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Introduction

G.A. Khoury and J.D. Gillett

This book is intended as a technical guide to those interested in designing, building and flying the airship of today. While aiming towards the future, mention is made - where appropriate - of the experience of earlier years when these point up relevant information.

Modern airships employ advanced technologies such as composite materials, computerised numerical finite element structural analysis, computer aided design, modern electronic systems, fly-by-light controls and the latest theories in aerodynamics as well as stability and control. Some aspects of modern design are borrowed from other disciplines while in certain areas such as envelope fabrics and automatic docking systems the technology is specifically developed for the airship. Mainstream aeronautical data are available in numerous publications and are not duplicated herein. This book is, therefore, devoted to those aspects of design and operation that are particular to airships.

A distinguishing feature of airships is their reliance on a light gas for lift. It is, therefore, necessary that all those involved with airships have a good understanding of the basic principles of aerostatics. A brief outline of the subject is given in Chapter 2 on Basic Principles and a more detailed treatment is given in Chapter 8 on Aerostatics.

The bare hull of the conventional airship is of the classic streamline form. The conventional airship is, however, essentially a low-speed vehicle with the power requirement being approximately proportional to the cube of the airspeed. Higher speeds require a rapid escalation of weight and fuel consumption, while structure weight increases to meet the higher aerodynamic loading. Despite elegant streamlining, the aerodynamic drag of an airship is high. For a typical airship in steady axial flight, part of the total aerodynamic drag owes its origin to the bare hull and the remainder is generated by fins, engines and the control car. The latter appendages produce drag not only because of their own resistance but also through their interference with the flow over the main hull. The ‘bare hull’ drag could account for about 60-70% of the total, the proportion increasing with airship size as the appendages become smaller in relation to the hull. The aerodynamics of airships is briefly discussed in Chapter 2 (Basic Principles) and in more detail in Chapter 3 (Aerodynamics). Boundary layer control is also discussed in Chapter 14 on Improvements.

The most significant contribution to the development of the Stability and Control of the modern airship (Chapter 4), stems from advancements in computer technology. It
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is now feasible to undertake hitherto difficult, if not impossible, analysis and simulation which has enabled the attainment of new levels of insight and understanding. This in turn has encouraged the development of more detailed and more accurate aerodynamic and dynamic models of the airship culminating in extremely comprehensive non-linear simulation models. The digital computer is now also firmly established for the control of air vehicles and is the nucleus of the EFCS (electronic flight control systems), which can be used to very good effect in the airship. The euphoria, however, is tempered when it is realised that the performance of the EFCS is limited by the effectiveness of the aerodynamic control surfaces it drives. New developments may overcome this limitation to a certain extent by integrating control of the propulsion unit thrust vectoring into the overall control strategy.

The importance of good Weight Estimates and Control (Chapter 9) during all phases of the design of an airship, especially in the early stages, cannot be over-emphasised. The amount by which the airship is ‘overweight’ has a more direct effect on the performance than it would on a conventional fixed- or rotary-winged vehicle. Every additional kilogram of weight is one kilogram lost in available payload. Also, because an airship is very fuel efficient, any lost fuel capacity through this increased weight has an effect on endurance, which can be several orders of magnitude greater than for a heavier-than-air aircraft. Because endurance is one of the primary benefits of an airship - and in many cases its sole raison d’être - accurate preliminary weight estimation, and strict weight control, are vital.

Many of the major developments in materials of this century, particularly in the areas of specific strength, have been instigated by the aerospace industries. These developments/advances have fundamentally changed the design of aircraft. The introduction of such materials as lightweight strong alloys, fibre reinforced composites or honeycomb materials have all had major impacts on the design of aircraft structures while improvements in high temperature properties through alloy development and manufacturing methods (e.g. directionally cast, single crystal, or metal matrix composite turbine blades) have transformed engine technology. Most of these developments, and especially the introduction of stronger lighter materials (e.g. Kevlar) have helped airship design through lighter gondolas, nose cones, battens and tail fins. These consequences are a spin-off from material developments aimed at conventional airframe rather than as airship specific developments. However, it is major developments in textile engineering that have been uniquely responsible for advances in airship design, and for this reason Chapter 6 on Materials will consider those developments only. The advances in other structural materials have been adequately covered in other publications.

