VIBRATION REDUCTION DESIGN WITH HYBRID STRUCTURES AND TOPOLOGY OPTIMIZATION

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ABSTRACT

The hybrid structures show excellent performance on vibration reduction for ship, aircraft and spacecraft designs. Meanwhile, the topology optimization is widely used for structure vibration reduction and weight control. The design of hybrid structures considering simultaneous materials selection and topology optimization are big challenges in theoretical study and engineering applications. In this paper, according to the proposed laminate component method (LCM) and solid isotropic microstructure with penalty (SIMP) method, the mathematical formulations are presented for concurrent materials selection and topology optimizations of hybrid structures. Thickness distributions of the plies in laminate components are defined as materials selection design variables by LCM method. Relative densities of elements in the components are defined as topology design variables by SIMP method. Design examples of hybrid 3-bar truss structures and hybrid floating raft with vibration reduction requirements verified the effectiveness of the presented optimization models.

Keywords: hybrid structure; vibration reduction; materials selection; topology optimization

INTRODUCTION

The vibration reduction plays important role in ship, aircraft and spacecraft designs. Hybrid structure is widely used to reduce vibration and control weight in ship, aircraft and spacecraft design for mechanical behavior, the inelastic damping behavior, and strength of hybrid structure, presently. Meanwhile, the topology optimization is the better method for vibration reduction and weight control.

In present study focus on optimal design methods for hybrid structure considering vibration reduction. Yang (2012) proposed a laminate component method (LCM) on modeling of hybrid structure for materials selection (type and size) design. By introducing the concept of laminate component, materials selection optimization design of hybrid structure is formulated as a size or topology optimization problem with all materials for selection within one structural analysis model. In study of structure design methods, mechanical behavior, the inelastic damping behavior, and strength of metal-hybrid structures are investigated (Hidde 1992, Asundi 1997, Kawai 1998, Botelhoa 2006). Blasques (2012) presents a novel framework for simultaneous optimization design of topology and laminate properties of laminated composite beam cross sections. The majority of the hull structures are manufactured by metal materials which can decrease the costs; and some important components are fabricated by composites materials which can decrease structure weight and vibration levels (Barsoum 2003, Cao 2007). The design of metal-composite hybrid structure involves simultaneous determinations on materials selection, topology, geometry, and components dimensions.

In addition, structural dynamic performance like vibration levels and eigenfrequency must be taken into account for the purpose of vibration and noise reduction. Rahul (2006) dealt with optimization of hybrid fiber reinforced plastic laminated plates subjected to impact loading, Finite element method (FEM) and genetic algorithm (GA) have been used to obtain optimum laminate in terms of minimizing the cost, weight of graphite/epoxy–aramid/epoxy hybrid laminates while maximizing the strength.

The topology optimization for vibration reduction and weight control has been widely investigated. Sigmund (1999) suggested topology optimization procedure as a tool for smart materials design and discussed two applications in composite structures. Kravanja (2005) studied the simultaneous topology and size optimization of mechanical structures by the Mixed Integer Nonlinear Programming (MINLP) approach, and general multilevel MINLP formulations for mechanical superstructure were presented. Sun (2011) dealt with topology optimization of composite structure using Bi-directional Evolutional Structural Optimization (BESO) method. Stress concentration in composite structure can be reduced by BESO method and geometry of structure is easy to fabricate by techniques currently available. Coelho (2011) developed a computational procedure for two-scale topology optimization problem using parallel computing techniques, the material properties were designed in micro and macro scale respectively. Lee (2012) proposed an approach for topology optimization of structures under design-dependent pressure loading. Cherkaev (2012) introduced a new type of optimal isotropic structure for multi-material composites. Rakshit (2008) explored simultaneous geometry design and material selection for statically determinate trusses with continuous optimization model, and the available materials for selection were put in a database with design index along with the corresponding best geometry.

However, investigations of vibration reduction and weight control design on simultaneous by hybrid structure and topology optimization design are very scarce. One challenge in this problem is the establishment of a unified structural analysis and optimization model for different settings of materials selection and components topology distributions during solving iterations. The other challenge is the definitions of materials selection design variables and topology design variables in one optimization model, these design variables are all discrete variables in nature. In this paper, by applying the proposed laminate component method (Yang, 2012) and SIMP method, the mentioned challenges are attempted. The mathematical formulations for concurrent materials selection and topology optimization of hybrid structure are proposed with respect to vibration reduction constraints. Typical metal-composite hybrid structures optimization examples are performed to demonstrate the effectiveness of the proposed models.

