DESIGN MODIFICATIONS AND ENHANCEMENT OF ADAPTABILITY OF MOORING STRUCTURE FOR MEDIUM SIZE AEROSTAT

Amit Kumar\(^1\), R K Sharma\(^1\), Dr. S C Sati\(^2\)

\(^1\)(Scientist, Mechanical Engineering Division, ADRDE, DRDO, Agra, India)
\(^2\)(Director, ADRDE, DRDO, Agra, India)

ABSTRACT

Detecting the threat and having sufficient reaction time well in advance, before the sinister comes, is of prime concern for safeguard of the nation. Various payloads e.g. electro-optic sensor, radar etc. are available for this purpose but the earth’s horizon effect imposes limitation on its coverage. Aerostat system provides platform to integrate payloads and keep them at desired altitude which increases line-of-sight and in turn coverage significantly. Aerostats are system of systems with amalgamation of multi-domain technologies. It consists of aerodynamic shaped, helium filled balloon which is fabricated using special fabric. These balloons are moored on ground using a particular mechanical structure known as mooring structure which is the backbone of aerostat system. It is used for mooring the huge balloon, mounting winch systems, to provide agility and carrying out repair/maintenance of balloons. To design and realize the mooring structure, various load cases have been considered for different configuration. The criticality is associated when the side wind strikes the balloon and rotation of structure is restricted. In such situations a heavy drag force acts on the balloon and accordingly huge twisting moment is transmitted to the structure which results in high stresses. The first proposed design modification eradicates the transmission of this twisting moment on mooring tower, reduces the stress and hence offers the scope to reduce the weight of structure. The second design modification involves making air bag frame adjustable which will provide cushioned support to balloon belly all the time in moored condition and keep it horizontal for stable configuration of balloon. Third design modification involves fastening of length pieces to mooring tower and close haul swing frames. Incorporating this will result in enhanced adaptability i.e. the same mooring structure can be used for different sizes of balloon in medium size (2000-3500 cum) category. All these aspects are well supported by modeling and analysis performed in solidworks and ANSYS software respectively. To avoid any data loss, the finite element model has been developed in ANSYS itself.
Keywords: Aerostat, Confluence Point, Cradle, Moore, Nose Probe, Wind-Vaning.

I. INTRODUCTION

A term “aerostat” is a result of merging two Greek words: “aer” – “air” and “statos” – “standing”. Aerostat is based on lighter-than-air technology and plays vital role during peace time surveillance at border areas. The available payloads may be mounted on aircraft to perform similar operations but due to expensive adventure, they are not used in this way. Aerostats are system of systems with amalgamation of multi-domain technologies. Broadly, Aerostat system consists of aerodynamically shaped lighter-than-air gas filled aerostat balloon, mooring system, winch system, gas management system, power management system, ground control station, tether, balloon health monitoring system and payloads. Balloon is used for mounting desired payload, winch system is used for controlled deployment, retrieval and parking of aerostat balloon at desired altitude, gas management system is used for inflation and top up of balloon, power management system is used for providing power to payloads as well as winch systems, ground control station is used for recording of data and other electrical and electronic interfaces, tether is used to connect balloon with winch system along with electrical power supply and two way data transmission to integrated payloads and health monitoring system is used for maintaining differential pressure between inside gas and outside air within a specified range so that the balloon can remain in aerodynamic shape all the time in flight. This medium size Aerostat system has been indigenously designed and developed by ADRDE, Agra [1]. The developed system trial was conducted successfully at IIT Kanpur [1]. Fig. 1 [2] and 2 [3] shows the actual trial picture of aerostat system with its various sub-systems for moored and deployed case respectively.

