MULTIDISCIPLINARY DESIGN OPTIMIZATION OF STRATOSPHERIC AIRSHIP

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Abstract

This paper describes a methodology for shape optimization of the envelope of an airship for long endurance missions at stratospheric altitudes. Gertler Series-58 shape generation scheme is selected for optimization studies, in which the envelope shape is driven by four shape parameters and fineness ratio. The values of these parameters are obtained by satisfying the condition of airship geometry. Effect of operational parameters viz. location, altitude, wind etc. on sizing of airship are discussed. For multidisciplinary design optimization (MDO) A composite objective function is formulated which incorporates the value of envelope volumetric drag coefficient (C_{DV}), circumferential hoop stress (σ_{hoop}) on the envelope, area of solar array and envelope surface area. The optimization is carried out using an open-source implementation of a robust stochastic algorithm, viz., Genetic Algorithm.

1 Introduction

There is a global interest in design and development of stratospheric airships [1], which can serve as a long endurance platform for deployment of equipment for several commercial and strategic applications e.g., next generation wireless broadband telecommunications [2], digital broadcasting [3], coastal surveillance [4], remote sensing and GPS augmented navigation systems [5]. These airships are designed to be able to maintain a quasi-stationary position at altitudes of around 20 km, where ambient winds are of low magnitude. Such airships function as low-altitude satellites, but offer much shorter transmission distances and ranges with high resolution, and lesser signal propagation errors. They are much more economical compared to satellites, as they can be relocated or brought down and refurbished with latest equipment.

The power requirements for an airship are two-fold, to meet the needs of the on-board mounted equipment, as well as the propulsive power needed to either maintain its station in the presence of ambient winds, or to travel at a required speed when it is to be relocated. Since such airships are to be deployed for long durations (several weeks or months), the only practical mechanism to address their power needs is a Solar Regenerative Fuel Cell (SRFC) system. In such a system, adequate amount of solar arrays are mounted at the top of envelope of the airship. During day time, the solar arrays generate enough power to meet the needs, and any excess power is used to charge the onboard batteries, which meet the power requirements at night time, or during lean periods. The working principle of a typical SRFC is depicted in Fig. 1.

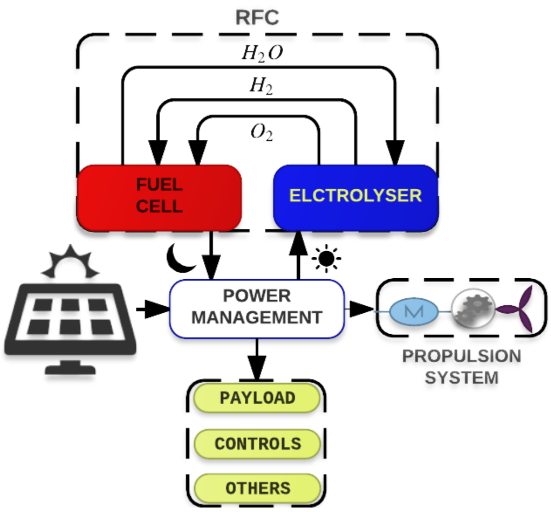

Fig. 1. Working Principle of SRFC

Several researchers have proposed methodologies and approaches for conceptual design and sizing of stratospheric airships [6-9]. The shape of the envelope is one of the most critical elements in the design of such systems, and envelope shape optimization is a key area of research in this field [9]. Concurrent subspace optimization techniques have also been applied to the conceptual design and sizing of airships [10]. A critical review of all these methodologies has been carried out by Alam and Pant [12].

There is a need to develop a simple yet accurate and more realistic multidisciplinary design methodology, keeping in mind the operating scenario and meteorological conditions. For example, high winds lead to steep rise in drag, which results in higher power requirements, i.e., larger solar arrays. At the same time high wind can also maintain the efficiency of solar cells by restricting temperature rise. Therefore, a multidisciplinary design and analyses approach is needed to locate a truly optimal design.

This paper describes such a methodology, which can be used for initial sizing of stratospheric airship, to meet the user-specified requirements of payload weight and power.