LAMINATE COMPONENT METHOD FOR HYBRID STRUCTURE OPTIMIZATION

Laminate component method (LCM) was firstly applied in materials selection (type and size) optimization design of hybrid structure (Yang 2012). Based on LCM method, materials selection optimization design can be formulated as a continuous optimization problem to avoid the conventional discrete optimization model depending on materials database and materials design index method. The laminate component method consists of three main steps.

1) First, replace the design components in hybrid structure with laminated composite components that each ply fabricated by different materials for selection.

2) Second, discretize and construct finite element model of the hybrid structure.

3) Finally, define thickness of each ply or materials topology distribution of each ply in laminated composite design components as materials selection design variables, establish optimization model with vibration reduction constraints and complete optimization.

An engineering design example of hybrid floating raft with LCM method is shown in Fig.1. The laminate component method firstly assumes each design component (No.1 to No.7)
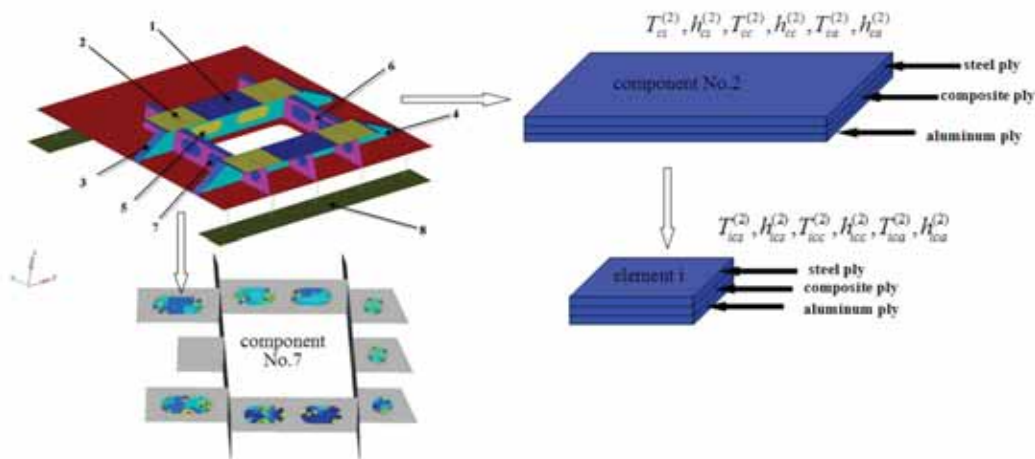

Fig. 1 Design domains and laminate components in continuum hybrid structure

is made of laminate plate with available materials for selection as each ply – steel ply, composite materials ply and aluminum ply (as shown in component No.2 in Fig.1), then finite element model of hybrid structure is constructed. Finally thickness of each ply is defined as materials selection design variables, optimization model is established and solved. Though there are four materials selection optimization models according to LCM method, in which materials elastic modulus, thickness of ply, and materials topology distribution are defined as design variables respectively, the use of thickness as materials selection design variables is the reasonable choice when topology optimization design is also required. Model II can avoid the discreteness and complexity of the structural analysis model due to the variation of materials elastic modulus and materials topology distribution. As a continuum structure, hybrid floating raft is composed by web plates, rib plates, flange plates and panels. These plates (design components) are easily replaced by laminated composite plates with LCM method.

SIMP METHOD FOR STRUCTURAL TOPOLOGY OPTIMIZATION

Many topology optimization methods like homogenization method (Bendsøe 1989, 2003), density method, evolutionary structural optimization method (Xie 1997) and ICM method (Sui 1998) have been investigated and applied in engineering. SIMP method is a widely used simple topology optimization approach (Zhou 1991) combined the finite element method and density method. A topology optimization problem based on SIMP where the objective is to minimize compliance can be written as

$$\underset{\mathbf{X}}{Min} \quad C(\mathbf{X}) = \mathbf{U}^T \mathbf{K} \mathbf{U} = \sum_{e=1}^{N} (x_e)^p \mathbf{u}_e^T \mathbf{k}_e \mathbf{u}_e$$

$$s.t. \qquad \frac{V(\mathbf{X})}{V_0} \leq f$$

$$\mathbf{K}\mathbf{U} = \mathbf{F}$$

$$0 < x_{\min} \leq x_e \leq 1 \qquad \qquad \textbf{(1)}$$

where $\mathbf{U}$ and $\mathbf{F}$ are the global displacement and force vectors, respectively, $\mathbf{K}$ is the global stiffness matrix, $\mathbf{u}_e$ and $\mathbf{k}_e$ are the element displacement vector and stiffness matrix, respectively, $\mathbf{X} = [x_1, x_2, \cdots, x_e, \cdots x_N]^T$ is the vector of design variables of relative densities of elements, $X_{\min}$ is a vector of minimum relative densities (non-zero to avoid singularity), N is the number of elements used to discretize the design domain, p is the penalization power (typically p=3), $V(\mathbf{X})$ and V_0 is the material volume and design domain volume, respectively and f is the prescribed volume fraction.

