Optimization of a Stiffened Interstage Structure of a Launch Vehicle using Differential Evolution Algorithm in Indigenous FE Software

Manash Kumar Bhadra*[1], Shachindra Nath Sharma, Partha Ajit Surve, Vinod G

Vikram Sarabhai Space Centre
Indian Space Research Organisation
Thiruvananthapuram, Kerala 695022
Email: manash.bhadra2009@gmail.com

Abstract

Optimization has become synonymous to improvement in the context of design of launch vehicle structures. Problem is challenging because it not only involves multiple variable but also multiple objectives and constraints. The paper presents a method to optimize a stiffened interstage structure of a launch vehicle using differential evolution algorithm. The optimization was carried out to find the optimal number of stiffeners required and the optimal geometry of the hat stiffener that will minimize the hardware mass for specified axial compressive load, natural frequency and the strength of the material. The proposed method is implemented in finite element analysis software using Python based scripting.

Keywords: *Optimization, stiffened structures, differential evolution, finite element analysis*

1. Introduction

In the last decade Evolutionary algorithm (EA) appears as an important optimization and search technique. EA is a set of modern heuristics search method and it is a subdivision of Evolutionary Computations (EC). It is a popular problem-solving method used world-wide optimization problems because of its flexibility and robustness innate from Evolutionary Computation. In case of complex problems it can be used successfully. For a complex and multivariate function for finding the overall range or minimum or maximum, Differential Evolution (DE) which is a popular EA technique can be used. The algorithm is particularly well-suited for problems that are non-linear and have many local optima, as it is based on the idea of genetic algorithms and simulates the process of natural evolution.

The inter stage is an inevitable portion in the launch vehicle and it interconnects two stages of the vehicle. The interstage that is provided between the first stage (solid rocket motor stage) and second stage (earth storable liquid stage) is considered for study. Closely stiffened shell structure preferred over monolithic structures to increase the stiffness to withstand the structural, inertial aerodynamic loads. The closely stiffened structure comprises typically hat sections made out of metal or composite called stinger which is fastened to the skin shell. The structure is cylindrical in shape. Closely stiffened shell type construction is adopted with uniformly spaced stiffeners along the circumference. The elements of the hat namely flange side web and crown will have the crippling strength by design whereas the skin needed wrinkling strength and shear strength additionally. A typical interstage structure modelled in indigenous software is shown in figure-1. In this paper, optimal number of stiffeners required and the best geometry of the hat stiffener that will minimize the hardware mass for a typical column is determined using differential evolution algorithm. Natural frequency and the maximum value of effective stress are considered as design constraints. The proposed method is implemented in finite element software using Python based scripting. The finite element model is developed in a parametric form using Python interface and the model can be used to optimize interstage structure with different diameter and height as well.

[1] Corresponding author: E-mail: manash.bhadra2009@gmail.com

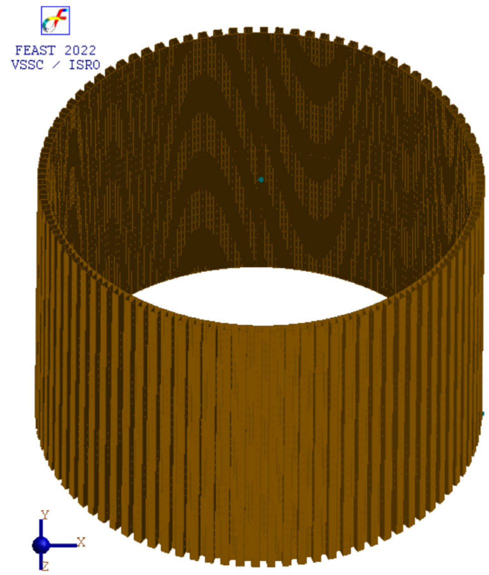

Figure 1: Typical launch vehicle interstage structure

2. Literature Review

Layout optimization of stiffeners in large shell structures was studied by Savine et al [1]. They proposed the extension of the stiffener element-based techniques. Stiffeners integrated to components are considered as sets of beam elements. The assembly is simulated in the ground structure which is meshed using structural elements like shells and beams. In the optimization process, the stiffener which is intrinsically a beam is represented as an equivalent framework. The components are free to move over the shell surface, without any re meshing operation in this method.