Figure 1: Aerostat moored on mooring structure

Figure 2: Aerostat deployed using winch system on mooring structure
The present paper will focus on further design modifications and scope for enhancement of adaptability of mooring structure for various advantages. Mooring structure is the backbone of aerostat system. Mooring structure comprised of one main structure known as boom, two close haul swing frames, one mooring tower and one hydraulic actuator. The solid model of different parts of mechanically integrated mooring structure has been shown in the published paper by Amit Kumar et al [4]. Winch sub-systems are mounted on boom. Boom is supported by bearing for agility so meticulous care has been taken, during its design phase, in terms of center of gravity balancing, starting torque of structure and tether routing. Center of gravity balancing is important from structural stability point of view. Starting torque of bearing should be minimum. This is important for onset of structure rotation whenever sideways wind strikes the balloon. This phenomenon is known as wind-vaning. Due to wind-vaning, the moored balloon along with structure self aligns itself in the direction of wind and the stresses developed in balloon fabric is minimum. Tether is stored on main winch drum, passes over the boom and emerges at flying sheave for attachment to balloon. Tether routing is also challenge for structural design because it consists of fiber optic cable which cannot be bent beyond the permissible value of bending radius. Two close haul swing frames are required to mount two close haul winches which in turn are used for mooring of aerostat balloon. Mooring tower is required to latch the balloon nose with the help of cradle in moored condition. Since the system is required to be transported on road, from one deployment site to other, so mooring tower and close haul swing frames are designed foldable. The folding and unfolding of mooring tower can be carried out using hydraulic actuator while both the close haul swing frames can be done manually.

Aerostat balloons are moored on mooring structure by capturing balloon at three locations. One location is balloon nose and other two locations are two close haul line confluence point which are emerging from balloon on its both side. To moore the balloon at nose, one mechanical structure is patched to balloon nose known as nose probe. In the present system, the cradle is directly bolted on the top of mooring tower. The function of cradle is to latch the balloon nose with the help of cradle in moored condition. To moore the balloon at close haul confluence points, two high strength low weight ropes are used. One end of the rope is attached to close haul confluence point and another end is attached to close haul winch mounted on close haul swing frames. With the help of these winches, the ropes can be winded and unwounded which results in controlled vertical movement of balloon as per requirement. In the moored condition, no winding/unwinding operations are done.

The mooring structure for medium size aerostat has been successfully designed, realized and tested but further design modifications [5] and enhancement of adaptability are suggested which would yield better results in various aspects. The present paper focuses to highlight the aspects for design modifications and enhancement of adaptability proposed for medium size of aerostat.

2. DESIGN MODIFICATION

2.1 Mounting Bearing at Mooring Tower Top

In the moored condition, the forces acting on the aerostat balloon are force of buoyancy acting at center of buoyancy, aerodynamic forces acting at center of pressure, gravity force acting at center of gravity, close haul line cable tension (acting on both sides of balloon) and reaction forces at the nose probe. Various forces acting on balloon at their respective locations are shown in fig. 5 [5]. The forces are being transferred to mooring structure at three locations viz. mooring tower top, left close haul swing frame and right close haul swing frame. All reactions forces transmitted are acting at the bolted interface of cradle, left close haul winch and right close haul winch on the structure. The forces and moments transferred to mooring structure and their respective locations are shown in fig.6.
Entire mooring structure is mounted on bearing, which under the normal operating condition is free to wind vane. Any sideways wind tends to rotate the entire mooring structure and balloon self re-aligns along the direction of striking wind. Sometimes, for the purpose of repair, maintenance and integration of payload, the mooring structure is required to be locked at a particular configuration. Locking the structure in a particular configuration makes it vulnerable towards the randomly striking wind. When wind strikes the balloon along its longitudinal axis, the aerodynamic drag force acting on balloon is minimum. The situation worsens as the striking wind changes its direction. The aerodynamic force becomes maximum, when wind strikes perpendicular to the longitudinal direction of balloon in horizontal plane. Due to associated criticality, this case has been considered to show the effectiveness of design modification.