In this paper, SIMP method is used to define the topological design variables of elements in each laminate component or components without materials selection design requirement. For the elements with materials selection design requirement, each element consists of multiple material plies according to laminate component method, and X_e is the topological value of the eth laminate element. X_e has no

connection with materials selection design, and it only decides the existence of the element. For the elements without materials selection design requirement in components, each element consists of isotropic material, X_e denotes the existence of the element.

HYBRID STRUCTURE DESIGN FOR VIBRATION REDUCTION BY MATERIALS SELECTION AND TOPOLOGY OPTIMIZATION ON SIMULTANEOUS

THE MATHEMATICAL MODEL OF HYBRID STRUCTURE DESIGN

By applying LCM method to deal with materials selection, and applying SIMP method to define the component topology in hybrid structure, the concurrent optimization model for materials selection and topology design is formulated as Eq.2. The weight of hybrid structure is considered as the objective function with acceleration vibration level differences, stresses and displacements on designated points and elements as constraints.

$$
\begin{aligned}
Find \quad & \mathbf{T}_s = [t_{1s}, t_{2s}, \cdots, t_{ms}, t_{m+1s}, \cdots, t_{ns}]^T \\
& \mathbf{T}_c = [t_{1c}, t_{2c}, \cdots, t_{ic}, \cdots, t_{mc}]^T \\
& \tilde{\mathbf{X}}_i = [\mathbf{X}_1, \mathbf{X}_2, \cdots, \mathbf{X}_i, \cdots, \mathbf{X}_n]^T \\
Min \quad & Weight = \sum_{i=1}^{m} \sum_{t=1}^{T_{iT}} (t_{ic} \cdot \rho_c + t_{is} \cdot \rho_s) \cdot se_{it} \cdot x_{it} + \sum_{i=1}^{m} \sum_{t=T_{iT}+1}^{T_i} (t_{ic} \cdot \rho_c + t_{is} \cdot \rho_s) \cdot se_{it} + \\
& \sum_{i=m+1}^{n} \sum_{t=1}^{T_{iT}} t_{is} \cdot \rho_s \cdot se_{it} \cdot x_{it} + \sum_{i=m+1}^{n} \sum_{t=T_{iT}+1}^{T_i} t_{is} \cdot \rho_s \cdot se_{it} \\
s.t. \quad & \sigma_e^L \leq \sigma_{ek}[\mathbf{T}_s, \mathbf{T}_c, \tilde{\mathbf{X}}_i] \leq \sigma_e^U \\
& \delta_{pk}[\mathbf{T}_s, \mathbf{T}_c, \tilde{\mathbf{X}}_i] \leq \bar{\delta}_p \\
& a_{Aj}^{\max} \leq a_A^U \\
& a_{Bj}^{\max} \leq a_B^U \\
& 10^{L_r/20} - \varepsilon \leq a_{Aj}^{\max} / a_{Bj}^{\max} \leq 10^{L_r/20} + \varepsilon \\
& f^L \leq j \leq f^U \\
& t_{ic} = sca \cdot t_{is} \\
& t_{is}^L \leq t_{is} \leq t_{is}^U \\
& \mathbf{X}_i = [x_{i1}, x_{i2}, \cdots, x_{it}, \cdots, x_{iT_{iT}}]^T \\
& 0 < x_{\min} \leq x_{it} \leq 1 \\
& i = 1, 2, \cdots, n; \ e = 1, 2, \cdots, E; \ k = 1, 2, \cdots, K; \\
& p = 1, 2, \cdots, P; \ t = 1, 2, \cdots, T_{iT}
\end{aligned}
$$

(2)

The meanings of design variables and constraints are listed in Nomenclature. $n \geq m$ means some components no materials type selection design requirements.

