Structural Optimization of Payload Fairing Used for Space Launch Vehicles

H. Atar, and   E. Acar

Abstract— **Space Launch Vehicle (SLV) is a system to transport and place the Payloads (PL) such as satellites, experimental tools, and observation robots into desired orbit. PL are transported in Payload Fairing (PLF) that is a part of SLV and protects PL from environmental effects exposed during SLV's flight. PL capacity is the major criteria in design of SLVs. One option to increase PL capacity of SLV is to minimize PLF weight while protecting the volume allocated for PL. In this study, an Optimization System (OS) is developed to minimize PLF weight while maintaining the PLF structural design strong enough to protect PL from effects such as aerodynamic and inertial loads that emerged from flight conditions. Tabu Search is integrated to the OS to perform optimization. Structural analysis program is integrated to the OS to evaluate the structural strength. It is found that an optimized and structurally appropriate PLF configuration can be selected with Tabu Search integrated OS.**

Index Terms—**Structural optimization, payload fairing, Tabu Search, heuristic methods.**

I.   INTRODUCTION

Space Launch Vehicle (SLV) is a system that is used to transport Payloads (PL) like satellites, experimental vehicles, and observation robots to outside of atmosphere and place them to the desired orbit. SLV is composed of stages which has propulsion generators and Head Module (HM) which transport PL inside it. When the propellants inside of stages run out of, the stages are separated from SLV. After the stages separated from SLV, next stage starts to operate and generates the propulsion needed to transport PL to the target orbit. PL is transported inside PLF which protects PL from environmental effects exposed during flight.

Existing PLF design is given in **Hata! Başvuru kaynağı bulunamadı.**. Diameter of present design is 2500 mm. PLF is composed of cylindrical and conic section. PLF consists of longitudinal and transverse beams in it.

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PLF consists of 20 pieces of longitudinal beam and 10 pieces of transverse beam in cylindrical section and 20 pieces of longitudinal and 4 pieces of transverse beam in conic section. PLF nose is conic shaped. PLF material is aluminum. The shell thickness of PLF is 2 mm. The beams inside the PLF are I-beam.

There exists various studies in literature on structural optimization of PLF.   In the prior examples of PLF optimization, Analytical Hierarchy Process method was used. Different design and production criteria were considered while realizing this method. Best PLF composite material was chosen by scoring PLFs that produced from different composite materials according to the criteria [2]. Another method that used was hybrid heuristic method. Both Genetic Algorithm and Sequential Quadratic Programming were used in optimization system [11]. Also, HyperSizer program and finite element model were used to optimize Minotaur Launch Vehicle PLF design in relevant study [1]. MATLAB Genetic Algorithm Tool was used another study subjected structural optimization. In this study ANSYS analysis program was used to get structural analysis results [5, 8]. 2-D roof and tower cage systems were optimized using this method.

In this study, the weight of a PLF is minimized while maintaining the PLF structural design strong enough under aerodynamic and inertial loads. Tabu Search is used to perform optimization, and a structural analysis program is integrated to optimization to evaluate the structural strength.

II.   THEORETICAL GROUND

Firstly, mathematical model is constructed inside the PLF structural optimization study. Criteria which should be considered for optimization system is determined during this phase of study. Information related to mathematical model is given in Section A.

Optimization System (OS) is established by using inputs gathered from mathematical model. PL structural design is optimized by using OS. Detailed information related OS is given in Section B.