In the present system, the cradle is directly bolted on the top of mooring tower which is designated as configuration 1 in this paper. Cradle can rotate freely about its transverse axis. Due to cylindrical compatibility between nose probe of balloon and cradle, the aerostat balloon can freely rotate about its longitudinal axis. Due to these free rotations, the moments along transverse axis and longitudinal axis are zero at the mooring tower top. The rotation of cradle about its vertical axis is not allowed which is prime cause of transmission of twisting moment on mooring tower top and hence results in high stresses in structure. Apart from this, restricting the rotation of cradle about vertical axis has disastrous effect on balloon too. As the vertical axis rotation of cradle is restricted, the aerostat balloon will tend to bend about the patched ring of nose probe due to the moment. This phenomenon will develop high stress in balloon fabric and balloon may fails. Under the limiting cross wind condition, the reaction forces and close haul cable tension has been estimated. The reaction force and moment estimation is based on the assumptions that the system is in static and dynamic equilibrium and balloon is rigid. The results, as per the co-ordinate axes shown in figure 5, are tabulated in Table 1. The reaction forces estimated shows that the transmitted twisting moment at tower top is 215200 N-m, which is very high, and is result of large drag force and large offset of its point of application from the mooring tower top. This twisting moment develops very high stresses in mooring structure.

To get rid of twisting moment, the proposed design modification is to mount a suitable bearing at the top of mooring tower and cradle should be mounted on this bearing. In this paper, this configuration has been designated as configuration 2. The provision will be made to lock the bearing
at a particular position, if required. By adopting this design modification, the cradle will be free to rotate about its vertical axis too. With the help of this configuration 2, the balloon can freely yaw and twisting moment will vanish from mooring tower top. It will also minimize the scope of bending of balloon about the patched ring of nose probe. The transferred forces to mooring structure have also been estimated for this configuration 2 according to the assumptions explained above. The results are shown in above Table 1.

Table 1: Estimated forces and moment transferred to structure for both configurations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Configuration 1</th>
<th>Configuration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction forces &amp; moment at tower top</td>
<td>R_y = 2000 N; R_z = 14000 N; M_y = 215200 N·m;</td>
<td>R_y = 2000 N; R_z = 800 N</td>
</tr>
<tr>
<td>Resultant left close haul cable tension</td>
<td>T = 3326 N</td>
<td>T = 3326 N</td>
</tr>
<tr>
<td>Resultant right close haul cable tension</td>
<td>T = 3326 N</td>
<td>T = 15071 N</td>
</tr>
</tbody>
</table>

The mooring structure FEA model has been developed in ANSYS software. The modeling, elements selected and meshing methodology have been carried out according to the published paper by Amit Kumar et al [6]. The forces at tower top have been applied at the bolting interface of cradle for configuration 1 and at the bolting interface of bearing for configuration 2. The close haul cable tension has been applied at the bolting interface of respective close haul winches. In both the configurations, the structure is in locked position so all the bolting interfaces of bearing with boom are restrained. With the help of ANSYS solver, the FE analysis has been carried out and the results in terms of stress profile has been shown in fig. 7 for configuration 1 and fig. 8 for configuration 2.

![Figure 7: stress profile for configuration 1](image1)

Peak Von-Mises Stress = 319 MPa

![Figure 8: stress profile for configuration 2](image2)

Peak Von-Mises Stress = 53.7 MPa

The peak stress developed in configuration 1 is 319 MPa and occurs on the mooring tower. The FOS is coming out to be 2.19. The peak stress developed in configuration 2 is 53.7 MPa and occurs on the main beam of boom. The FOS is coming out to be 13.03. The increase in FOS is very significant on incorporating proposed design modification. The moment of inertia of the boom members is comparatively very high with respect to members of mooring tower. And hence the peak stress does not have any adverse effect on structure.
2.2 Making air bag frame adjustable

The purpose of the airbags is to support aerostat balloon belly in moored condition and keep the aerostat balloon in horizontal position. The air bags are located above the control cabin of mooring structure. There are two metallic frames which are welded to the boom of mooring structure one on each side. Each frame consists of an inflatable air bag. These airbags provide cushioned support to aerostat balloon to keep it in horizontal position. The air bags during trial are shown in fig. 1 which shows a gap between air bag and lower profile of balloon.

