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Aerodynamic influences on a tethered high-altitude lighter-than-air platform system to its behavior

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ABSTRACT

The goal of this study was to investigate the influence of aerodynamic factors on the static behavior of a tethered high-altitude lighter-than-air platform. The system design comprised a lighter-than-air vehicle and a tether cable, and the conceptual platform configuration of such a system is studied herein. Governing equations were derived to model the static behavior of the system, and the effects of aerodynamic lift and buoyancy were parametrically analyzed based on the advection distance of the platform under storm conditions. The aerodynamic lift and buoyancy of the hull were shown to have nonlinear effects. We further analyzed the influence of the aerodynamic drag created by the tether. Since this was shown to have a significant influence, we concluded that the cable should ideally have a cross-sectional shape resembling the airfoil of a heavier-than-air aircraft. However, it is sufficient to ensure that the drag coefficient is of the order of 10^{-1}.

1. Introduction

A firm lighter-than-air (LTA) vehicle for use in the lower stratosphere would provide a platform for a wide range of space activities. In the early 2000s, Japan Aerospace Exploration Agency (JAXA) conducted R&D on a free-flying LTA stratospheric platform. This was aborted because appropriate propulsion units with sufficient thrust were not available, and the high-altitude performance was inadequate. However, the potential merits of such a platform remain. A stratospheric platform would be the ideal launchpad for rocket-powered space transportation systems. An alternative approach is the tethered high-altitude platform, comprising an LTA vehicle[1] and a tether cable. This is similar to the rockoon systems [1] that were successfully used for space observation in the 1950s and 60s.

Stratospheric platforms could replace rockoon systems as high-frequency, high-load capacity space launch facilities. Fixed wing heavier-than-air (HTA) aircrafts have been tested [2,3], in which the rocket is released in the lower stratosphere. Current aircrafts have an upper payload weight limit of approximately 100 [t], but launch velocities near the speed of sound can be achieved in the lower stratosphere. However, rocket installation on and separation from HTA aircraft remains technically challenging. As rockoon systems have been successfully deployed in the past, the moored LTA platform is a promising alternative to HTA aircraft launch systems.

A tethered lower-stratospheric platform might also find applications in fields such as agriculture [4], defense [5], meteorology [6], environmental science [7], and telecommunications [8,9]. This type of platform offers a useful bridge between space and ground, as the influence of cloud cover can be ignored even at altitudes above 10 [km]. Such a system would have the following advantages:

- No thrust is required to maintain the altitude of the platform (thus, the system uses an LTA vehicle instead of an airship); no maintenance on the ground is also required.
- The tethered platform can hold the mooring position within the length of the rope.

The tether cable can be used to transmit electricity, and replenish the buoyancy gas. A cargo carrier called “a climber” can ascend and descend the cable, supplying payloads.

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[1] As general definitions, LTA vehicle (or LTA hull) refers to an unpowered aircraft, airship shows a powered one, and aerostat (or LTA aircraft) includes both. The terms are used accordingly.

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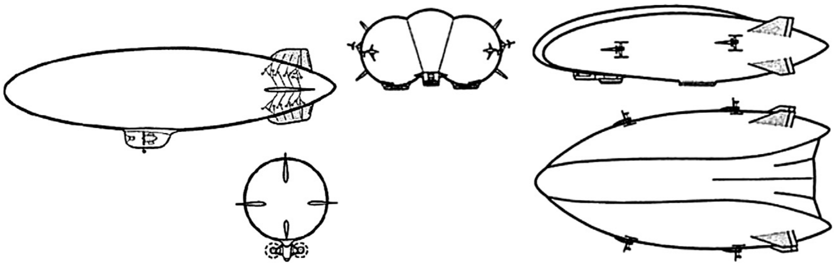

(a) (b)

Fig. 1. Typical geometries of (a) axisymmetric [24] and (b) hybrid [22] airships.

Mooring is based on the aerostat principle, which has been extensively researched since the 1970s [10–13]. Recent research efforts have addressed both practical low altitude applications by replacing balloons with weathervaning aerostats, and research into mooring of balloons at high altitudes.