A composite objective function is devised which takes into account various factors that influence airship performance, including aerodynamics, structures, energy and weight. The envelope shape is parameterized in terms of some geometry related parameters; and the optimum shape that minimizes this composite objective function is obtained. Constraints are imposed on the volume of the airship, to ensure comparability of the design results. Optimal solutions are obtained using an evolutionary technique, viz., Genetic Algorithm

2 System modeling for analyses and optimization

In the past, drag was often considered in airship optimization. When the coefficient of drag was smaller, the airship shape was considered more optimal [10]. In fact, the practical studies gradually show that many factors restrict the airship shape and resistance is only one of the several important factors, which also include weight, structural strength etc. After screening and contrasting to determine the most important factors on airship, coefficient of drag (C_{DV}), surface area of the airship envelope (Ae), minimum hoop's stress (σ_{min}) and area of the solar array (A_{sa}) are employed in the present study.

2.1 Gertler Series-58 Shape Generator

For design, analyses and optimization of airship, *Gertler Series 58 Shape Generator* ([13], [14]) (Eq. 1) has been considered, which is parameterized in terms of some geometry related parameters; and the optimum shape that minimizes composite objective function is obtained.

$$y^2(x) = D^2\left[a_1\left(\frac{x}{L}\right) + a_2\left(\frac{x}{L}\right)^2 + a_3\left(\frac{x}{L}\right)^3 \dots + a_6\left(\frac{x}{L}\right)^6\right] \quad (1)$$

Where, a_1, a_2, a_3....a_6 are shape coefficients whose values are driven by geometrical parameters of airship viz. m (location of maximum diameters), r_o (Nose radius), r_1 (tail radius) and C_p (prismatic coefficients).

2.2 Model of surface area

The surface area of the envelope 'A_e' can be calculated using Eq. (2) as:

$$A_e = 2\pi \int_0^L y\sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \quad (2)$$

2.3 Model of volumetric drag coefficient

In order to seek the drag of the airship envelope, volumetric drag coefficient (C_{DV}) is calculated as per the formula quoted by Cheeseman in [15].

$$C_{DV} = \frac{0.172\left(\frac{L}{D}\right)^{\frac{1}{3}} + 0.252\left(\frac{D}{L}\right)^{1.2} + 1.032\left(\frac{D}{L}\right)^{2.7}}{Re^{\frac{1}{6}}} \quad (3)$$

Where, L is the envelope length, D is the maximum diameter of the envelope and R_e is the Reynolds number.

2.4 Model of Minimum Hoop Stress

Several researchers have estimated the circumferential hoop stress (σ_{hoop}) by assuming the airship body to approximate a thin cylinder with hemi-spherical ends. In this study, the pressures are obtained by considering the Elastic Engineering theory. A generalized moment equation is derived based on the Elastic theory with an assumption of linear distribution of mass along the length of the airship.

In order to maintain positive internal pressure, the minimum inner pressure (Δp) consisting of static pressure (p_{static}), Munk pressure (p_{dyn}) and internal differential pressure (p_{diff}) are calculated using Eqns. (4) to (7) as:

$$\Delta p = p_{static} + p_{dyn} + p_{diff} \tag{4}$$

The static pressure is caused by static bending moments, which is kept 15% higher to avoid nose caving.

$$p_{static} = 1.15\left(\frac{1}{2}\rho_a v^2\right) \tag{5}$$

Munk pressure caused by dynamic bending moment for a given pressure coefficient (c_p) can be expressed as:

$$p_{dyn} = c_p\left(\frac{1}{2}\rho_a v^2\right) \tag{6}$$

Differential pressure due to lifting gas and outside air is given by:

$$P_{diff} = (\rho_{a} - \rho_g) g \frac{D}{2} \tag{7}$$

The hoops stress can be calculated using Eq. (8) as:

$$\sigma_{hoop} = \Delta p \frac{D}{2} \tag{8}$$

2.5 Model of Power requirement

Total power requirement (P_{total}) of an airship consists of payload systems (P_{pay}), control systems (P_{ctrl}) and propulsion systems (P_{thrust}). The payload power and the control systems power are assumed to be constant at 10 W and 11 kW, respectively.

$$P_{total} = P_{Pay} + P_{ctrl} + P_{thrust} \tag{9}$$

The energy used for propulsion system can be calculated as,

$$P_{thrust} = D_{total} \frac{v}{\eta_{prop}} \tag{10}$$

Drag 'D' acting on the airship can be obtained using Eq. (11) as:

$$D_{total} = \frac{1}{2} N \rho_a v^2 C_{DV} V^{\frac{2}{3}} \tag{11}$$

Where,

$$V = \pi \int_0^l y^2 dx \tag{12}$$

The total energy Q_{total} is estimated using Eq. (13) as:

$$Q_{total} = P_{total} t_{day} + P_{total} \frac{t_{day}}{\eta_{conv}} \tag{13}$$

Where, t_{day} and t_{night} are the duration of day and night time respectively and η_{conv} is the conversion efficiency for storing the energy.