Advanced design procedures for design of metallic launch -vehicle cylinder under axial compression was studied and presented by Wagner et al [2]. They conceived the orthogrid stiffened cylinders from NASAs SBKF and demonstrated and validated in this study. Metallic launch vehicle shells with orthogrid stiffened panels were developed and verified. A design curve for the buckling load of orthogrid shells delivered typically 20% higher KDFs on average compared to the design curve for equivalent isotropic shells. The buckling factor depends on the L/R ratio which results in improved KDFs for the orthogrid short shells while relating to the empirical NASA SP-8007. An orthogrid cylinder which is having different buckling characteristics like column buckling, skin buckling and local buckling are examined during the design of actual launch-vehicle shells.

Zheng et al [3] analyzed the stiffness and critical force of a lattice cylinder theoretically by equivalent continuum method. The four failure modes for a lattice cylinder under axial compression are global buckling, two strut buckling modes (including out-of-plane strut buckling and in-plane strut buckling) and strength failure. Curves of load capacity and the failure maps revealed that the failure of large-scale lattice cylinder is generally dominated by global buckling due to the small thickness of the shell.

Vikhar and Baba [4] studied about Evolutionary Algorithms (EA). The study involves the implementation of its generic procedure and a critical summary of Evolutionary Algorithms. The merits of evolutionary algorithms over classical techniques of optimization are discussed. The various invariants of EA comprise of Genetic Programming (GP), Genetic Algorithm

(GA), Evolutionary Programming (EP) and Evolution Strategies (ES) are also counted in this study. Various extensive refinements were focused in the area of evolutionary algorithms to solve real life problems.

Beielstein et al [5] explains how the evolutionary algorithms can be adapted to work well in dynamic or noisy optimization problems and with multiple objectives. The study outlines the state of art in evolutionary algorithms. It also presents the important nontechnical treatment of evolutionary algorithm ideas. They also presented some recent developments from theory and also attempted the tuning of the algorithms. Real-world problems connected with typical applications of evolutionary algorithms are finally shown with special emphasis on data-mining applications.

Koke et al [6] presented optimization of a grid interstage structure with unit cell approach. The capability of the unit cell in combination with the augmented lagrangian particle swarm algorithm is used to solve mixed-integer constrained optimization problems. The optimization of the grid structure is tried by only with stability constrained. The most critical factor is the local buckling of bars. The stability criteria was driven by a monolithic helix and its implementation in the unit cell because of the variable moment of inertia for the axial bars. The stiffening effect of the sandwich is the scope of the future study.

Sleight et al [7] studied about the composite structural design concepts for the pre-V interstage structure as a part of NASA's advanced composite technologies project. Structural design and analysis were performed with the help of "Hyper sizer" design sizing software and "Nastran" finite element analysis software. This study revealed that the structural weight of the closely stiffened panel design is 11% lesser compared to the honey comb sandwich design. The interstage design was shorted in length based on the detailed investigation and higher loads were enforced to reflect the current state of Ares-V within the NASA constellation program

Bagheri et al [8] developed a genetic algorithm optimization of a ring stiffened cylindrical shells for axial and radial buckling loads. The four constraints viz, fundamental frequency, structural weight, axial buckling load and radial buckling load are imposed. Optimized stiffening cylindrical shells leads to a reduced structural weight, higher natural frequencies and larger axial and radial buckling loads simultaneously. The upper and lower bounds of the design variables influenced the optimum results considerably. The axial and radial buckling loads considerably influenced by the distributions of eccentricity and spacing of the stiffeners.

Collier et al [9] studied and proved that hat stinger stiffened panels are the most effective to carry the buckling load experienced in the Ares V Heavy Launch Vehicle. Closely stiffened panel concept is 20% lighter compared to honeycomb sandwich concept. The weight savings in the hat stiffened panels overcome the weight of the ring frames, connected joints and fasteners even if ring frames are required for buckling stability. to Optimization of the closely stiffened panels are more complex than sandwich panels because of more optimization variables. However, this offers more customization and weight savings opportunities. Automated analysis tool like Hyper Sizer similar to ref-7 is needed to fully explore the design space.

Hrstka et al [10] studied the improvements of Real Coded Genetic Algorithms built on differential operators avoiding Premature Convergence. Several forms of evolutionary algorithms used for global optimization on real domains presented in the study. Real coded methods with several improvements in general exhibit better behaviour on real domains than binary algorithms. The positive impact of the differential operators due to the possibility of self-adaptation is demonstrated. Real encoded differential algorithm enhanced by the technology described in this study is a widespread and reliable method of solving of all proposed test problems.