The forces acting are shown in fig. 9 in case of balloon not supported by air bags. When there is no support by air bags, the balloon has always a tendency to bend about the outer ring of nose probe due to bending moment. The bending of balloon will depend on the direction of striking wind. The second aspect is that, sometimes there is a possibility of vertical gust to strike the balloon. The vertical gust will make the balloon to go down about the transverse axis of cradle. The downward movement of balloon about transverse axis of cradle may result in striking of balloon aft with ground or the mechanical part of mooring structure. This phenomenon again may cause balloon fabric damage/tearing.

To get rid of such adverse effects, the modification proposed in mooring structure is to make air bag frames adjustable i.e. the position of air bags in vertical direction can be varied up and down. By doing so, it will make air bags in contact with balloon all the time by adjusting its vertical location. The adjustable arrangement can be done mechanically or hydraulically. Various arrangements are also available off the shelf in the market.

3. ENHANCEMENT OF ADAPTABILITY

The present mooring structure has been designed to accommodate 2000 cum aerostat balloon. As the size of balloon changes, the location of close haul line cable confluence point and maximum diameter of aerostat balloon changes. Fabrication of different mooring structure for different sizes of balloons is an expensive adventure. The scope to accommodate a little variation of size of balloon on same mooring structure has been discussed in paper by Amit Kumar et al [6]. The present section is focused on further enhancement of adaptability of mooring structure. The idea is to accommodate aerostat balloon lying between 2000 cum to 3500 cum on the present structure.
As the size of aerostat balloon increases from 2000 cum, the location of close haul cable confluence point moves towards the aft side. The lateral span between both the close haul line cable confluence points and maximum diameter also increases. For effective mooring of aerostat balloon, the close haul line cable confluence point must lie towards the mooring tower side of the structure with respect to close haul winches and the lowest contour of balloon should not touch the mooring structure top metallic surface. Keeping close haul line cable confluence point left offers a pulling force on balloon for easy de-latching of balloon nose probe from cradle in case of onset of aerostat deployment and also provides aid to adjust the nose probe location during its latching to cradle. The contact of balloon to structure top metallic surface is important to avoid because it may damage the balloon fabric. It must be supported by cushioned air bags.

The modification proposed to enhance the adaptability of structure is to fabricate length pieces for mooring tower and close haul swing frames. By mounting length piece at the top of mooring tower caters close haul line confluence point shifting along the axial direction of balloon and also the increase in maximum diameter of balloon to not to touch the metallic top of structure. Mounting length pieces to close haul swing frame caters increment in lateral separation of close haul line cable confluence point. In moored condition, the close haul line cables should be tangent to balloon. If the lateral span of close haul winches not considered, the partial wrapping of close haul cable will occur with balloon, which may result in dimpling in balloon and will offer damaging effect.

Based on the design constraints, the length piece of mooring tower required to moore 3500 cum aerostat balloon on the mooring structure, designed for 2000 cum aerostat balloon, has been calculated and is coming out to be 1.52 m with respect to 5.5 m of original length of mooring tower. Total length of mooring tower in new configuration will be 7.02 m. In the same way, calculation for estimation of length piece of close haul swing frames has also been carried out and the length of length piece for both the frames is coming out to be 0.85 m each. Total span between the both the close haul winches becomes 10.2 m while the original structure has 8.5 m.

![Figure 11](image)

**Figure 11:** Solid model of mooring tower, left close haul swing frame and right close haul swing frames, their length pieces and bolted to respective frames

The present section will explain methodology to fasten the length pieces on mooring tower and close haul swing frames respectively. The two base plates on which the cradle is mounted have eight holes on each plate. Two similar plates are also welded at the top of mooring tower having holes at the same locations. The cradle is mounted at the top of tower by using suitable fasteners. To mount the length piece at the top, the first step involves folding the tower and bringing the tower top
in the reach of mechanic standing on the top surface of mooring structure. After that, cradle is required to be unbolted and one end of length piece is to be placed on the available welded plates. The length piece is fastened using suitable bolts. After fastening length piece, the cradle is fastened at the other end of length piece following the same methodology. The fig. 11 shows the original tower, length piece and length piece bolted on tower. The close haul swing frames are within the reach of mechanic standing on ground. Mounting of length pieces for close haul swing frames are easy and follows the same methodology.