Based on the proposed model, a single unified structural analysis and optimization model is implemented during

the optimization procedure. The variation of topology and materials types during optimization iteration can be accounted in a single structural analysis model by changing thickness and relative density of each element. Then the analysis results from this single structural model are used in the single proposed optimization model as Eq.2. Optimization model and structural analysis model are unified in one model.

$$T_{iP} = T_{is} + T_{ic}$$

$$T_{is} = [1 + f(t_{is})]/2 \cdot t_{is} + t_{s\min}$$

$$T_{ic} = [1 - f(t_{is})]/2 \cdot t_{is} \cdot sca + t_{c\min}$$

$$f(t_{is}) = \text{sgn}[\sin(1000 \cdot t_{is} \cdot \pi)]$$

T_{is} is the equivalent thickness of steel layer in the *ith* component after transformation, and the T_{ic} is the equivalent thickness of composite material layer in the *ith* component after transformation. sgn is the sign function. The values of $f(t_{is})$. k is a non-negative integer. $t_{s\min}$ and $t_{c\min}$ are minimal thickness for steel layer and composite material layer respectively to avoid element stiffness matrix singularity. The numbers of design variables for topology, size and material selection optimization and the element numbers in FEM model in the presented concurrent optimization are large, therefore a long computation time will cost to get one optimization result(in this example, more than twenty hours for an optimal results). For the larger structure with more design variables and elements, advanced computer or workstation, and more effective optimization algorithm should be considered.

The mathematical formulations after transformation are presented in Eqn.3.

The meanings of design variables are same as Eqn.2.

ILLUSTRATING METHOD BY EXAMPLE

STEEL-COMPOSITE MATERIAL HYBRID 3-BAR TRUSS STRUCTURE DESIGN

The method of materials selection and topology optimization on simultaneous through combining the LCM method and SIMC method for Hybrid structure design is illustrated by a 3-bar truss structure as an example. Fig.2 shows the dimensions and connection of 3-bar truss. Available materials for selection are steel and fiber reinforced composite. Thickness of steel_plate is 15mm; girder is made of 100x50x10 steel L-bar. The materials parameters for selection are steel and composite material in Table 1. Boundary conditions, reference points and loading conditions are shown in Fig. 3. There is a 454kg concentrated mass at point A. A 100N vertical force acts on point A in Z direction with frequency range 1-100Hz. The modal damping loss factor for structural frequency response is 2%. Constraints for optimization design are: (1) AVLD>5dB at point A, B and E. (2) Allowable displacement at point C is 1mm. (3) Maximum acceleration amplitude for the reference points is 0.5g.

Table 1 Materials parameters

steel	*Young's modulus*	*210 GPa*
	Poisson's ratio	0.3
	density	7850kg/m^3
fiber reinforced composite	Young's modulus	E_{11}=27285.7MPa
		E_{22}=26142.8MPa
	shear modulus	G_{12}= 9242.9MPa
		G_{23}= 9242.9MPa
		G_{13}=9242.9MPa
	Poisson's ratio	0.14
	damping coefficient	η_{11}=0.0729
		η_{22}=0.0715
		η_{12}=η_{23}=η_{13}=0.1068
	density	1600kg/m^3
	ply angles	$[90^0/0^0]_s$

$$Find \quad \mathbf{T}_s = [t_{1s}, t_{2s}, \cdots, t_{ms}, t_{m+1s}, \cdots, t_{ns}]^T$$
$$\mathbf{T}_c = [t_{1c}, t_{2c}, \cdots, t_{ic}, \cdots, T_{mc}]^T$$
$$\tilde{\mathbf{X}}_t = [\mathbf{X}_1, \mathbf{X}_2, \cdots, \mathbf{X}_i, \cdots, \mathbf{X}_m]^T$$

$$Min \quad Weight = \sum_{i=1}^{m}\sum_{t=1}^{T_{iT}}(T_{ic} \cdot \rho_c + T_{is} \cdot \rho_s) \cdot se_{it} \cdot x_{it} + \sum_{i=1}^{m}\sum_{t=T_{iT}+1}^{T_i}(T_{ic} \cdot \rho_c + T_{is} \cdot \rho_s) \cdot se_{it} +$$
$$\sum_{i=m+1}^{n}\sum_{t=1}^{T_{iT}}t_{is} \cdot \rho_s \cdot se_{it} \cdot x_{it} + \sum_{i=m+1}^{n}\sum_{t=T_{iT}+1}^{T_i}t_{is} \cdot \rho_s \cdot se_{it}$$