Design study for structural optimization of a hat-stiffened laminated composite panel for an upper cover panel of a typical passenger bay of a blended wing body transport airplane configuration completed by Vitali et al [11]. The adequacy of a hat-stiffened composite panel for the upper cover panel is investigated and compared to a thick sandwich panel on the basis of weight. The structural optimization is framed using the panel weight as the objective function with constraints on stress and buckling. The optimization conducted with the response surfaces resulted in weight savings.

3. Problem Definition

A closely stiffened interstage structure of typical diameter 2000mm and height 1500mm is to be designed for an upper bound load carrying capacity of 150kN and natural frequency of 50 Hz. The maximum stress in the structure to be less than the 0.2% proof strength of Aluminum Alloy. The number and sizing of the hat stiffener is to be estimated which satisfies the above conditions.

4. Research Methodology

4.1. Differential evolution

The optimization problem is framed as a search for the optimal solution in a population of candidate solutions. At each iteration, DE generates new candidate solutions by combining the existing solutions in a way that reflects the genetic variation that occurs in natural populations. The algorithm iteratively refines the population by selecting the best candidate solutions and incorporating their characteristics into the next generation. The central idea behind DE is to generate trial solutions by combining two or more existing solutions in the population. The combination process involves selecting three random solutions from the population and generating a new trial solution by adding a weighted difference of two of the selected solutions to a third solution. The new trial solution is then compared to the existing solutions in the population, and if it provides a better solution, it is added to the population for the next iteration. One of the key advantages of DE is its ability to explore a large search space effectively, making it well-suited for problems with a high number of variables and complex landscapes. The algorithm is relatively simple to implement, as it only requires a small number of user-defined parameters, and can be easily adapted to a wide range of optimization problems. In addition to its effectiveness, DE also has several other advantages. It is a robust algorithm, meaning it is insensitive to the choice of initial population and can still produce good results even when the starting population is not very well-suited to the problem. DE is also a highly parallelizable algorithm, meaning that it can be easily parallelized and run in parallel on multiple processors or GPUs to achieve fast convergence. Despite its many advantages, DE is not without limitations. One of the main drawbacks of the algorithm is that it can be sensitive to the choice of control parameters, such as the population size and the weighting factor used in the combination process. It is also important to note that DE may not always find the global range; minimum or maximum of a function, as it is possible that the algorithm may converge to a local minimum instead. Differential Evolution is a powerful optimization technique that has proven to be effective in a wide range of optimization problems. Its ability to explore a large search space, robustness to the choice of initial population, and parallelizability make it an attractive choice for researchers and practitioners. Despite its limitations, DE remains a valuable tool for solving complex optimization problems and continues to be widely used in a variety of fields, including engineering, finance, and biology. The different steps in a differential evolution are shown in figure-2.

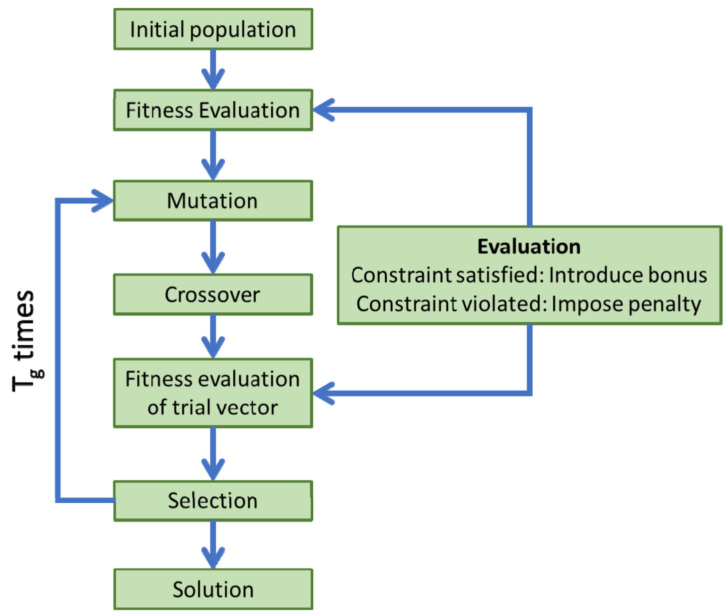

Figure 2: Flowchart of different steps in differential evolution algorithm

4.2. Optimization Details

Table 1: *Design and optimization parameters*

Design objective	Minimize the weight of the interstage structure	
DE parameters	Population size	50
	Number of generations	30
	Crossover rate	0.90
	Scaling factor	0.85
Design variables	Height of the stiffener	10mm to 100mm
	Width of the stiffener	10mm to 200mm
	No. of stiffener	12 to 120
Design Constraints	Minimum natural frequency	60 Hz
	Maximum von Mises stress	350 MPa
	Minimum buckling load	150kN
Material property	Young's Modulus	70000 MPa
	Poisson's ratio	0.3
Dimension details	Internal diameter	2000 mm
	Height	1500 mm