2.6 Model of Solar Area requirement

In the present study an approach similar to Wang et al. [11] is adopted. In which, for simplicity the airship geometry is assumed to approximate a cylinder. The radius of the envelope at the mass center r_{gc} is taken as the radius of the cylinder.

So, area of solar array (A_{sa}) required can be estimated by using Eq. (14) as:

$$A_{sa} = \iint y(x)\left(1 + \left(\frac{dy}{dy}\right)^2\right)^{1/2} dx d\xi \tag{14}$$

Where, dx is elementary length along length and $d\xi$ is angular width of elementary area of solar panel along circumferential direction.

To find the total length of solar panel X_{SC} and included angle ξ, as a limit of Eq. (15), energy supplied (Q_{sup}) can be equated to total energy required (Q_{total}) as:

$$Q_{sup} = Q_{total} \tag{15}$$

Where, Qsup can be calculated by Eq. (16) as:

$$Q_{sup} = \iiint \eta_{SC} I_d \cos\theta r_{gc} dx d\xi dt \tag{16}$$

Where, η_{SC} and I_d are solar conversion efficiency and normal solar irradiance values respectively. And θ is angle between surface normal vector and I_d. Eq. (16) was integrated for the whole day time (t_{day}) to get total power supplied.

2.7 Wind Model

NASA *Horizontal Wind Model* (HWM07) was used to plot the wind conditions at different geographic locations. Fig. 2 illustrates the variation of wind over the year at the height of 20 km.

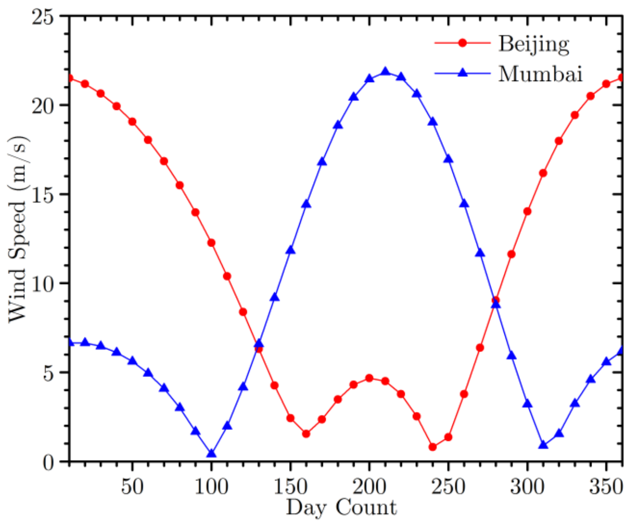

Fig. 2. Variation of wind over the year

The variations of wind speed with altitude for baseline cases are shown in Fig. 3. The figure illustrates the justification for the operational height of stratospheric airship to be around 20 km. However, a band of 17 km to 25 km needs to be explored to identify the optimum design with respect to a specified altitude of operation, for any specific location.

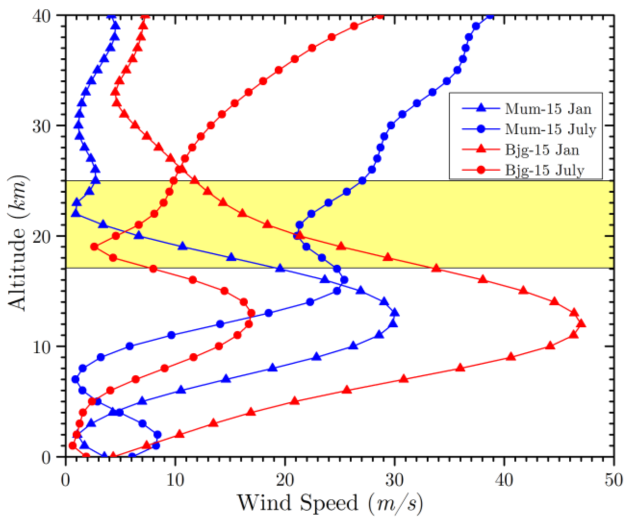

Fig. 3. Variation of wind with altitude

2.8 Solar Irradiance Model

Solar Irradiance Model by Dai and Fang [16] has been integrated into the methodology for power output calculation from solar cell. Model estimates the direct solar irradiance as:

$$I_d = I_n e^{[-0.103 m_a^{0.571} - 0.081(\omega m_r)^{0.213} - \tau^{0.91} m_r^{0.87}]} \quad (17)$$

$$m_r = [\sin\alpha + 0.15(3.885 + \alpha)^{-1.253}]^{-1} \quad (18)$$

$$m_a = m_r \frac{p_a}{1013} \quad (19)$$

Where, α is the solar elevation angle and m_r and m_a are the relative and absolute air mass respectively.