The modified structure can accommodate 3500 cum balloon. The forces and moments transferred for this case has been carried out according to methodology and assumptions explained in section 2.1. The forces and moments are estimated based on the forces experienced by 3500 cum balloon. The results are shown in Table 2.

**Table 2: Estimated reaction on mooring structure after mounting length pieces**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction at tower top</td>
<td>$R_y = 2420$ N; $R_z = 17500$ N; $M_y = 350000$ N-m;</td>
</tr>
<tr>
<td>Resultant left close haul cable tension</td>
<td>$T = 8610$ N</td>
</tr>
<tr>
<td>Resultant right close haul cable tension</td>
<td>$T = 8610$ N</td>
</tr>
</tbody>
</table>

**Figure 12:** FEA result of structure after mounting length pieces Peak Von-Mises Stress = 481 MPa

The mooring structure FEA model development methodology and application of loads and boundary conditions have been carried out according to section 2.1. The FEA result in terms of von-mises stress has been shown in fig. 12. The peak Von-Mises stress observed is 481 MPa which is occurring on mooring tower and FOS corresponding to chosen material is 1.45.
The reactions have also been calculated for the mooring structure after incorporating the design modification proposed in section 2.1. Table 3 shows the estimated values.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction forces &amp; moment at tower top</td>
<td>( R_y = 2420 \text{ N}; R_z = 5227 \text{ N}; )</td>
</tr>
<tr>
<td>Resultant left close haul cable tension</td>
<td>( T = 8610 \text{ N} )</td>
</tr>
<tr>
<td>Resultant right close haul cable tension</td>
<td>( T = 24303 \text{ N} )</td>
</tr>
</tbody>
</table>

**Figure 12:** FEA result of structure after incorporating design modification suggested in section 2.1; Peak Von-Mises Stress = 114 MPa

The FEA for the structure has also been carried out. The FEA result in terms of von-mises stress has been shown in fig. 13. For this configuration of modified mooring structure, the peak Von-Mises stress observed is 114 MPa which is occurring on the main beam of boom and FOS is 6.14. The stress profile on structure in this case shows same pattern as was observed in section 2.1 results.

4. **CONCLUSION**

It is concluded from the above discussion and analysis results that mounting the bearing at the top of mooring tower will entirely eradicates the twisting moment transmitted from balloon to mooring tower. High twisting moment results in high stresses in structure. Incorporating the design modification and carrying out the analysis results in significant reduction of peak stress. Since the system is unmanned so such a huge FOS may result in over designing of system and hence it provides the scope to reduce the weight of structure too. The system is supported on single bearing so reduction of weight is of paramount importance to make the structure lighter. The second design modification facilitates the effective mooring of balloon on mooring structure. Four locations bi-directional gripping (two close haul line cable tension and two air bags contact force) is always more effective gripping than unidirectional two locations gripping to keep balloon horizontal in moored condition. The third design modification offers the utilization of same mooring structure for a series
of balloons lying between 2000-3500 cum range (medium size category). Fastening of length pieces to mooring tower and close haul swing frame and loads transferred from 3500 cum balloon to mooring structure results in quite high peak stress and FOS of 1.45. Due to unmanned system, the operation of system under 1.46 FOS is also recommended but the peak stress developed in structure restricts further increase in size of balloon. The remarkable advantage of implementation of first modification in this case is observed and also offers excellent result. Implementation of this design modification results in 114 MPa of peak stress and 6.14 FOS in structure. The system in this case is recommended to be operated under design survival wind condition too with 3500 cum balloon.

5. ACKNOWLEDGEMENT

The authors wish to express their sincere appreciation to their many colleagues who provided enthusiastic and dedicated assistance over the course of realization of system. Particular thanks are due to Sh. A. Pal, Sc ‘F’ & PD for his technical suggestion and valuable comments during the trial of system.

REFERENCES