The TCOM Corporation continues to conduct research on the first of these [14,15]. Advanced research is being carried out on the design of aerostats with novel conformations [16–18]. Attempts are being made to develop an airborne wind energy turbine system [19]. The altitude that can be achieved by tethered systems is limited by the weight of the tether, and this must be addressed if high-altitude systems are to be realized. Mooring at an altitude of 20 [km] has been reported [20], making lower stratospheric LTA platforms a practical proposition. In addition, hybrid aerostats have been developed [21,22] that take advantage of both buoyancy and aerodynamic lift. These are expected to replace conventional balloons in high-altitude applications.

The goal of the current study was to develop a high-altitude LTA platform. Our design is for an LTA vehicle geometry for lower stratospheric use. The body has a membrane structure, offering a flexible aerodynamic shape that is responsive to winds. To investigate the static response of the tethered system to wind pressure, we used the relationship between aerodynamic performance and the advection distance of the platform as the index. The study made a quantitative comparison of the aerodynamic performance of tethered high-altitude LTA platform systems to investigate the hull geometry.

The full research project involved the following steps:

1. We investigated the static behavior of the system under storm conditions to confirm the practicality of the proposed system [23].
2. We investigated the optimal geometry of the platform and produced a design concept for the LTA vehicle geometry. To minimize the weight while achieving the necessary volume, the hull was given a membrane structure. The research clarified the technical challenges that this poses in manufacture.
3. We defined a set of missions and developed the necessary equipment: the avionics and a climber. This next step will be to define practical manufacturing methods.
4. We explored the marketing and business models that would be needed to bring the system to market. This work is as necessary as the engineering stage.

In this paper, we discuss only the first of these steps. We start by introducing the static response to the drag on the tether and the aerodynamic lift and buoyancy of the LTA vehicle. Section 2 describes each component of the system. Section 3 derives the governing equations for the static response and provides the problem definition. Section 4 reports the analytical results. We present our conclusions in Section 5.

2. Tethered high-altitude platform system

2.1. Platform configuration

2.1.1. Selection of hybrid-LTA hull configuration

If the mooring point is set to the lower stratosphere, a spherical platform is practically enough. In this research, however, the LTA hull was designed to allow active control of the platform, efficient operation, and use in a wide range of applications.

JAXA's stratospheric platform has an axisymmetric airship shape [24–26] as shown in Fig. 1(a). In the mid-1990s, an alternative hybrid airship design concept was proposed. This is shown in Fig. 1(b).

The hybrid LTA hull combines the aerodynamic lift of an HTA aircraft with the buoyancy of an LTA vehicle. Since this produces a greater upward force than an axisymmetric hull, the hybrid LTA vehicle has outstanding stability and excellent aerodynamic performance, even at low speeds. In a conventional axisymmetric design, complex ballast loading and unloading operations are needed to adjust buoyancy, but the hybrid design renders that unnecessary. However, as the hybrid LTA hull is unstable under roll, measures must be taken to ensure stability when exposed to crosswinds. A steerable platform may require thrusters and control surfaces when operated in the lower stratosphere.

2.1.2. Aerodynamic performance of the aerostats

Fig. 2 compares the aerodynamic performance of the axisymmetric oval and hybrid aerostats. These approximate values provided the inputs to the governing equations for the static response of the system. The reference area of the LTA hull $S_{\mathrm{ref}}^{(\mathrm{hull})}$ was given by Eq. (1):

$$S_{\mathrm{ref}}^{(\mathrm{hull})} = V^{\frac{2}{3}}. \tag{1}$$

Here, V is the volume of an LTA hull filled with buoyant gas. The LTA vehicle is assumed to have the similar operational conditions, with a Reynolds number $Re \gtrsim 10^7$ and a Mach number $M \lesssim 0.2$. Both ranges are used when controlling an LTA vehicle near the ground. If we assume that the operation takes place in the lower stratosphere, the ranges should be extended as follows:

$$Re \gtrsim 10^6, \; M \lesssim 0.5. \tag{2}$$

The aspect ratio AR for an axisymmetric LTA hull is given by Eq. (3):

$$AR = \frac{4}{\pi FR}. \tag{3}$$

Here, FR is the aspect ratio when seen in plan and K is the induced drag, given by the following equation using the induced drag coefficient C_{D_L}:

$$K = \frac{C_{D_L}}{C_L^2}. \tag{4}$$

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