$$\omega = \omega_m e^{(-0.44\Delta H)} \quad (20)$$

$$\tau = \tau_m e^{(-0.691\Delta H)} \quad (21)$$

Where, τ_m and ω_m are the values at measured site, and ΔH is the difference of altitude from measured site in *km*.

Fig. 4 plots the variations in available solar radiation for baseline cases i.e., for two different cities viz. Mumbai and Beijing, in Winter (15-Jan) and Summer (15-Jul) solstice.

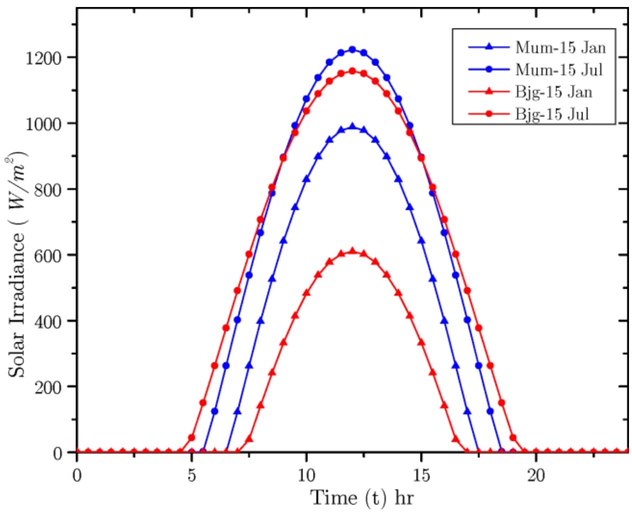

Fig. 4. Solar Irradiance availability

3 Objective Function and Design Variables

Several objective functions can be selected for determining the optimum envelope shape, e.g., minimum volumetric drag coefficient, minimum hoop stress and a composite objective function incorporating more than one objective function. To consider the influences of various factors on the optimization of the shape, a composite objective function involving C_{DV}, A_e, σ_{min} and A_{sa} is devised as follows:

$$F_{com} = w_1 \frac{C_{DV}}{C_{DV,ref}} + w_2 \frac{A_e}{A_{e,ref}} + w_3 \frac{\sigma_{min}}{\sigma_{min,ref}} + w_4 \frac{A_{sa}}{A_{sa,ref}} \quad (22)$$

Where $C_{DV,ref}$, $A_{e,ref}$, $\sigma_{min,ref}$ and $A_{sa,ref}$ are the values of parameters corresponding to the reference shape.

Design variables related to sizing are shown in the Fig. 5. For baseline case all the shape parameters are kept constant. For MDO all nine parameters have been given a bound as a range. Tab. II enlists upper and lower bound of all the design variables.

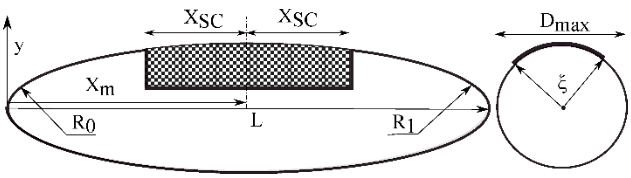

Fig. 5. Airship profile with design variables

TABLE II: Design variables with bounds

Design Variable	Lower bound	Upper bound
m	0.4	0.6
r_0	0	1
.r_1	0	1
c_p	0.6	0.7
L/D	2	6
X_{SC} (m)	20	100
ξ (deg)	50	100
ALT (km)	17	25

4.1 Results of Sensitivity Analyses

To understand the effects of various parameters sensitivity analyses have been carried out. Table I lists the input parameters for sensitivity analyses.