Airship Structures are described in Chapter 7. In earlier airships, stress analysis was conducted laboriously and manually with the risk of errors in the calculations ever being present. Structural analysis has since benefited considerably from the introduction of computerised finite element stress analysis methods. This added to the advances in material sciences, joining techniques, design aids, atmospheric awareness and aeronautics, allows the opportunity for efficient modern airships to be introduced at competitive prices.
Introduction

Systems are the physical means of achieving a designed function. They consist of components, control mechanisms, and sensors. Some systems are essential to the operation of others, such as those that are power sources; examples being electrical, hydraulic, and pneumatic. Airship systems include most of the major and minor groups found on all aircraft and a few that are peculiar to lighter-than-air aircraft. The items described in Chapter 10 on Systems can be found on most airships but the design, complexity, and location may differ considerably from type to type. Some systems may be peculiar to airships designed for particular missions, such as an inflight replenishing in military applications. The major systems not covered in Chapter 10, such as Stability and Control and Propulsion, are instead described in Chapters 4 and 5 respectively.

The issue of Ground Handling and Mooring (Chapter 11) is still seen as one of the most problematic areas of airship operation. Significant improvements are, however, taking place in this area with the development of thrusters and automatic docking systems. The future solution of ground handling and mooring requirements is very closely associated with the provision of adequate control to enable precise low speed flight to be undertaken reliably and safely. Given this, the remaining issues are concerned with ensuring that the structure of the airship is of adequate strength to resist the loading anticipated whilst the craft is moored.

The tasks of the pilot described in detail in Chapter 12 on Piloting are valid for small and medium sized non-rigid airships up to about 20 000 m³ volume. Non-rigid airships larger than this are likely to require amended techniques as they would exhibit different characteristics owing to their size, mass and inertia. Rigid airships will require different techniques owing to their greater options on ballast, mass, power plant and gondola (or car) locations, as did the great rigid of the past. The differences in piloting an airship from that of fixed- or rotary-wing flight includes lower speeds and slower responses, dependence on the availability of a ground handling party, and the possibly greater impact of certain meteorological conditions. Every landing is different owing to a combination of meteorological, locational and on-board factors. The airship pilot has, therefore, almost become a part-time meteorologist. It appears that pilots of rotary-wing and fixed-wing aircraft can make equally good airship pilots. However, some pilots who have spent 20 years or more flying at 400 knots may experience more than a little difficulty in adjusting to the low speed environment and indeed may never quite master airship flying. Airship pilots would, however, benefit from at least some basic flying training in heavier-than-air craft, alongside which they will eventually have to operate.

The payload limitations of heavier-than-air aircraft are, in most cases, imposed by airfield performance and weight, altitude, and temperature limited climb considerations. In contrast, the payload of airships is generally limited by the gas lift available in the climatic conditions prevailing at the cruise flight altitude. This means that the key cruise altitude, temperature conditions, payload and mission profile must be established very early in the design process, as alterations to these can cause big changes to volume. Only at extremely short airfields does take-off performance become a limitation. This and other comparisons with heavier-than-air aircraft are
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explained in Chapter 13 on Performance. Points of difference that are known to have caused misunderstandings are dealt with first.

Many of the airship’s principal operational problems are associated with the functions of buoyancy control, of fuel consumption and of interface movements - i.e. landing, mooring, load exchange and take-off. Certain modifications to the basic airship concept have been introduced in recent years which help to some extent in the above areas. An obvious example is vectored thrust - originally used on a number of early airships before World War II and then re-introduced for the Airship Industries Skyship series in the 1980s. Control effectiveness has also been improved, with reduced pilot effort, in experimental ships using fly-by-wire or fly-by-light transmissions in place of direct tension cables. The US Navy’s rigid airships of the 1930s also used exhaust water recovery, with some success, to reduce in-flight weight loss owing to fuel consumption, and this technique has also been proposed for modern diesel-powered projects, although such an installation does not yet appear to have flown. In addition to these proven expedients, many other theoretical approaches to buoyancy, fuel consumption and interface problems are constantly being proposed. Many of these are impractical, usually because of the weight penalty involved. Other ideas may have a marginal applicability in particular cases. Such proposals are made repeatedly by different agencies. Chapter 14 on Improvements, therefore, sets out to survey briefly, and to evaluate critically, some of the more common of these concepts.