A.   Mathematical Model

Decision variables and parameters of the mathematical model used for the PLF structural design optimization is given in TABLE I and TABLE II, respectively. The upper and lower bounds of the design variables are provided in TABLE IV.
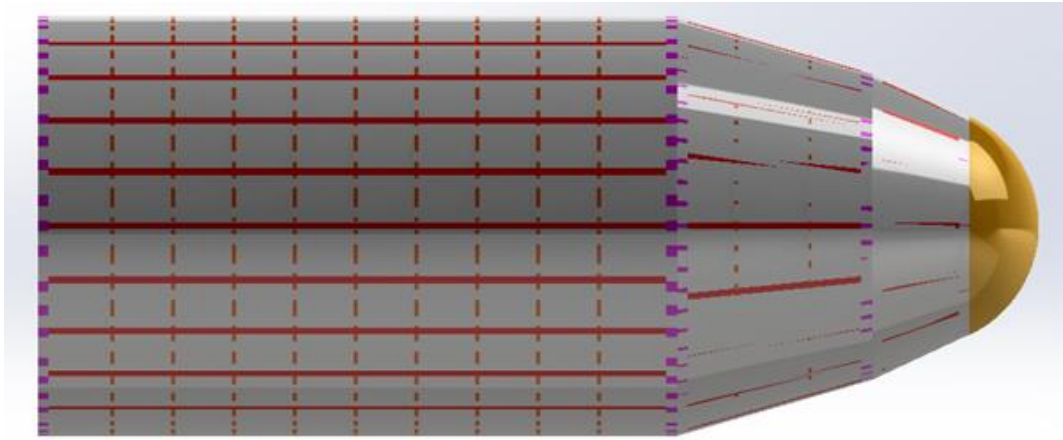
Fig 1. Payload Fairing (PLF)

TABLE I
DECISION VARIABLES OF PAYLOAD FAIRING STRUCTURAL
DESIGN

No	Decision Variable	Definition
1	a	Number of transverse beam in Cylindrical Part of PLF
2	c	Number of transverse beam in conical part of PLF
3	materialType	Material type used in PLF (Aluminum, Magnesium, Steel)
4	shellThickness	Shell thickness of PLF
5	beamType	Beam type of PLF (I Beam, Z Beam, H Beam, R Beam, C Beam, T Beam, L Beam, W Beam)
6	beamLength	Beam length of PLF

TABLE II.
MATHEMATICAL MODEL PARAMETERS OF PAYLOAD FAIRING
STRUCTURAL DESIGN

No	Parameter	Definition
1	$beamArea_i$	Beam section area for beam type i
2	beamLength_a	Beam length of beam used in cylindrical section
3	$beamLength\_c_l$	Beam length of beam used in conic section
4	$shellArea_j$	Section area of shell number j
5	$Smax_k$	Stress limit of material type k used in PLF
6	$Tmax_k$	Tip deflection limit of material type k used in PLF
7	yogunlukm	Density of material m used in PLF

TABLE III.
INITIAL VALUES AND LOWER-UPPER LIMIT OF VARIABLES

Variable	Unit	Initial Value	Upper Limit	Lower Limit
a	piece	10	1	15
c	piece	4	1	6
MaterialType	N/A	Al	N/A	N/A
ShellThickness	mm	2	1	2.5
BeamType	N/A	I	N/A	N/A
BeamLength	mm	20	10	25

N/A: Not Applicable

Mathematical model of the PLF structural optimization is given below;

Objective Function

$$\min \sum materialType_m * density_m$$

$$* (\sum_i beamArea_i * beamLength_a * a$$
$$* beamType_i$$
$$+ \sum_i \sum_l beamArea_i$$
$$* beamLength\_c_i * c * beamType_i$$
$$+ \sum_j shellArea_j * shellThickness) \qquad (1)$$

Constraints

$$S < \sum_m Smax_m * materialType_m \qquad (2)$$

$$T < \sum_m Tmax_m \qquad (3)$$

$$a > 1 \qquad (4)$$

$$c > 1 \qquad (5)$$

$$shellThickness \geq 1\ mm \qquad (6)$$

$$\sum_m materialType_m = 1 \qquad (7)$$

$$\sum_i beamType_i = 1 \qquad (8)$$

$$beamLength \geq 10\ mm \qquad (9)$$

$$a, c \text{ integer} \qquad (10)$$

Equation (1) is the objective function of the mathematical model. The aim of PLF structural design optimization problem is minimizing the mass, which is the summation of beam and shell masses. The mass values are obtained by multiplying the

densities and the volumes of the PLF cylindrical and conical section beams and PLF shell parts.