$$s.t. \quad \sigma_e^L \le \sigma_{ek}[\mathbf{T}_s, \mathbf{T}_c, \tilde{\mathbf{X}}_t] \le \sigma_e^U$$
$$\delta_{pk}[\mathbf{T}_s, \mathbf{T}_c, \tilde{\mathbf{X}}_t] \le \overline{\delta}_p$$
$$a_{Aj}^{\max} \le a_A^U$$
$$a_{Bj}^{\max} \le a_B^U$$
$$10^{L_v/20} - \varepsilon \le a_{Aj}^{\max}/a_{Bj}^{\max} \le 10^{L_v/20} + \varepsilon$$
$$f^L \le j \le f^U$$
$$t_{ic} = sca \cdot t_{is}$$
$$t_{is}^L \le t_{is} \le t_{is}^U$$
$$\mathbf{X}_i = [x_{i1}, x_{i2}, \cdots, x_{it}, \cdots, x_{iT_{iT}}]^T$$
$$0 < x_{\min} \le x_{it} \le 1$$
$$T_{ip} = T_{is} + T_{ic}$$
$$T_{is} = [1 + f(t_{is})]/2 \cdot t_{is} + t_{s\min}$$
$$T_{ic} = [1 - f(t_{is})]/2 \cdot t_{is} \cdot sca + t_{c\min}$$
$$f(t_{is}) = \text{sgn}[\sin(1000 \cdot t_{is} \cdot \pi)]$$
$$i = 1, 2, \cdots, m; \ e = 1, 2, \cdots, E; k = 1, 2, \cdots, K;$$
$$t = 1, 2, \cdots, T_{iT}; \ p = 1, 2, \cdots, P$$

(3)

Bar No.	Initial thickness of steel ply (mm)	Initial thickness of composite laminate (mm)	Optimal thickness of steel ply (mm)	Optimal thickness of composite laminate (mm)	Optimal topology density
Comp_1	20	0.03	0.005	46.632	0.435
Comp_2	20	0.03	0.005	46.632	0.385
Comp_3	20	0.03	19.1	0.03	0.062
Objective function	Initial weight (kg)	60.5	Optimal result (kg)	33.7	——

Optimization results are shown in Table 2. It shows that the weight of truss decreased from 60.5kg to 33.7kg. Fig. 4 shows topological densities of bars after optimization. Since density value for bar Comp_3 is less than 0.062, it is deleted in final structural design shown in Fig.5. In final optimal topology of structure, two bars are kept, in which bar Comp_1 and bar Comp_2 are made of composite materials.
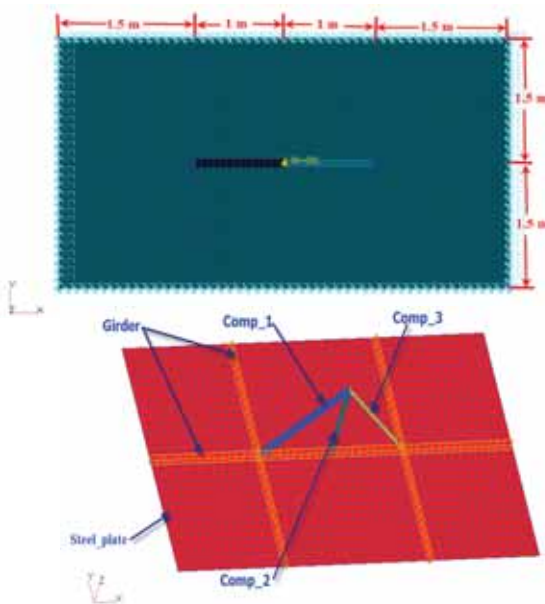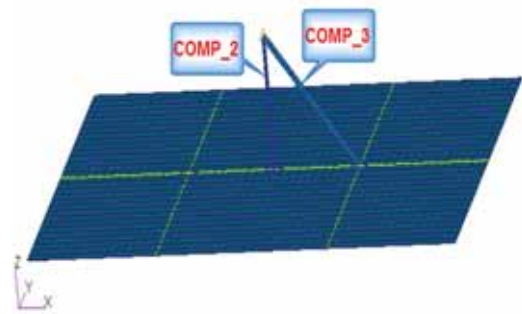

Fig.2 Dimensions of 3-bar truss

Fig.3 Boundary and loading conditions

Fig.4 Topological densities of bars

Fig.5 Final topology of 3-bar truss

STEEL-COMPOSITE MATERIAL HYBRID FLOATING RAFT DESIGN

A typical engineering floating raft is used for illustrating the feasibility of above method. The structure of the floating raft (Yang 2012) is shown in Fig.1 and Fig.6; definitions of each component are listed in Table 4.