Unconventionality may be attributed to an airship if a major feature of the design is significantly altered from the ‘conventional’, such as the overall shape, method of lift, source of power, structural configuration, type of lifting gas, or mode of control. These are described in Chapter 15 on Unconventional Designs which looks at hybrid (dynastats, rotastats and rotating hull airships), unmanned, hot air, solar and many other designs. A more detailed mathematical analysis is, however, given for the cases of the lenticular and solar-powered airships in Chapters 14 on Improvements and 16 on Solar Power respectively.

The future of airships rests to a large extent on their economic viability, which is closely related to their unique characteristics, the specific roles that airships are able to fulfil, and on their market potential. These are the considerations examined in Chapter 17 on Roles and Economic Considerations. The last Chapter 18 is devoted to Design Synthesis of the complete airship which integrates many of the disciplines discussed in earlier chapters - a necessary process for achieving satisfactory design.
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Basic Principles

E. Mowforth

INTRODUCTION

This chapter deals with some of the basic parameters of airship design and operation under the headings:

- Principles of Aerostatics
- The Aerostatics of the Airship (see also Chapter 8)
- The Aerodynamics of the Airship (see also Chapter 3)
- Unconventional Designs (see also Chapter 15)

Most of these topics will be developed further in later chapters; the objective here is to offer an overview that will help to tie the more detailed treatments together.

PRINCIPLES OF AEROSTATICS

The term ‘aerostatics’ refers to the static buoyancy of any kind of body immersed in the atmosphere, just as ‘hydrostatics’ describes the same effect in water. In both cases the upward buoyancy force is equal to the weight of fluid displaced, which in air may be taken as:

\[ B = V \rho_a \]  \hspace{1cm} (2.1)

where:

- \( B \) is the upward buoyancy force acting on the body
- \( V \) is the volume of the body
- \( \rho_a \) is the mean density of the local atmosphere surrounding the body

(\( \rho_a \) will have a slightly non-linear variation over the height of the body arising from the curvature of the natural atmospheric pressure gradient, but a mean value in Equation 2.1 will be accurate enough for all practical purposes).
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This buoyancy force acts on all bodies within the atmosphere but is usually negligible compared with the weight of the body itself; the buoyancy of a human being at sea level, for example, is only about 0.12% of body weight. If, however, the weight \( W \) of the body can be made less than that of the displaced air, then there will be a net upward lift \( L \) given by:

\[
L = B - W
\]  
\[\text{(2.2)}\]

The obvious case to be considered is that of a balloon incorporating a closed flexible envelope of volume \( V \) filled with a gas of density \( \rho_g \) which is less than \( \rho_a \), for example hydrogen or helium. The total weight of the system will then be:

\[
W = V \cdot \rho_g + W_e
\]  
\[\text{(2.3)}\]

where: \( W_e \) is the weight of the envelope and all its attachments. In any real case the volume of the structure represented by \( W_e \) will be so small compared with \( V \) that its buoyancy will be negligible, and Equations 1, 2 and 3 may then be combined to give:

\[
L_d = V(\rho_a - \rho_g) - W_e = L_g - W_o
\]  
\[\text{(2.4)}\]

In Equation 2.4, \( L_d \) is the ‘disposable lift’ of the gasbag; this is the lift available for crew, fuel, payload, ballast and supplies when the fixed ‘empty’ weight \( W_o \) has been subtracted from \( L_g \), the ‘gross lift’ of the gasbag.

The term \((\rho_a - \rho_g)\) represents the gross lift per unit volume, or ‘unit lift’, of the combination of gas in the envelope and air outside it. At sea level in the International Standard Atmosphere, if the lifting gas is at the same temperature as that of the ambient atmosphere, pure hydrogen for example offers a unit lift of 11.183 N/m\(^2\) (0.0711 lb/ft\(^2\)), while pure helium, being twice as dense as hydrogen, generates the slightly lower unit lift of 10.359 N/m\(^2\) (0.0659 lb/ft\(^2\)).

