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Optimum design of aircraft panels based on adaptive dynamic harmony search

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ABSTRACT

Aiming at the optimization of aircraft panels, a modified version of harmony search (HS) algorithm is proposed based on the information of the harmony memory (a memory location where all the solution vectors are stored) for improvisation procedure, named as adaptive dynamic harmony search (ADHS) algorithm. In order to reduce the amount of calculation, response surface method is employed, and second-order polynomial with cross terms is used to construct the model. To demonstrate the advantage of the proposed algorithm, typical aircraft panels under buckling constraint are established, and several existing HS algorithms are compared. The effects of the number of improvisation (*NI*) and harmony memory size (*HMS*) are investigated and discussed in detail. Results indicate that the proposed ADHS can provide an optimum design in a robust manner, and local optimum solutions may be reduced based on the ADHS for optimization problems with multiple local minima. Finally, several useful information is obtained for the design of stiffened panels with cutouts.

1. Introduction

Due to high specific strength and stiffness, stiffened panels are widely used in various types of weight-critical applications to resist buckling and collapse, such as aircrafts and launch vehicles, etc. For a variety of reasons, e.g. easy access, inspection, etc, cutouts are usually inevitable for aircraft structures [1–7], which may cause remarkable reductions on both load-carrying capacity and structural efficiency. To compensate the performance loss caused by cutout, the topic on the design of stiffened shells with cutouts becomes ever more significant and urgent.

In the past, many researchers have undertaken the research on the buckling behavior of thin-walled panels with cutouts. Mahmoud et al. [8] studied the steel cylindrical shells with various sizes of elliptical cutouts under axial compression. Schlack et al. [9] determined the buckling load of square plates with a circular central hole by experiment, and the results agree well with the predictions by the Ritz energy method. Later, Tennyson [10] found that the membrane stress concentration factors of circular cylindrical shells under axial compression increase rapidly with the growth of curvature parameter. Until now, many investigators have investigated the effects of cutouts on the metal shells or composite shells [11–13]. To mitigate the decline of load capacity and stability caused by cutouts, much attention was paid to the thin-wall structures reinforced by stiffeners [14–16]. It is worth noting that those works mentioned above are mainly focused on straight stiffeners, and their enhancement approach is relatively fixed. The primary reasons that cause this situation mainly include the limitation of current manufacturing technology and design method. As for this, for certain types of aircrafts, the cutout are still reinforced by straight stiffeners [17,18], which are easy for manufacturing, assembly, inspect and design optimization. Fortunately, as manufacturing technologies are developed rapidly, new manufacturing processes (e.g. additive manufacturing) make it more convenient to reinforce thin-wall structures by curvilinear stiffeners, which can greatly enhance the load-carrying capacity. However, for the design optimization of curvilinear stiffeners, it is still a very challenging problem due to the high-dimensional inherence. Kapania et al. [19] summarized the previous research works of curvilinear stiffened panels, and found that curvilinearly stiffened panels have larger design space as well as lightweight potential in comparison with straight stiffeners. As for recent works, more and more researches are focused on the mechanical behavior of curvilinearly stiffened panels under shear load or combined compression-shear load. For instance, the mesh-free method is used to study the buckling and static behavior of curvilinearly stiffened panels [20,21]. Wang et al. [22] performed the buckling optimization of curved stiffeners based on a global/local coupled strategy, and a significant improvement of post-buckling performance was observed. In addition, a new shear deformation theory was developed for functionally graded

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plates and beams, and a satisfying accuracy was achieved [23–26]. In order to optimize the stiffener layout more effectively, many kinds of software are committed to this work. PANDA2 [27,28] can design composite stiffened shells under as many as five combined load cases based on gradient optimization algorithm. VICONOPT [29] is able to analyze the buckling and vibration problems of anisotropic plates. Furthermore, it can also optimize thin-wall structures under buckling constraints. Indeed, due to the introduction of NURBS [30,31] to describe the stiffener path, the computational cost of designing curved paths of stiffeners still face enormous challenges. Worse yet, in the design space, curvilinearly stiffened panels are always characterized by many local minima, which also increase the calculation burden remarkably. To solve this problem, more efficient global optimization algorithms and frameworks are crucial. The authors [32] proposed a novel stepwise design method to optimize cylindrical shells with curvilinear stiffeners. Mulani et al. [33,34] designed the stiffeners placement and size of stiffened panels by Response Surface Method (RSM), and the optimization process is decomposed into sizing optimization and stiffener placement optimization. Therefore, this approach is able to avoid trapping in local optimum and find global minima. In addition, dynamically reconfigurable quantum particle swarm optimization (PSO) was also used to find the optimal design of stiffened composite cylinders [35]. Compared with previous PSO algorithms, the quantum PSO can provide a more robust and reasonable optimal solution. It should be noted that above intelligence and genetic algorithms will cause much heavier computation burden compared to gradient-based optimization methods. In order to reduce the computational cost, a surrogate-based optimization framework with adaptive sampling was established by authors [36].