Table 3 Parameters of the floating raft

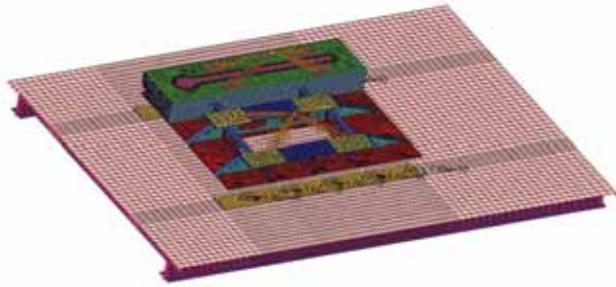| flexible pipes and concentrated mass	80 kg
compressor	294 kg
refrigeration pump	65 kg
dimensions of the floating raft	900mm/800mm/210mm
vibration isolator	BE-60

Fig.6 Finite element model of the floating raft

The Model of hybrid floating raft

The presented floating raft is a small scale model of special testing vessel in order to test the effect of vibration reduction optimization design. The joints between different components are assumed ideal. Parameters of the floating raft are shown in Table 3; the available materials for selection are steel and composite material in Table 1. Xiong (1996), and Xing (2005) investigated evaluation methods on vibration reduction of floating raft by finite element method and power flow method. Yu (2007) proposed a topology optimization model for the floating raft. The investigation results showed the effectiveness of finite element method and vibration level difference.

Fig.6 shows the finite element model of the floating raft mounted on the bottom deck of ship. The effect of vibration reduction is evaluated by AVLD at the referenced points shown in Fig.7, Aj and Cj (j=1,2,…,5) are top referenced points for isolators, Bj and Dj (j=1,2,…,5) are bottom referenced points for isolators. The unit forces act on the center of compressor and refrigeration pump at vertical direction from 1 Hz to 1000Hz.

The design requirements: 1) Determine the material types for components No.1 to No.7, and the thickness of each component; 2) Topology optimization design for component No.5 and No.7; 3) Vibration reduction requirements: AVLD at the referenced points > 20dB among 1 Hz and 1000 Hz; 4) Maximum accelerations at the referenced points: $a_{(Am)\,j}^{\max} \le 80 mms^{-2}$ $a_{(Cm)\,p}^{\max} \le 80\ mms^{-2}$; 5) Maximum vertical displacement less than 1/300 of the floating raft's length, which is equal to 6.7 mm; 6) Stress constraints: $\sigma_e \le 100$ MPa, this can be satisfied by defining the maximum acceleration limits.

The upper and the lower bounds on thickness design variables are 20mm and 4mm except component No.8. The upper and the lower bounds on thickness for the component No.8 are 60mm and 6mm. The lower bound for thickness is to avoid structural buckling and yielding. According to the design requirements, the thickness of composite laminates components should be 2.5 times of the replaced steel plates (sca=2.5).
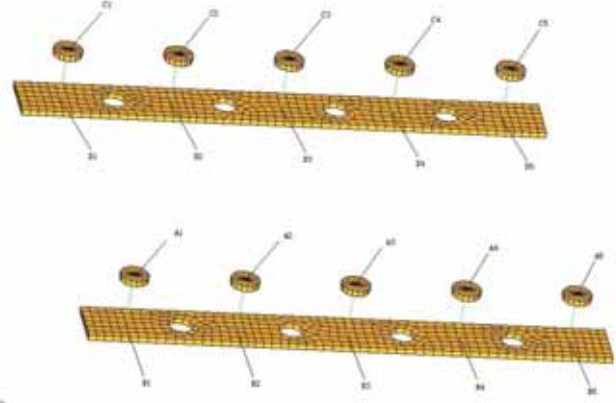

Fig.7 Locations of the reference points

Materials selection and topology optimization results on simultaneous

The results for the concurrent optimization of materials selection (type and size) and topology optimization are listed in Table 4 and Table 5 compared with Xie's results (2011) in which materials selection optimization are implemented considering vibration reduction constraints. Table 4 shows the comparisons of the objective function and the components thickness. Table 5 shows the comparison on the AVLD. Fig.8 and Fig.9 show the results of element density after topology optimization. Fig.10 and Fig.11 are the re-designed structure according to the topology optimization results. Fig.12 presents the iterative history of the objective function. It can be seen the structure weight reduces from 46.426kg to 25.940kg. Each constraint is satisfied and AVLD at some reference points are increased when materials of the web plates become composites. In the final hybrid structure, five components are made of composite materials which are quite different from the initial steel structure design.
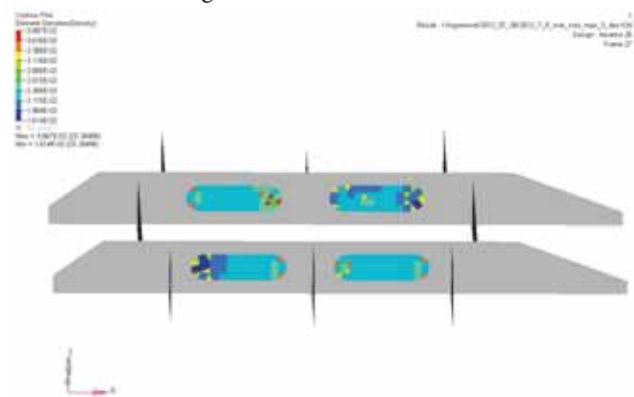