The actual mechanism of aerostatic lift is explained in Figure 2.1, which shows a sealed flexible envelope, assumed weightless, containing gas of density \( \rho_g \), at rest in an atmosphere of local mean density \( \rho_a \). The envelope is partially collapsed, its lower surface thus being drawn up into a flat plane on which the inner and outer pressures are equal. (This ‘flat’ appears at the bottom because the lifting gas is less dense than air; if it were more dense the flat would be at the top).

Starting from this level and working upwards, the internal and external pressures will both fall off with height and rates proportional to the respective densities, so that at a height ‘\( h \)’ above the base the internal pressure will have fallen by \( \rho_g \cdot h \) and the external pressure by \( \rho_a \cdot h \). The latter deficit will be greater, so that a differential pressure of \((\rho_a - \rho_g)h\) will act outwards across the envelope skin; this wedge-shaped pressure distribution spread over the internal surface of the envelope, will both prevent its collapse and furnish the resultant upward force represented by the ‘gross lift’ term \( V(\rho_a - \rho_g) \) in Equation 2.4. The pressure difference itself is small; at the top of a hydrogen gasbag 30 m (98 ft) high at sea level, for example, it will only reach
335 N/m² (7 lb/ft²), or about 1/300 of atmospheric pressure. With helium the pressure difference would be about 7% smaller.

The gross lift of a gasbag is determined by its volume $V$ and is totally independent of its shape. Free balloons, however, tend to favour a form approaching the spherical, because this offers both the smallest surface area to contain a given volume and the lowest skin tension for a given pressure difference across the skin; both factors facilitate a minimum-weight design.

So long as the gas in the envelope is free to expand - i.e. the envelope is only partially filled - and the gas and air temperatures remain equal, the disposable lift $L_d$ given by Equation 2.4 does not change with altitude. As the gasbag ascends the gas and air densities fall with decreasing pressure but the gas volume $V$ increases in the same ratio. Conversely, falling temperature tends to increase the densities but reduces the volume, so that the two effects again cancel out.

In any ‘real’ atmosphere the fall in pressure with altitude has a more pronounced effect than the corresponding fall in temperature, so that during ascent the gas will continue to expand until the gasbag is completely filled and no further expansion is possible. The altitude at which this occurs is termed the ‘pressure height’, because further ascent will cause the differential pressure across the skin of the gasbag to increase; the lift, however, will decrease.

![Diagram](image)

**Figure 2.1.** The mechanism of aerostatic lift.
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In conventional airships and balloons the gasbag skin, for minimum weight, is not designed to carry stresses far in excess of those encountered below the pressure height, which is therefore regarded as an operational ceiling. If this height is exceeded in an emergency, safety valves release gas to protect the envelope against pressure rupture. In recent years, however, high-altitude research has increasingly involved the use of unmanned 'pressure balloons' using envelopes that are strong enough to exceed the pressure height by a significant margin without rupture or gas release. These balloons are so designed that the net lift is positive, causing continuing ascent, above the pressure height; in rising further, however, the net lift falls to become zero at a predetermined equilibrium altitude; which the balloon will then, in theory, maintain indefinitely.

Figure 2.2. Variation of lift with altitude.
These effects of altitude are summarised in Figure 2.2, which shows a partially-filled gasbag leaving sea level at A and climbing with constant lift to the pressure height at B. Temperature equilibrium throughout is again assumed.

If the gasbag ascends beyond B its lift will diminish at a rate depending on whether or not gas is released - as through a safety valve - to prevent a build-up of differential pressure across the skin. If gas is released the lift will fall off to D, which, in effect, becomes the new pressure height for the reduced gas content; subsequent descent will take the gasbag down at constant lift to E. If no gas is released, however, the pressure - and hence the density - of the trapped gas will be higher than it would be if pressure were eased by valving off; lift will consequently be less, taking the ascent up to C rather than D. On subsequent descent the gas pressure will fall, and lift increase, as far as the point B; the lift will then remain constant at its original value back to A.

