuals are evaluated using some measure of fitness called objective function. To explore new design points, new individuals are formed by modifying less fit individuals by genetic operators. After several generations, the algorithm converges to the best solution, which is assumed to represent the optimum solution of the problem.

In this work, the goal is to find the optimum initial configuration of the structure. The structure weight has been used as objective function that is to be minimized by GA. For constant cross-section of beams, the structure weight can be calculated by Equation 1.

$$W = \sum_{i=58}^{i=1} \rho A L_i \qquad (1)$$

where W is the total structure weight, ρ is the material density, A is beam cross-section area and L is the beam lengths for each beam. A constant circular cross-section with a diameter of 10mm has been used for the beam elements. Since material density and cross-section area are constant, the structure weight will depend on beam length that will change with change in nodal positions. Twenty design variables have been considered to represent nodal locations of free design and centerline points. Within a layer of free design points, each free design point can take any position from a 4x4 position array (total 16 possible position for a free design point). On the other hand, since movement of centerline points is constrained in x-y plane, each centerline point can have four possible positions in z direction. The design constraint of this problem is that transitional displacement of the loading points should be less than 2mm when subjected to 1000 N at each loading point. Also, the mounting points and centerline points should be subjected to fixed and symmetry boundary conditions respectively. Therefore, the optimization problem in standard form can be written as-

$$\min F(X) = W \qquad (2)$$
$$\text{s.t.} \quad D_{loading\ points} \leq 2$$

To incorporate the constraint violation into optimization algorithm, a penalty term is added to the objective function and the combined function is called augmented function. Whenever a constraint is violated, the penalty term is greater than zero, with the magnitude of the penalty being proportional to severity of constraint violations. In this work, a constant penalty term (=100) is used. The augmented objective function definition including design constraints is given by Equation 2.

$$\varphi(x) = \begin{cases} F(X), & N_c = 0 \\ F(X) + 100, & N_c > 0 \end{cases} \qquad (3)$$

The optimization program initiates GA by creating a random initial population and each individual of the initial population is evaluated by the FE simulation program. In this work, an individual represents a set of nodal locations of all free design and centerline points. The program stores each individual and its fitness value so as to ensure not to reevaluate twice the same individual in successive generations. Then based on the augmented function values obtained from simulation output program, GA creates next generation and reevaluates this population using FE simulation program. The system algorithm runs until maximum number of generations have been reached or the cumulative change in the objective function value over ten generations is less than or equal to objective function tolerance (10E-06). A population size of 50 has been used in each generation and maximum number of generation is set to 100.

The optimization algorithm has run for 35 generations with 10392 FE simulations. Since the simulation model was one dimensional, it took only one and half hours to complete the entire analysis in a 2.30 GHz Intel (R) Core(TM) i5-2410M CPU with 8 GB ram. As such, this method is obviously very efficient for conceptual design purpose. The best-of-generation structure weight profile through evolution has been shown in Figure 4. It is seen from the figure that a weight reduction from 40 kg to 7.6 kg has been achieved by GA. The structure has undergone series of shape transitions during the optimization process. The best shape acquired after some arbitrary generations have been shown in Figure 5. Initially, at the beginning of optimization phase, the structure shape was very complex and irregular which gradually became regular and simple in successive generations. The best shape in entire optimization process has been achieved after 35 generations with structure weight of 7.6 g. The optimum initial configuration also satisfied the specified displacement constraints. So, GA is successful in finding optimum initial configuration of the structure for the given conditions.