TABLE I: Input Parameters

Input Parameter	Value
Design Altitude	20,000 m
Maximum design speed, v	25 m/s
Payload mass	1000 kg
Power required by Payload	10 kW
Power required by Control Systems	11 kW
Ratio of C_{DV}, total / C_{DV}, env	1.8
Propulsive efficiency	90 %
Solar array efficiency	12 %

Energy produced by the solar array of the airship are used by payload and system as well as it also fights with the wind to resist the drift and maintain quasi stationary position. However, performance of solar array is greatly affected by the temperature rise during day time. Upto 30% loss in efficiency of solar array can be observed for a typical operating condition and deployment site [17]. Fig. 6 highlights the effect of efficiency of solar array on the sizing of airship. An attempt to highlight the seasonal variation on the sizing of airship due to the variation in availability of solar irradiance over the year.

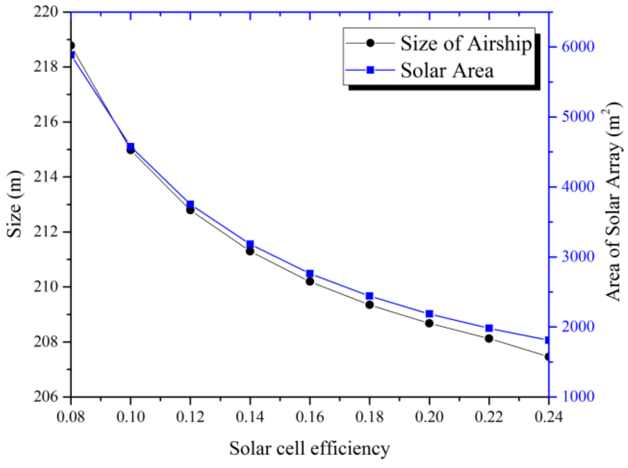

Fig. 6. Effect of Solar efficiency on sizing

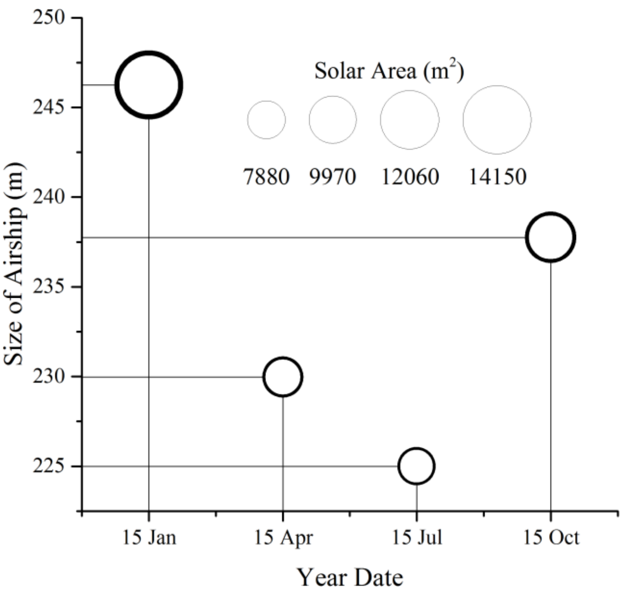

Fig. 7. Seasonal effects on Sizing of airship

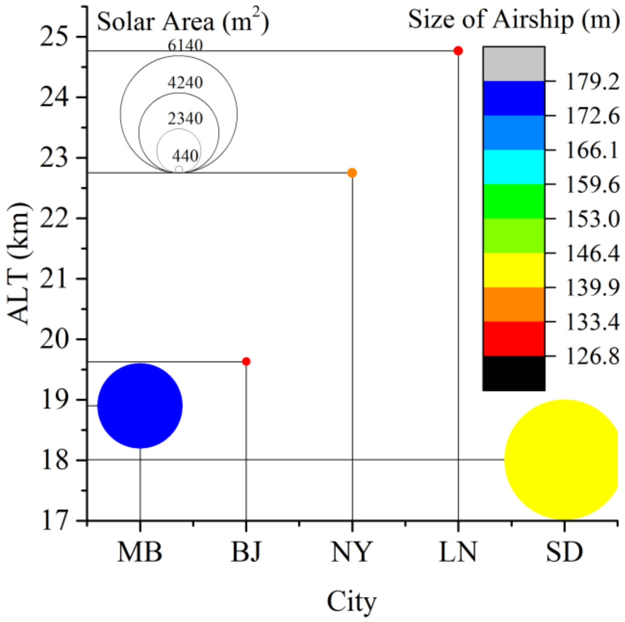

Fig. 9. Optimum altitude and size of airship for various locations

Fig. 6 and Fig. 7 have been plotted against the constant operational height of 20 km for Mumbai. For same requirements of payload and power, significant variation in sizing can be observed in Fig. 7. Smallest airship fulfilling the needs of power and payload can be design at summer time due to ample availability of solar energy. While Fig. 7 keeps the operational height constant, interesting results can be found by varying altitude (as shown in Fig. 8). At different season, different operational heights act as optimum due to the fact of variation in wind speed.