As a promising optimization technique, the HS algorithm was developed to search the optimum design of linear and nonlinear problems with both discrete and continuous variables [37]. This algorithm is in an analogy with music improvisation process where music players improvise the pitches of their instruments to obtain better harmony. During the improvisation process, all the solution vectors are stored in the harmony memory (HM), which is similar to the genetic pool in the genetic algorithm. In the HS algorithm, improvisation process continues to improve her/his contribution for a better state search of harmony [38,39]. The perfect harmony and improvisation group are corresponding to the global optimum and design variables, respectively. Originally, Geem et al. [40] developed the HS algorithm. Later, Mahdavi et al. [39] proposed the improved harmony search algorithm (IHS) whose parameters are dynamically updated at each iteration. Omran and Mahdavi [41] proposed the Global-best harmony search (GHS) algorithm based on a modified pitch adjustment rule where the best harmony is considered in new harmony memory. Kattan and Abdullah [37] extended the IHS based on the best-to worst harmony memory, adaptively. El-Abd [42] introduced an improved global-best harmony search (IGHS) algorithm and with a novel pitch generation scheme using the Gaussian and uniform distribution in the pitch process.

The structure of this paper is organized as below. In Section 2, the optimization method is introduced, including standard HS algorithm and a series of improved HS algorithm. On this basis, a modified version of HS algorithm (adaptive dynamic harmony search (ADHS) algorithm) is proposed based on the information of the harmony memory for improvisation procedure. In Section 3, the numerical model of curvilinearly stiffened shell is established. In order to reduce the amount of calculation, response surface method (RSM) is employed, and second-order polynomial with cross terms is used to construct the model. In Section 4, the optimum designs of aircraft panels are evaluated, and different harmony search algorithms are compared, and then the effects of the number of improvisation and harmony memory size are investigated.

2. Adaptive dynamic harmony search optimization

For the HS algorithm, there are five parameters including harmony memory size (*HMS*), harmony memory consideration rate (*HMCR*), pitch adjustment rate (*PAR*), bandwidth (*bw*) and number of improvisations (*NI*). In particular, *HMCR*, *bw* and *PAR* are the main parameters. In the improved versions of HS, some of these parameters are considered as a constant value or are computed dynamically using another parameter. To search the optimum of objective function, the sets of design variables are randomly generated based on those parameters, and five basic steps are included [40].

1) Define the optimization problem and parameters of the problem
2) Determine the initial values of the harmony memory
3) Create a new harmony memory
4) Update the harmony memory
5) Check the stopping criterion of the algorithm optimization: Terminate when the maximum number of improvisations is reached.

Based on the initial harmony memory in the second step, each generated member of the previous harmony memory are improvised using algorithm parameters such as *HMCR*, *PAR* and *bw*. This improvisation leads to a new harmony memory based on three rules: 1) consideration of the previous harmony memory members; 2) adjustment of the existing harmony memory; 3) random selection of each member of memory [43]. The parameter *HMCR* shows the selection rate of new memory from the previous harmony memory. The *PAR* is similar to the mutation of GA algorithm and adjusts the design variable of harmony memory randomly. Based on the randomness of improvisation in HS, the improvisation in harmony search optimization algorithms is introduced.

2.1. Harmony search

The memory consideration, pitch adjustment, and randomization are applied to improve new harmony for each design variable in the standard HS algorithm as follows:

Algorithm 1. The harmony search algorithm

IF $r_1 \le HMCR$ **then**	
$x_i'^j = x_i^j$;	/select from previous harmony memory/
IF $r_2 \le PAR$ **then**	
$x_i'^j = x_i^j + (2r - 1) \times bw$;	/adjust new harmony memory/
ENDIF	
ELSE	
$x_i'^j = x_i^L + r_3 \times (x_i^U - x_i^L)$;	/select from the domain of variables/
ENDIF;	
$F'^j = f(x'^j)$;	/Computing the objective function based on new harmony memory/

where, $r, r_1, r_2, r_3 \in [0,\ 1]$ are random numbers. $\boldsymbol{x}$ is the set of design variables, x_i^L and x_i^U are the upper and lower bounds of x_i respectively, which is the set of the possible range for each design variable. Hence, each design variable is placed in the domain $x_i \in [x_i^L, x_i^U]$.

2.2. Improved harmony search

The parameters of improved harmony search (IHS) including *PAR* and *bw* are dynamically updated during the evolution by the following equations [39]: