International Journal of Pressure Vessels and Piping 168 (2018) 39–48

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

The applicability and implementation of the discrete *Big Bang-Big Crunch* optimisation technique for discontinuous objective function in multi-material laminated composite pressure vessels

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ARTICLE INFO

Keywords:
Layered structures
Strength
Numerical analysis
Pressure vessels
Big Bang - Big Crunch optimisation

ABSTRACT

The *Big Bang-Big Crunch* (BB-BC) algorithm is implemented to optimise lay-up configurations of filament wound laminated cylindrical pressure vessels subject to internal pressure. The vessels are composed of a combination of two different types of lamina, a chopped strand mat and a direct roving lamina with different fibre orientations. These two types of layers are combined into one discrete design variable, creating a complex discontinuous objective function surface. Two optimisation cases are presented, in the first case, the inverse of the Tsai-Wu Strength Ratio is minimised, and in the second case, a cost factor is introduced to shift the global minimum to a singularity. To assess the performance of the BB-BC algorithm, the results of the optimisation runs are compared with the global optimum obtained by a brute-force method. In this study, an analysis of the effect of varying the population size on the efficiency and accuracy of the results, is presented. In addition, the influence of previous best fit candidate on the performance of the algorithm is also investigated. It is shown that the BB-BC algorithm is robust in optimising layup sequences even when the number of layers is high and when two different types of layers are present. In particular, it is shown that higher population sizes increases the accuracy of the results although it lowers the efficiency. In the presence of a singularity in the objective function, it is necessary that the new generations subject to further optimisation represent more the previous best fit candidate.

1. Introduction

Design optimisation is an indispensable aspect in the design process, irrespective from the type of manufacturing industry. It is a decision making tool which helps engineers find the best balance between manufacturing costs and other design variables such as strength, stability, reliability, weight *etc*. This process is crucial in keeping a leading edge over an ever growing worldwide competition. Implementing the right optimisation tools for specific engineering scenarios is one of the utmost important aspects in design. With the advent of composite materials, finding the right materials got even tougher since these novel materials can be tailor made to specific needs. Composite materials in the pressure vessel manufacturing industry are gaining momentum over their metallic counterparts due to improved strength to weight ratios. This advantage stems from advanced composite modelling techniques, good manufacturing methods and suitable optimisation techniques. This study is particularly focused on layup optimisation of filament wound pressure vessels with two types of layers, though the presented methodology also applies to layered composites in general. Filament wound pressure vessels are used in a wide variety of sectors such as in civil applications and the oil and gas sector. The manufacturing process mainly produces a stack of unidirectional fibre reinforced laminas (DR layers) but internal layers of chopped strand mat (CSM) are also included to ensure appropriate sealing [1]. Optimisation of layered composites can vary from, simply finding the ideal fibre orientation in a lamina for a given loading condition, to more challenging tasks of finding also the ideal layup sequence with different types of laminas referred to as the layup combination. Such optimisation problems can be non-linear, multimodal and multidimensional. Furthermore, the design parameters can either be continuous variables, such as the fibre direction angle, or discrete variables, such as different layup sequences whilst keeping the fibre direction fixed, or a combination of both.

The purpose of optimisation techniques is to find the global minimum or maximum of an objective function within predefined constrains on the design variables. The objective function can represent various final design factors such as efficiency, cost, quality and many others. Optimisation methods can be categorised as either involving mathematical programming techniques or population-based iterative

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https://doi.org/10.1016/j.ijpvp.2018.08.008
Received 23 January 2018; Received in revised form 23 July 2018; Accepted 22 August 2018
Available online 24 August 2018
0308-0161/

Nomenclature

Symbol

θ Off-axis angle, ^{0}
δ Fibre angle resolution, ^{0}
β Ratio controlling influence on new candidate based on $x_{best}^{(b)}$ and $x_c^{(b)}$
α Size of search space
bits The amount of design variables. Each design variable can represent either a chopped strand mat layer or a direct roving layer pair
CF Cost factor. The cost ratio of a direct roving layer to a chopped strand mat layer
combi Design variable defining the layup configuration
σ_i, σ_j (i,j = 1,2,6) Stress in the material coordinate system, MPa
F_i, F_{ij} (i,j = 1,2,6) Material strength tensors, MPa
f_i (i= 1,2,…,bits) Fitness value
k Number of divisions defining the DR winding angle resolution
$\min f\,(combi^b)$ (b= 1,2,…,bits) Optimisation problem – case 1
$\min g\,(combi^b)$ (b= 1,2,…,bits) Optimisation problem – case 2
N_P Size of population
$N(0,1)^b$ (b=1,2,…,bits) Random number following a normal distribution
n_{DR} Number of DR layer pairs
n_{CSM} Number of CSM layers
n_{combi} Total discrete values of the *combi* variable
S Shear strength, MPa
X_n $Y_n(n$ = t,c) Unidirectional strengths. Subscripts t and c denotes tension and compression respectively, MPa
x Integer representation of the *combi* variable
$x_{best}^{(b)}$ (b=1,2,…,bits) Best candidate design variable
$x_c^{(b)}$ (b=1,2,…,bits) Centre of mass design variable
$x_i^{(b)}$ (b=1,2,…,bits) (i = 1,2,…,N_P) Design variable
$x_{min}^{(b)}$, $x_{max}^{(b)}$ (b=1,2,…,bits) Minimum and maximum design variable limits
$x_{new}^{(b)}$ (b= 1,2,…,bits) New candidate design variable