Table-1 is given the design inputs used in the optimization of the closely stiffened cylinder. Linear buckling analysis has been carried out to evaluate the fitness of a particular solution. The finite element is discretized using an element size of 10mm. Mapped meshing is carried out using 3D shell elements. The constraints provided on the edge nodes at one end specified with all displacement and rotation degrees of freedom. For the nodes on the other cylindrical edge, hinged boundary condition is used. Edge load is applied axially in the model.

5. Results and Discussions

The optimization converged for a maximum load of 196kN. The optimal numbers of circumferential stiffeners are 90. The optimal depth of the side web and width of the crown of the stiffener are 30mm and 20mm respectively. The maximum von Mises 166.7MPa. Figure-3 shows the distribution of von Mises stress.

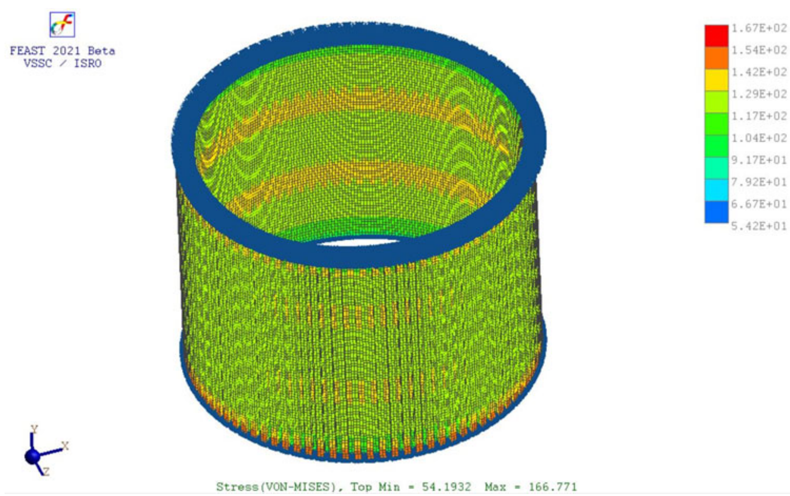

Figure 3: Distribution of von Mises stress

Figure-4 shows the variation of maximum fitness (critical buckling load in kN). The highest converged value is attained in the 15th generation and thus it justifies the number of generations considered. Evaluation of each candidate solution of the population took about 4 minutes and the total time taken for the optimization was 10 hours. The maximum displacement in mode 1 is 2.85mm and is shown in figure-5.

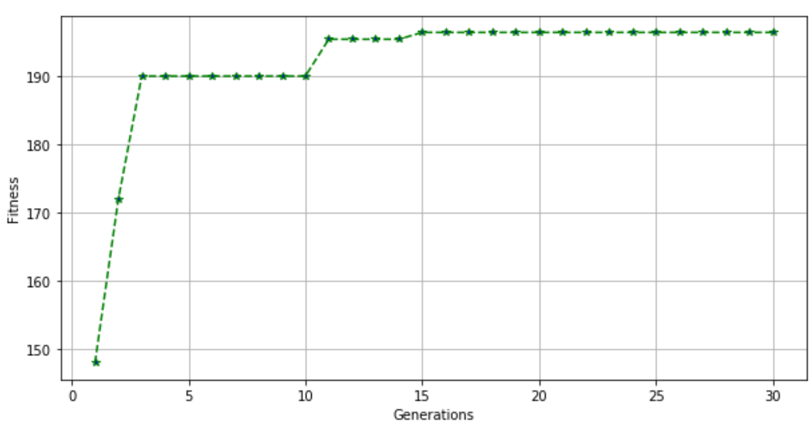

Figure 4: Variation of the fitness (critical buckling load in kN) in various generations