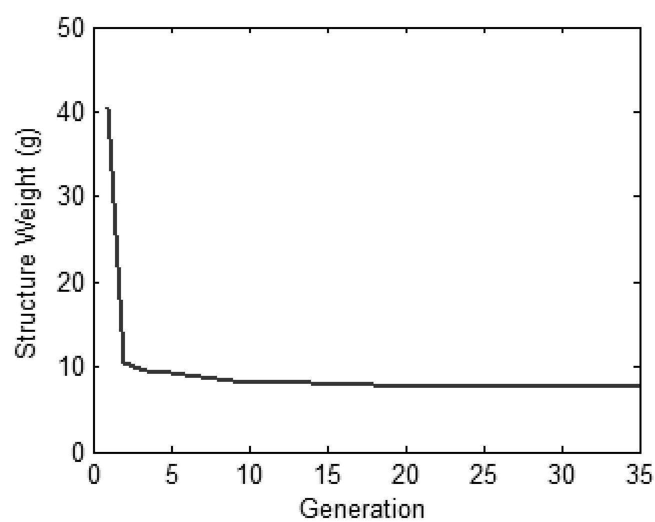

Figure 4 : Best-of-generation structure weight profile plot

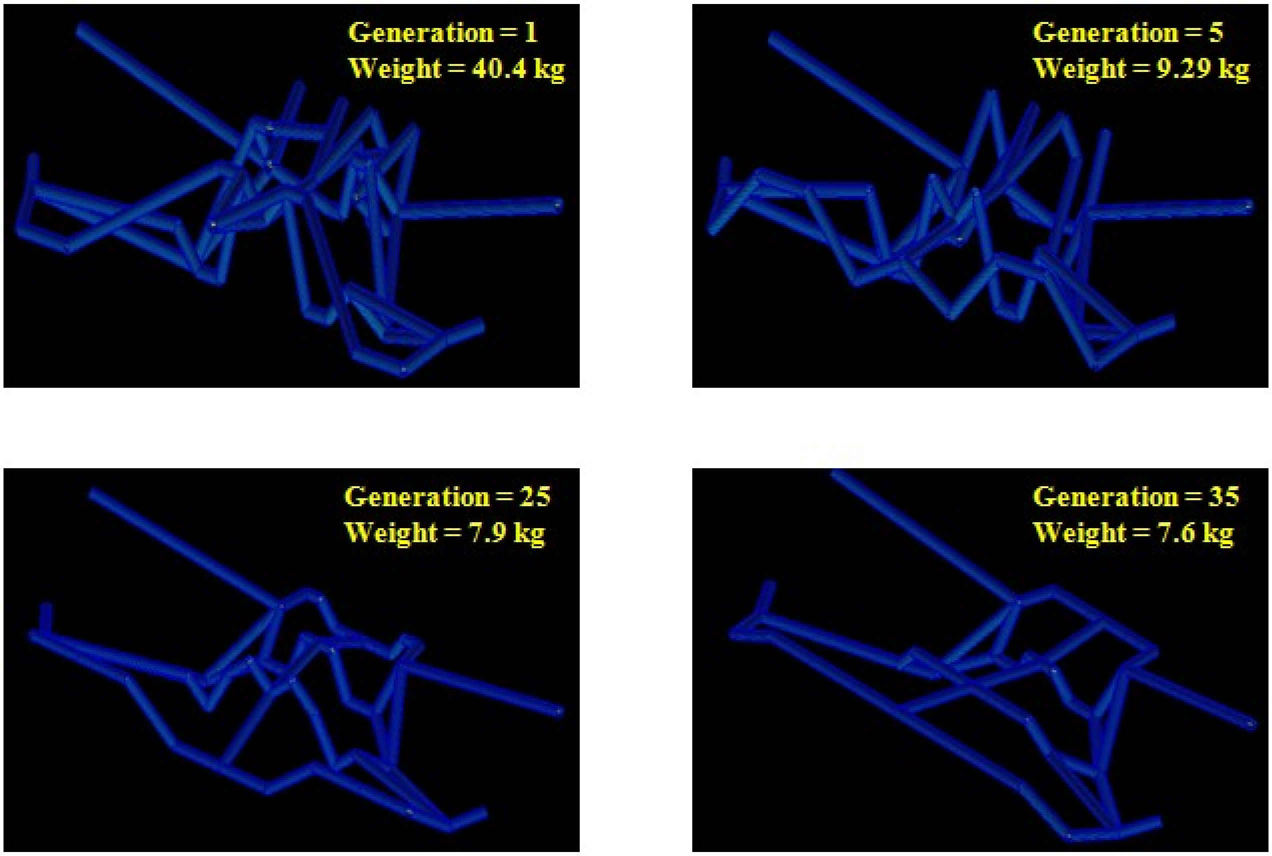

Figure 5 : History of evolved shapes of subframe during optimization process, fittest member in each generation.

CONCLUSION

Automated structural design optimization of auto-body structures based on integrated CAE tools can contribute substantially in conceptual design phase of vehicle development. This study introduces a simple conceptual design tool based on commercial CAE programs which can provide various design concepts that will be useful for detailed design stage. The biggest advantage of the proposed method is that it does not require computation intensive models and can provide results within couple of hours. The illustrative problem of automotive suspension component (subframe) design shows that the proposed GA-FEM coupled method is able to search for optimum initial configuration of the structure under the stiffness constraints of loading points. GA was also successful in converging towards a regular and uniform shape as expected from manufacturing point of view. The proposed methodology can be easily extended for other design problems with limited modifications in the optimization framework. Application of the method in more complicated design scenarios will be the objects for future research.

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