Abbreviations

BB-BC Big Bang – Big Crunch
CSM Chopped Strand Mat
DR Direct Roving
FPF First-Ply-Failure
TWFI Tsai-Wu Failure Index
TWISR Inverse of the Tsai-Wu Strength Ratio

methods. The former involves the calculation of the objective variable for various design sets to obtain the gradient of the objective function and eventually search for the optimal design set accordingly. These are mostly suitable for objective functions which vary smoothly with the design variables. On the other hand, population-based iterative methods are modern techniques [2] inspired from biological or other natural behaviour which evolved way before the mankind existence. These modern techniques usually start with a random population of feasible design variable sets which evolve by means of predefined operations through an amount of iterations. The optimal design is theoretically obtained after infinite iterations but the challenge is to obtain the optimal design after the least number of iterations. Such optimisation technique is ideal for problems with complex objective functions since the evolution is controlled by the outcome of the whole population. The success of these population-based optimisation techniques relies on various factors, one of which is the available computational resources due to their recursive and evolutionary nature. This is one of the main drawbacks of iterative optimisation techniques although nowadays, with cheaper and higher computation power availability, these methods are gaining popularity amongst researchers and design engineers.

There are several population-based optimisation methodologies but the most popular one used to find the optimal layup configurations in laminated composites is the Genetic Algorithm [3]. It was established around the 1970s by John Holland [4] and developed further by several other researchers [5]. Callahan and Weeks [6] presented the first implementation of the GA used to find the optimal design of laminated composites. In the meantime, numerous other population-based optimisation techniques were developed and used in layup optimisation problems. The review papers presented by Ghiasi et al. [7], Awad et al. [8] and Tabakov and Moyo [9] summarise and discuss the implementation of a considerable number of optimisation methodologies used in the design of laminated composite structures. In particular, Tabakov and Moyo [9] focus their review on the implementation of evolutionary optimisation algorithms to optimise the stacking sequence of fibre-reinforced laminated pressure vessels.

In this study, the Big Bang – Big Crunch (BB-BC) method is used to optimise the layup configuration of a combination of lamina in composite cylindrical pressure vessels. The BB-BC method is a relatively new optimisation methodology proposed by Erol and Eksin in 2006 [10] where the optimisation concept is based on the evolution of the universe according to the Big-Bang theory. The basic BB-BC algorithm contains just two operations namely; the big-bang, where a new population of feasible solutions is formed, and the big-crunch, where the population is shrunk into a single entity. The heuristic population-based optimisation methodology was successfully used in several optimisation scenarios such as to find the minimum weight of different space trusses [11,12], maximising the performance of multi-modal structural systems [13], finding the minimum weight of steel structures [14], damage detection in structural members [15], solving Economic Load Dispatch problems [16] and layup optimisation of laminated composites. [17], [18], [19], [20] Recently, Azad and Akış [19] applied the BB-BC optimisation methodology to minimise the weight and cost, in two separate cases, of multi-layered cylinders under internal pressure composed of isotropic materials. The optimisation involved two different types of design variables namely, the layer thicknesses (continuous) and the respective material (discrete). The results of the numerical experiments reported by Azad and Akış [19] show the advantages of multi-layer cylinders with respect to their single layered counterparts. No attempt was made to investigate the effect of varying optimisation parameters on the performance of the BB-BC algorithm. The most relevant work to this present study was carried out by Tabakov [17,18] who used the BB-BC algorithm to find the optimal fibre angles to maximise the first-ply-failure (FPF) pressure of laminated composite cylinders composed of DR layers only. In addition, Tabakov [17] showed that the BB-BC algorithm is considerably more efficient than the GA algorithm.

The application of the BB-BC algorithm to obtain the optimal layup configuration of cylindrical pressure vessels is very efficient when compared to the renowned Genetic Algorithm. [17], [18], [19], [20], [9] Although the BB-BC algorithm is relatively simple to implement, convergence to the global optimum of the objective function has not been challenged yet. Identifying the global extremum is especially relevant when designing laminated pressure vessels having two or more different types of materials such as DR and CSM layers. Due to structural integrity reasons [1], filament wound pressure vessels are rarely composed out of just DR layers but usually, CSM layers are included in the layup.

In this paper, the BB-BC algorithm is used to find the optimal layup