Equations (2), (3), (4), (5), (6), (7), (8), (9) and 10 are the constraints of mathematical model. Equation (2) constrains the stresses developed at the structural parts. This constraint is used to make the PLF structural design strong enough against to the stress emerged during flight. The 'S' value used in this term denotes the stress and it is obtained from PLF structural analysis. S_{max} value in Equation (2) is the maximum allowable stress of material represented by materialType$_m$.

Equation (3) constrains the deflections of the structural parts. This constraint is used to make the PLF structural design stiff enough. The 'T' value used in this term denotes the deflection is obtained from PLF structural analysis. T_{max} value in Equation (3) is the maximum allowable deflection of PLF.

Equation (4) constrains the number of transverse beam used in the cylindrical section of PLF. This constraint ensures the use of at least two transverse beams in cylindrical section. Equation (5) constraints the number of transverse beam used in the conical section of PLF. This constraint ensures the use of at least two transverse beams in conical section.

Equation (6) constrains the thickness of shell. The minimum value of this shell thickness is determined as 1 mm (due to manufacturing limits).

Equation (7) guarantees to choose at least and only one material type for PLF. There alternatives are evaluated during optimization. These alternatives are aluminum, steel and magnesium. Equation (8) guarantees to choose at least and only one beam type for PLF. The beam types evaluated in OS are 'Z' beam, 'C' beam, 'T' beam, 'L' beam, 'W' beam, 'I' beam and 'R' beam.

Equation (9) constrains the length of beam used for PLF design. The minimum value of this beam length is determined as 10 mm.

Equation (10) defines that variables 'a' and 'c' can take only integer values.

When the mathematical model is inspected, structural analysis program should integrated to the OS to obtain the stress 'S' and deflection 'T' values. Details of the OS is explained next.

i. Optimization System (OS)

PLF structural optimization study contains a multi-disciplinary engineering approach. The OS developed in this scope includes more than one subsystem that belongs to different engineering branches.

OS basically contains the following three subsystems;

- Heuristic Subsystem,
- Design Subsystem,
- Analysis Subsystem.

The flow chart explaining the working principle of OS is given in **Hata! Başvuru kaynağı bulunamadı.**.
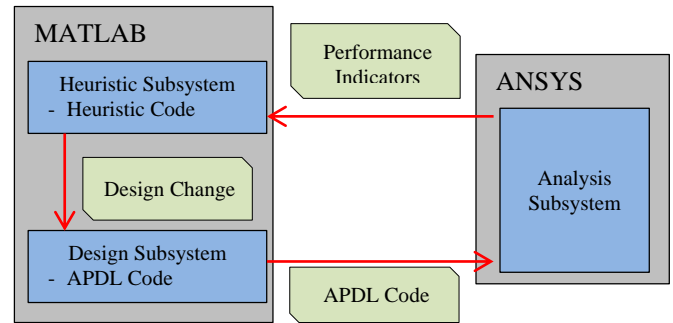

Fig 2. Flow Chart of Optimization System

Design, Analysis and Heuristic Subsystems work together and each subsystem gets the inputs, works over the inputs, creates the outputs and gives it to next subsystem. Each subsystem working principle is explained in the following sections.

a. Heuristic Subsystem

The inputs of Heuristic Subsystem are the existing PLF design and the performance indicators. The output of this subsystem is the design change of existing PLF design. This output is given to Design Subsystem to update the PLF design. All design variables describing the PLF design are evaluated as decision variables in Heuristic Subsystem. These decision variables are transformed into Heuristic Subsystem optimization moves and so objective function of PLF structural design is become optimized. Heuristic method used in Heuristic Subsystem is coded, and the whole logic and scanning operations of the heuristic method are realized using MATLAB.

Tabu Search is determined as a suitable heuristic method for PLF structural optimization. Tabu Search is coded in MATLAB to be integrated to OS. Initial values, neighbors and lower/upper limits of decision (design) variables used in Tabu Search are given in

.