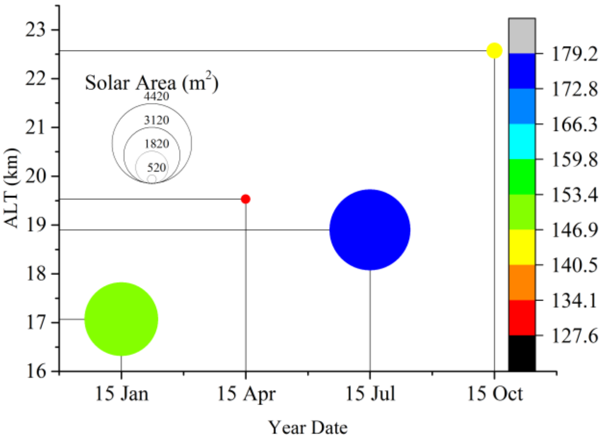

Fig. 8. Optimum deployment altitude at different seasons

Fig. 6 and Fig. 7 have been plotted against the constant operational height of 20 km for Mumbai. Fig. 9 demonstrates the effect on sizing for five different cities viz. Mumbai (MB), Beijing (BJ), New York (NY), London (LN) and Sydney (SD). Variations in geographic location of cities considered affect the sizing significantly.

4.2 Results of Optimization

In this section, the results after performing optimization using Genetic Algorithm (GA) are presented. Firstly, a baseline case was run keeping all the design variables related to shape of airship as constant to obtain the reference parameters. Then, optimization was run to obtain the optimal results.

The comparison of optimized shape and reference shape for F_{comp} listed in Eq. (17), is shown in Fig 10.

Table III compares the results output for key parameters and improvements after optimization. It can have noticed that in almost each key parameters, optimized shape has better results.

TABLE III: Output Parameters

	Ref. Shape	Opt. Shape	% Imprt.
Solar Area	7889	7306	7.39
Hull Area	31223	32514	-4.13
Drag Coeff.	0.0365	0.0356	2.47
Hoop Stress	1733.6	1649.4	4.86
Comp. Func	100.0	97.3976	2.60

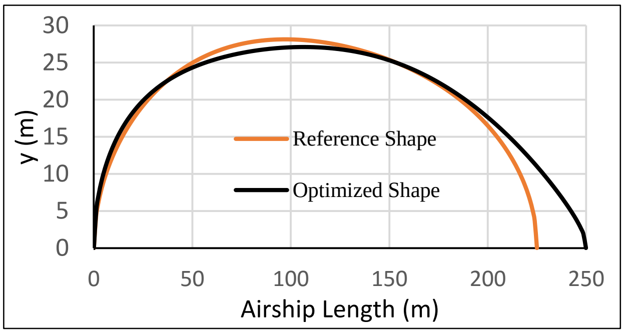

Fig. 10. Comparing optimum shape with reference shape

5 Conclusions

A new and simpler methodology for multidisciplinary design optimization of stratospheric airship has been proposed, with lesser number of assumptions compared to other such methodologies reported in literature. The efficacy of the methodology in arriving at the output parameters, and in carrying out sensitivity analyses of key parameters has been demonstrated. Methodology couples the various model viz. solar, wind, aerodynamic, structure etc. for multidisciplinary design and analyses.

It has been observed that, GA shows a good convergence to find the optimal solution for given constraints. It is also observed that the numerical values of shape coefficients (a_1, a_2, a_3,…,a_6) are very sensitive. For the given constraints, many combinations of design values to imaginary solution. To take care of the same, an additional penalty functions were imposed, to overlook the values which results in imaginary output of the shape function. The methodologies explained have some limitations especially in solar area calculation and structure modelling. There is a need to develop an all-encompassing methodology consisting of different models, which would be able to carry out sizing and arrive at the more realistic optimal configuration fulfilling any given requirements with low cost, high payload capability, and least size and weight.

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