ISBN - 978-93-95038-50-8

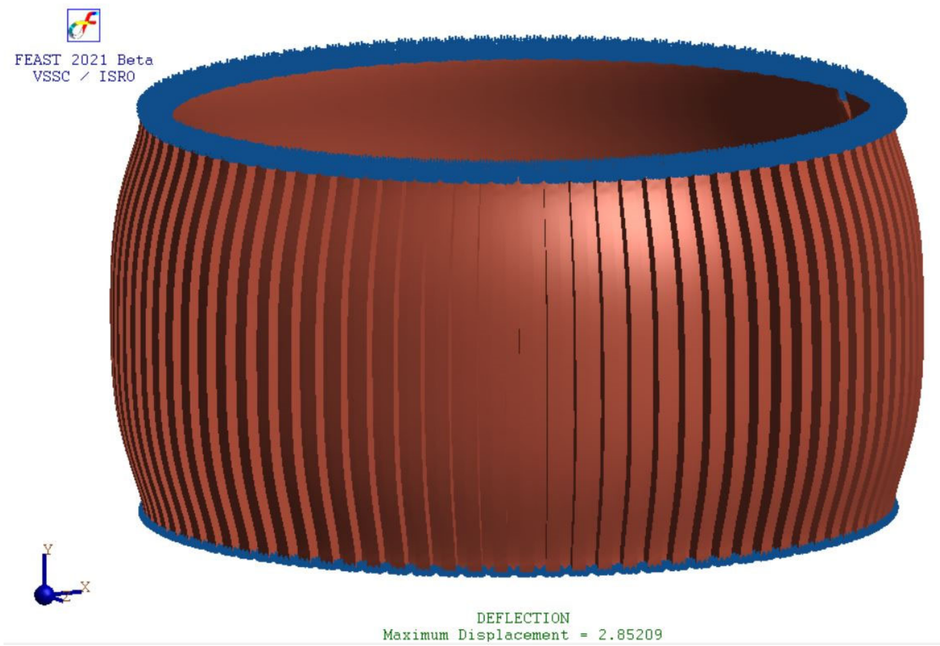

Figure 5: Displacement in mode-1

6. CONCLUSIONS

Differential evolution algorithm was used to find the optimal configuration of the closely stiffened panel which minimizes the mass of the interstage structure while satisfying the constraint in natural frequency and material strength. The evaluation of the candidate solution was carried out in indigenous finite element analysis software using its Python interface. The established method can be extended to find the optimal design of conical interstage structure and structures with cut-out after incorporating the required modification in the model.

ACKNOWLEDGEMENTS

The authors are grateful to Santhosh SS and Venkateswaran KP for their guidance.

REFERENCES

1. Florient Savine, Franc, Ois-Xavier, Irisarriedric Julien, Yannick Guerin.C and Angela Vincenti, “A Component-based method for the Optimization of Stiffener Layout on Large Cylindrical Rib-Stiffened Shell Structures”, Springer ,2021
2. H.N.R. Wagner, C. Huhne, S. Niemann, “Buckling of launch-vehicle cylinders under axial compression: A comparison of experimental and numerical knockdown factors”, Thin Walled Structures, 2020
3. Q Zheng, D Jiang, C Huang, Shang, X.Shang, S Ju, “Analysis of failure loads and optimal design of composite lattice cylinder under axial compression”, Composite Structures (2015)
4. Pradnya A.Vikhar and Shri Sant Gadge Baba “Evolutionary Algorithms: A Critical Review and its Future Prospects”, International Conference on Global Trends in Signal Processing, Information Computing and Communication, 2016
5. Thomas Bartz-Beielstein, Jurgen Branke Jorn Mehnen and Olaf Mersmann “Evolutionary Algorithms”, Wires Data Mining and Knowledge Discovery, June 2014
6. H. Koke, L. Weib and C. Huhne, “Effective Lightweight Design of a Rocket Interstage Ring through Mixed-Integer Optimization”, Research and Applications in Structural Engineering, Mechanics and Computation, 2013

7. David W.Sleight, Thammaiah Sreekantamurthy, Daniel N.Kosareo, Robert A.Martin and Theodore F.Johnson, "Structural design of Ares V Interstage Composite Structures", American Society of Aeronotics and Acoustics, April 26, 2012
8. M.Bagheri, A.Jafari and M.Sadeghifar, "A Genetic Algorithm Optimization of Ring Stiffened Cylindrical Shells for Axial and Radial buckling Loads", February 25 2011
9. Craig Collier, James Ainsworth, Phil Yarrington and Ryan Lucking, "Ares V Interstage Composite Panel Concept and Ring Frame Trade Spacing Studies", American Institute of Aeronautics and Astronautics, 2010
10. Ondrej Hrstka and Anna Kucerova, "Improvements of Real Coded Genetic Algorithms based on differential operators preventing Premature Convergence", Advances in Engineering Software, 2004
11. Roberto Vitali, Oung Park, Raphael T, Haftka and Bhavani V.Sankar, "Structural Optimization of a Hat Stiffened Panel Using Response Surfaces", Journel of Aircraft", January 2002