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Development of a hybrid meta-heuristic algorithm for combinatorial optimisation and its application for optimal design of laminated composite cylindrical skirt

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Abstract

This paper presents a hybrid meta-heuristic algorithm called multiple start guided neighbourhood search (MSGNS) algorithm for combinatorial optimisation which combines the good features of popular guided local search algorithms like simulated annealing and tabu search. It has been organized as a multiple start algorithm to maintain a good balance between intensification and diversification. The proposed hybrid meta-heuristic algorithm has been employed to solve optimal stacking sequence design problem of laminate composite structures. First, the algorithm has been employed to solve the problem of optimal stacking sequence of a composite plate for which the results of various algorithms are available in the literature. This study is basically to validate and also to demonstrate the effectiveness of the proposed algorithm over several existing meta-heuristic algorithms.

Later, a practical design example of fiber-reinforced composite cylindrical skirt of solid rocket motor of aerospace vehicle is investigated. A skirt is a potential element for weight reduction in rocket motors as it leads to reduction of the total weight of solid rocket motor. Due to its significance for solid rocket motors, it is proposed to optimise the weight as well as cost of the fiber-reinforced composite cylindrical skirt subjected to a buckling strength constraint and an overstressing strength constraint under aerodynamic torque and axial thrust. This is achieved by arriving at an optimal stacking sequence for the cylinder satisfying all the design constraints and also by employing multiple composite materials. Classical laminate theory combining with elastic stability theory of thin shells is used to arrive at buckling strength and overstressing strength of the fiber-reinforced composite cylindrical skirt. The Tsai-Wu failure criterion is employed to assess the first ply failure. Buckling strength and failure strength of the cylindrical skirt is described by using buckling load factor and overstressing load level factor. Numerical simulations carried out in this paper clearly demonstrate the superiority of the proposed MSGNS algorithm over the popularly used combinatorial algorithms like genetic algorithm and simulated annealing.

Keywords: Combinatorial optimisation; Laminate composites; Meta-heuristic algorithm; Tabu search; Simulated annealing; Cylindrical shell

1. Introduction

Laminated composite construction of panels and other structural elements is currently being used for many applications in aerospace, automotive, civil and defence industries. Laminated composites have several advantages over more traditional materials including greater specific strength, specific stiffness, corrosion and fatigue resistance, and energy absorption among others. Multi-layer and sandwich construction also offer many opportunities for analysts and designers to tailor their properties to the specific requirements of a given application. The tailoring is mostly achieved by optimising the mechanical properties, thereby increasing the load carrying capacity of the structure. Optimisation of composite laminates with respect to ply angles to maximise the strength is necessary to realise the full potential of fiber reinforced materials.

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In the past, ply angles are often employed as continuous design variables in the design optimisation of laminated composites and solved using gradient based methods [1,2] to improve performance of the structure. However, these methods found to have severe limitations as stacking sequence design involves discrete design variables i.e. ply angles, which must be converted to continuous variables before the problem is solved. Once the optimal continuous–valued solution is found, it must be rounded to the nearest manufacturable ply angle, which may result in a design which is either non-optimal or violates certain imposed constraints. Hence discrete optimisation techniques where discrete ply angles can be considered as design variables are more relevant for stacking sequence design problems. It is well known that most practical laminates are restricted to some discrete sets of ply orientation angles 0°, 90° and ±45° because of the availability of experimental data for structural verification of the behaviour. This practical restriction makes the stacking sequence design problem a combinatorial optimisation problem, which is not easy to solve.

For stacking sequence optimisation of laminate composite structures, genetic algorithm (GA) is the most widely and popularly used method. A detailed survey of discrete optimisation and global design optimisation methods applied to stacking sequence optimisation can be found in the review paper of Venkataraman and Haftka [3]. Even though GA is being popularly used for stacking sequence optimisation, it is proposed to develop an alternative meta-heuristic algorithm for combinatorial optimisation of laminate composites keeping the following things in view.

(i) GA is a population-based algorithm and requires considerable number of generations to converge, which involve large number of function evaluations. Practical engineering problems require detailed finite element simulations (based on more refined theories) for the evaluation of the objective function, which is computationally very expensive. It is shown by Venkataraman and Haftka [4] that rapid increases in computer processing power, memory and storage space have not eliminated computational cost and time constraints faced by engineers using structural optimisation for design. In view of this, it is highly desirable to explore alternative optimisation algorithms, which can converge faster with least number of function evaluations and thereby improve the computational performance of the stacking sequence optimisation problem.

(ii) The No Free Lunch (NFL) theorems [5] have established mathematically that the behaviour of all algorithms when analysed over all possible optimisation problems defined over some research space is same and no algorithm has performance advantage. Hence according to NFL theorem, the average behaviour of all optimisation algorithms is same. However, as shown by Droste et al. [6], a particular algorithm performs better over a subset of the entire function set consisting of all optimisation problems. Hence it is worthwhile to explore alternative algorithms for stacking sequence optimisation of laminate composites, which can be more effective.

(iii) SA is generally more reliable in finding global optimum and unlike GA, simulated annealing algorithm uses single individual to perform the search. Several researchers while solving other combinatorial problems [7,8] have established that simulated annealing outperforms GA both in computational performance and also in finding the global optimum solutions.

The focus of this paper is to propose an alternative meta-heuristic algorithm by combining good features of simulated annealing and tabu search. In order to build diversification mechanism into the proposed meta-heuristic algorithm, the algorithm is organized as a multiple start algorithm. The proposed hybrid meta-heuristic algorithm is first employed to solve the problem of stacking sequence optimisation of composite laminate plate for buckling load maximisation. This problem is chosen as a first case study basically to validate the proposed hybrid meta-heuristic algorithm by comparing with the results published in the literature and also to demonstrate the computational performance of the algorithm by comparing with several other meta-heuristic algorithms. Later a more practical problem of optimizing a cylindrical skirt is taken up as the second case study.

A skirt is a key element of a rocket motor and is in cylindrical shape. The skirt of solid rocket motor is commonly subjected to aerodynamic torque and axial thrust during operation. Hence, buckling due to combined loads and failure due to overstressing are two major concerns in the safe and reliable design of the skirt. From the structural integrity point of view, fiber reinforced laminate composite is a preferred material for skirt over the conventional steel. Apart from this, economy, ease of fabrication and compatibility are the other major issues that favors laminate composites over steel. The fiber-reinforced composite skirt is attached using various bonding/winding or riveting methods to transfer loads through the motor case assembly. In order to satisfy the strength requirement, the fiber-reinforced composite skirt is usually treated as a laminated cylindrical shell structure consisting of discrete plies with orientations of 0°, ±45°, 90°.

Designers often attempt to reduce the weight of the solid rocket motor in order to meet the system needs of aerospace vehicles. Reducing its weight results in increased flight range of the vehicles and increased efficiency of the solid rocket motor. The skirt is one of the potential elements for weight reduction in rocket motors as it leads to an overall reduction in the total weight of the solid rocket motor. Weight reduction of the skirt is achieved not only by using fiber-reinforced composite materials, but also by improving the design of the lamination configuration.