TABLE IV.
NEIGHBORS AND STEPS OF VARIABLES

Variable	Step	Neighbors
a	Increasing and decreasing 1	a+1, a-1
c	Increasing and decreasing 1	c+1, c-1
materialType	Other all materials	
shellThickness	Increasing and decreasing 0,1	shellThickness+0.1, shellThickness -0.1
beamType	Other all beam types	
beamLength	Increasing and decreasing 1	beamLength+1, beamLength -1

In the first part of Tabu Search, the moves on the existing PLF design decision variables given in TABLE IV are realized and new PLF designs are obtained. The APDL codes of the new PLF designs are written to the text document. The text documents created for all neighbors are given to the ANSYS analysis program as an input. ANSYS analysis program conducts the structural analysis and gives the results of

performance indicators in the form of a text document to the Heuristic Subsystem to be evaluated.

If both maximum stress and maximum deflection values are smaller than the desired values, the PLF design is assessed as feasible and the move is realized on PLF design. The assessment process is completed for all neighbors. The objective function values are calculated for all feasible PLF neighbors and the neighbor having the best objective function value is determined as the selected neighbor.

The move of selected neighbor is controlled whether it is in Tabu list or not in the next phase. In the continuation of this phase;

- If the selected neighbor move is in the Tabu list, the selected neighbor is controlled whether it is better than the best solution or not.

  o If the selected neighbor has better objective function value than the best solution, the selected neighbor is accepted as the next solution and the best solution, and the iteration number is increased.

  o If the selected neighbor is not better than the best solution, the next better neighbor solution is accepted and this phase is repeated.

- If the selected neighbor move is not in the Tabu list, the selected neighbor is controlled whether it is better than the best solution or not.

  o If the selected neighbor is better than the best solution, the selected neighbor is accepted as the next solution and the best solution, and the iteration number is increased.

  o If the selected neighbor is not better than the best solution, the selected neighbor is accepted as the next solution, and the iteration number is increased.

Tabu list is updated in the next phase. The new move of the selected neighbor is added to Tabu list and the oldest move in the Tabu list is deleted. Neighbor moves are stored in the Tabu list to preserve repetition of the same move. Thus, different parts of the solution cluster can be searched and evaluated. This provides the diversification over the problem. In case the solution is better than the best solution despite it is in the Tabu list, this solution is set as next solution. This situation is called as aspiration criteria and this process provides intensification over the solution cluster.

The flowchart of the process described above is given in Fig 3.

b.   Design Subsystem

This subsystem applies the design changes to the PLF structural design during the optimization iterations. Design changes include changing the dimensions of PLF mechanical components, the material of PLF and the configuration of PLF. These changes are reflected to the design by using ANSYS Parametric Design Language (APDL).

APDL is coded by using MATLAB and shared with ANSYS. In each iteration of the OS, the design is updated automatically with APDL parametric definition. Design changes, which are the output of Heuristic Subsystem, become inputs of the Design Subsystem to update the design. Updated APDL, which is the output of Design Subsystem, is given to Analysis Subsystem as an input.

c.   Analysis Subsystem

PLF structural analysis is realized to determine the performance indicators (e.g., stresses and deflections) of the existing or the updated PLF design. Performance indicators show the effectiveness of the design and they are evaluated to determine whether the design is feasible or not.

PLF structural analysis is conducted using ANSYS. APDL code of the updated APDL design is transferred to the Analysis Subsystem from Design Subsystem. ANSYS computes the performance indicators of the updated design and these performance indicators are transferred to Heuristic Subsystem as an input.

III.   RESULTS AND DISCUSSION

The optimization runs are conducted by using the OS. The runs are executed by using a workstation with Intel Core i7 64bit processer and 8GB RAM. The results of the optimization runs are given in TABLE V. It is observed that the PLF mass can be reduced from 180.51 kg to 75.58 kg (reduced by 58.7%).