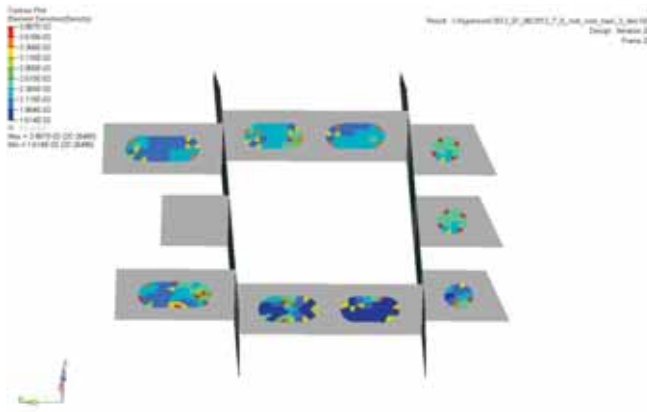Fig.8 Topology optimization result for hlb-hole component

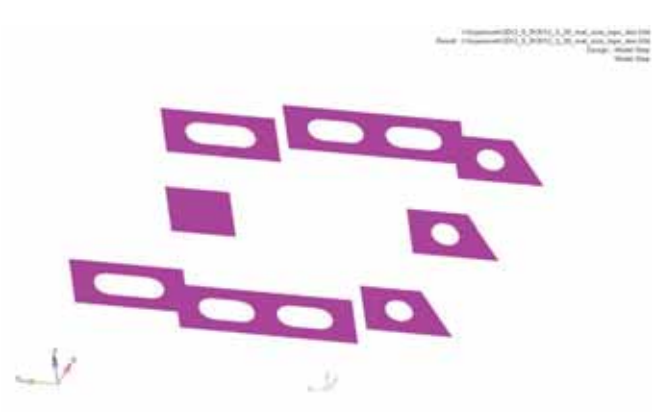Fig.9 Topology optimization result for zlb-hole component
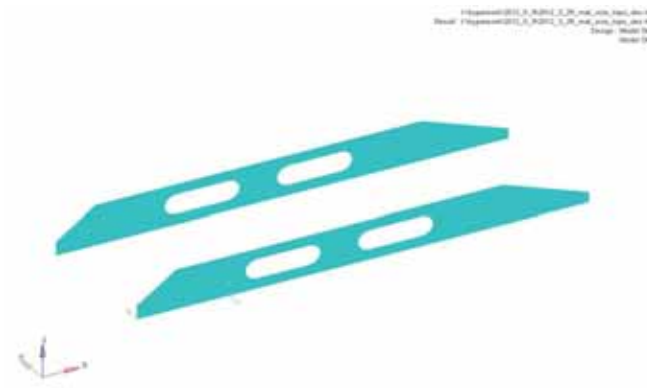