TABLE V
RUN RESULTS FOR DIFFERENT NUMBER OF ITERATIONS

Number of Iteration	a	c	Material Type	Shell Thickness	Beam Type	Beam Length (mm)	Objective Function Value(kg)
0	10	4	1	2	1	20	180,51
5	10	4	3	1,6	1	20	144,89
10	10	4	3	1,1	1	20	100,03
20	10	4	3	1	1	11	80,83
50	7	6	Mg	1	3	10	75,58

TABLE V also shows that the shell thickness is reduced to its lower limit of 1 mm. Another change observed for the PLF design is the material type. Magnesium is used instead of aluminum and this change decreases the PLF weight by 40%.

It can be seen that the decision variables a and c are also design critical in terms of PLF flight loads. It is found that the optimizer reduces the number of beams in the cylindrical part (a) and increases the number of beams in the conical part (c) to decrease the PLF weight while maintaining the stresses and deflections below the specified constraint values.

Another criteria that can be used to evaluate the performance of OS is the run time of the system. The run times are listed in TABLE VI, which shows that the run time increases exponentially with respect to the iteration number. Therefore, it is required to keep the iteration number as low as

possible. The evolution of the objective function value through iterations are depicted in Fig 4, which shows that 30 iterations are enough for OS to get near optimal solutions.
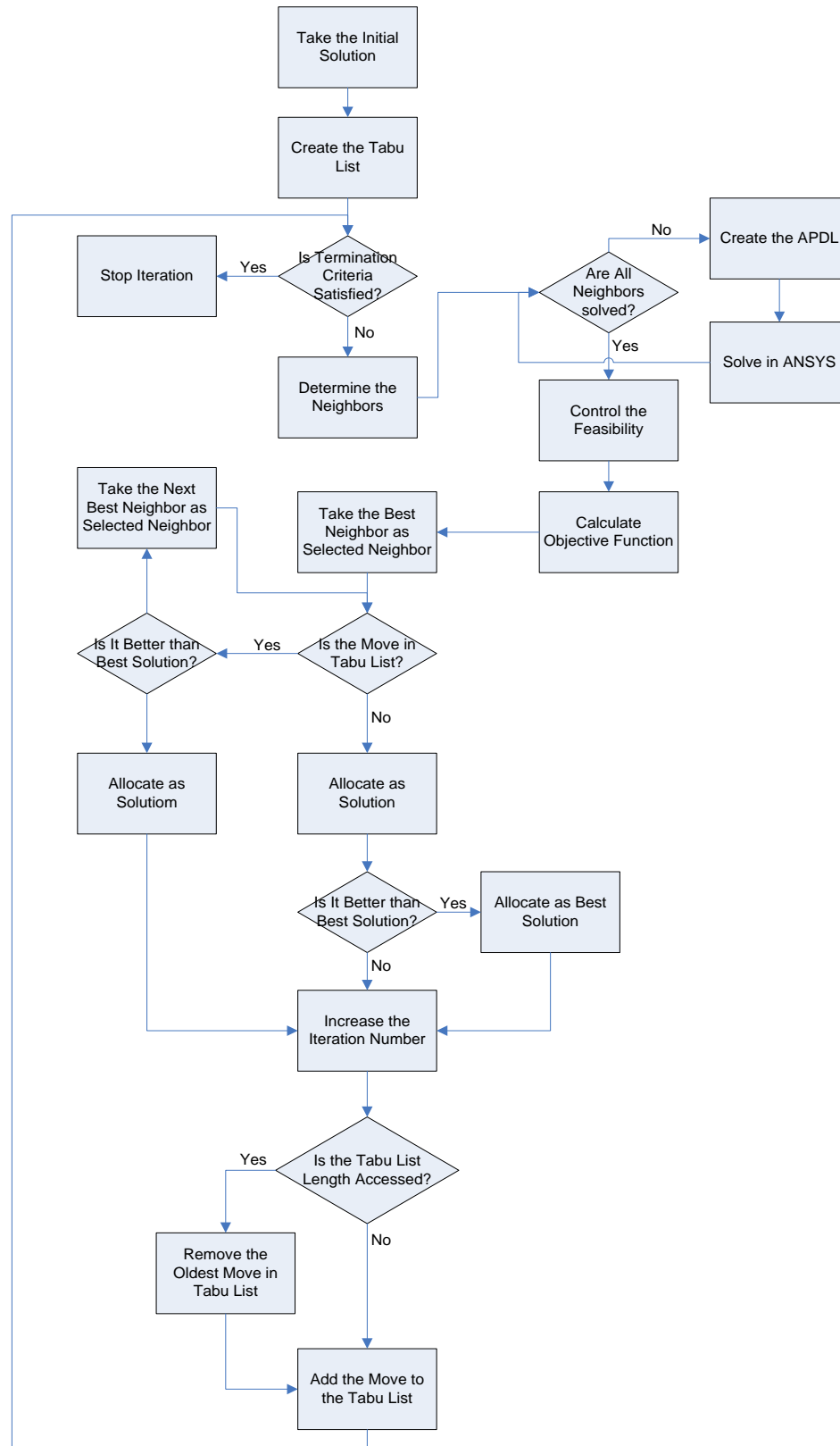
Fig 3. Optimization Subsystem Flow Chart

TABLE VI.
THE RUN TIMES FOR DİFFERENT ITERATION NUMBERS

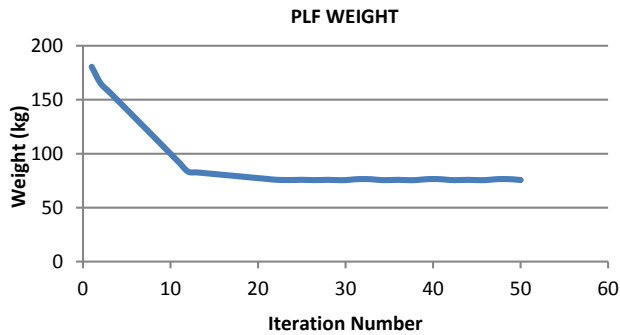| Iteration Number	Run Time (second)
5	503
10	1086
20	3174
50	10573

Fig 4. PLF Weight Change for Different Iteration Numbers

IV.   CONCLUSION

In this study, Payload Fairing (PLF) used in Space Launch Vehicles was optimized using Tabu Search, which is a heuristic method. Optimization results showed that the optimum PLF design should have 1mm shell thickness, and that PLF material should be aluminum. PLF beam length should be 10 mm. The number of beams in the conical section should be six, and the number of beams in the cylindrical section should be seven. This design changes resulted in 58.7% weight reduction. It was also found that 30 iterations were enough for OS to get near optimal solutions and high performance from OS, and that Tabu Search can be used to optimize PLF design and to get the good solutions efficiently.

Future study could focus on using other heuristic methods (e.g., Genetic algorithm, simulated annealing, etc.) and the most suitable method for PLF design could be determined.

ACKNOWLEDGMENT

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BIOGRAPHIES

Hakan ATAR was born in Aydın, Turkey in 1990. He received his BS in Industrial Engineering and double major BS in Mechanical Engineering at the TOBB University of Economics and Technology of Turkey where he is currently receiving his MS degree since 2013.
Since 2013 he is serving as System Engineering and Technology Management Engineer in Space Systems Company in Ankara. He is working as system engineering responsible of the projects and technology management engineer of Engineering Directorate. His research area includes design optimization of mechanical systems. His research on design optimization of mechanical system is focused on heuristic methods.

Erdem ACAR received his BS and MS degrees in Aerospace Engineering at the Middle East Technical University in 1999 and 2002, respectively, and his PhD degree in the same field at the University of Florida in 2006. He served as postdoctoral research associate at the Center for Advanced Vehicular Systems of the Mississippi State University from 2006 to 2008. He began his academic career in 2008 at the TOBB University of Economics and Technology of Turkey, where he is currently an Associate Professor at the Department of Mechanical Engineering. He is actively engaged in teaching and research. His primary areas of teaching include structural analysis and reliability assessment of mechanical systems. His research efforts are focused on design optimization of mechanical systems, with strong emphasis on reliability-based design optimization and surrogate-based design optimization. He has published around sixty refereed journal and conference papers in the above areas. He is an associate fellow of AIAA, and a member of the AIAA Non Deterministic Approaches Technical Committee.