Fig.11 Re-design for zlb component
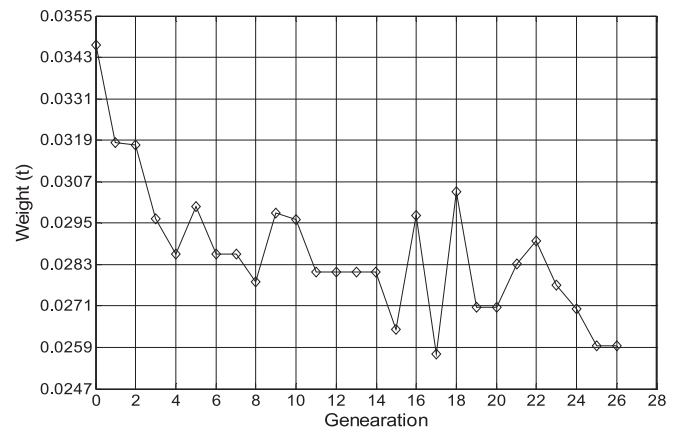

Fig.10 Re-design for hlb component

Fig.12 The iterative history of objective function

Table 5 values of AVLD and acceleration on referenced points

Reference point No.		a_{Ah}^{max} (mm/s²)	a_{Bh}^{max} (mm/s²)	AVLD (dB)	a_{Ch}^{max} (mm/s²)	a_{Dh}^{max} (mms²)	AVLD (dB)
1	Initial value	73.00	5.45	22.54	74.19	5.51	22.58
	Optimal value (Xie 2011)	70.25	4.25	24.37	73.40	4.37	24.51
	Optimal value	67.41	4.23	24.05	71.48	4.39	24.23
2	Initial value	69.05	2.74	28.04	69.42	2.75	28.05
	Optimal value (Xie 2011)	66.48	2.64	28.01	68.89	2.68	28.21
	Optimal value	64.10	2.56	27.97	67.41	2.60	28.28
3	Initial value	64.20	5.09	22.02	64.76	5.12	22.04
	Optimal value (Xie 2011)	61.87	3.79	24.27	64.51	3.88	24.43
	Optimal value	59.78	3.86	23.80	63.46	4.00	24.01
4	Initial value	59.39	6.92	18.67	59.94	6.99	18.67
	Optimal value (Xie 2011)	57.38	4.72	21.70	59.95	4.87	21.81
	Optimal value	55.88	4.91	21.12	59.33	5.13	21.26
5	Initial value	266.48	3.41	37.86	55.19	3.44	24.10
	Optimal value (Xie 2011)	79.60	2.73	29.29	55.47	2.80	25.93
	Optimal value	50.00	2.76	25.16	55.28	2.86	25.72

Table 4 thickness of components and objective function

Component No.	Design variables (Plate)	Initial thickness of steel ply (mm)	Initial thickness of composite ply (mm)	Optimal thickness of steel ply (Xie 2011) (mm)	Optimal thickness of composite ply (Xie 2011) (mm)	Optimal thickness of steel ply (mm)	Optimal thickness of composite ply (mm)
1	mb_1	10.01	0.03	9.9803	0.0492	4.687	0.030
2	mb_2	20.01	0.03	0.0164	49.9589	0.005	12.660
3	mb_3	6.01	0.03	5.9920	0.0200	0.005	11.514
4	zlb_1	6.01	0.03	0.0050	14.9876	0.005	11.754
5	zlb_hole	6.01	0.03	——	——	4.657	0.030
6	hlb_1	6.01	0.03	0.0243	14.9393	0.005	12.006
7	hlb_hole	6.01	0.03	——	——	0.005	12.120
8	squares	16.00	——	16.3988	——	14.70	——
Objective function	——	Initial weight(kg) 46.426		Optimal weight (Xie 2011) 36.480		Optimal weight (kg) 25.940	

CONCLUSIONS

The hybrid structure optimization design for materials selection (type and size) and topology considering vibration reduction has been implemented. Combining LCM and SIMP method, a concurrent materials selection and topology optimization model for hybrid metal-composite structures is established. Typical steel-composite hybrid floating raft and hybrid truss are optimized for vibration reduction by the proposed model. The contributions of the research work and observations are summarized as follows:

1. By the proposed approach, the design variables for topology and materials selection can be combined in a unified structural finite element analysis model, in particular, combined in each element of the design domain of the hybrid structure.

2. The optimization results also verified the effectiveness of the use of composite materials in vibration reduction design. The initial all metal-made structure of 3-bar truss and floating raft become hybrid structure after optimization design with most of components made of composite materials.

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NOMENCLATURE

AVLD: the acceleration vibration level difference, AVLD= 20 lg (a_A/a_B)

a_A, a_B : accelerations at point A and B

T_s : vector of thickness design variables for the components made of metal/steel.

T_c : vector of thickness design variables for the components made of composite materials

$\tilde{\mathbf{X}}_t$: vector of overall topology design variables defined by SIMP method

$\mathbf{X}_i = [x_{i1}.x_{i2},\cdots,x_i,\cdots x_{iT_i}]^T$: vector of topology design variables for the ith component, x_{it} is the topology design variable of element t in component i.

m : number of the composite components in hybrid structure

n : number of the metal/steel components

T_i : total number of the finite elements in the ith component

T_{it} : total number of topology design variables in the ith component

se_{it}: area of the ith element in the ith component

ρ_s, ρ_c : density of steel and composite materials.

σ_{ek} : stress of the eth element under the kth loading case

σ_e^L, σ_e^U : lower and upper limit of element stress.

δ_{pk}, $\bar{\delta}_p$: displacement at point p under the kth loading case, upper limit of displacement at point p.

k : loading case number.

a_{Aj}^{max}, a_{Bj}^{max} : maximum acceleration amplitude at point A and B in the frequency j Hz

a_A^U, a_B^U : upper limit of the maximum acceleration amplitude at point A and B

L_r : lower limit of AVLD.

f^U, f^L : upper and the lower bounds of frequency domain.

t_{is}^{L}, t_{is}^{U}: upper and the lower bounds of the thickness design variables for metal/steel components.

ε, sca : relax parameter and equivalent scale of thickness for metal/steel and composite material

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