It follows that, for a given profile of atmospheric pressure and temperature against height, the pressure height will depend upon how much gas is in the gasbag to begin with. This quantity can be defined by an ‘inflation fraction’ \( I = V/V_0 \), where \( V \) is the effective volume of the contained gas and \( V_0 \) is the maximum volume of the gasbag itself. A particular value \( I_0 \) may be assigned to the condition at sea level.

As the air and gas densities are equally affected by pressure and temperature, it follows that:

\[
I_0/I = \rho_a/\rho_{a0}
\]  
(2.5)

and pressure height will then be that at which \( I = 1 \), i.e. \( \rho_a/\rho_{a0} = I_0 \). Numerical values can be assigned for a specific density profile, for example that of the hypothetical International Standard Atmosphere (ISA) as a reference base for altitude-related parameters (Table 2.1).

For a given value of \( I_0 \) the lift will remain constant up to the pressure height, as already explained. For the particular case where the gasbag is full at sea level (\( I_0 = 100\% \)) the gross lift will have its greatest possible value \( V_0(\rho_{a0} - \rho_{g0}) = L_{g0} \), and the disposable lift will also have its maximum value \( L_{d0} = L_{g0} - W_0 \). This, however, is a somewhat academic value, because when \( I_0 = 100\% \) the pressure height is at sea level and the gasbag cannot ascend without losing lift. In practice \( I_0 \) must always be less than 100\%, and the disposable lift is then - from Equation 2.4 - \( L_d = I_0L_{g0} - W_0 \). The ratio of actual to theoretical maximum disposable lift is then:

\[
L_d/L_{d0} = (I_0L_{g0} - W_0)/(L_{g0} - W_0)
\]  
(2.6)

In a typical airship the ‘empty’ weight \( W_0 \) is about half the gross lift at sea level, \( L_{g0} \), so Equation 2.6 becomes \( L_d/L_{d0} = 2I_0 - 1 \), and the resulting values are collected in Table 2.1 to show how quickly the disposable lift falls off with increasing pressure height. It follows that balloons and airships operate most effectively at low altitudes.
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Table 2.1. Pressure Height and Disposable Lift (ISA)

<table>
<thead>
<tr>
<th>$L_0$ %</th>
<th>Pressure Height</th>
<th>$L_d/L_{do}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>ft</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
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<tr>
<td>90</td>
<td>1085</td>
<td>3555</td>
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<td>5010</td>
<td>16440</td>
</tr>
<tr>
<td>50</td>
<td>6660</td>
<td>21845</td>
</tr>
<tr>
<td>40</td>
<td>8580</td>
<td>28155</td>
</tr>
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Assuming always that gas and air temperatures remain the same, an increase in atmospheric temperature has the effect of increasing the volume of the gasbag whilst decreasing the densities of gas and air in the same ratio; the lift then remains the same but the effective inflation fraction is increased and the pressure height therefore lowered. In the ISA ‘tropical maximum’ condition, for example, the air temperature is taken to be $30^\circ$C above ISA and this increases the low-altitude inflation fraction by about 10%. It follows that to reach a given pressure height in a tropical climate, the initial gas content - and therefore the disposable lift - must be less than for the same pressure height in the ISA. The converse is true in a cold climate; the ISA ‘Arctic minimum’ (ISA - $30^\circ$) causing a fall in inflation fraction of about 10% with a corresponding rise in pressure height.

A different temperature effect is that of ‘superheat’, in which exposure to direct sunlight, or a rapid ascent into a colder region, causes the gas temperature to rise above that of the surrounding atmosphere. This results in an increase in lift, firstly through the increase in volume and secondly through the decrease in gas density. The former effect predominates; near ISA sea level, for example, a superheat of $10^\circ$C will increase the lift of a helium gasbag by 4%, of which 3.5% is due to volume change alone.

An extreme case of deliberate superheat is of course the hot air balloon, which generates its lift by heating an envelope full of air by means of a propane burner at the open neck. For practicable temperatures the unit lift is small compared with helium or hydrogen; at $100^\circ$C, for example, hot air generates an ISA sea level lift of 3.1 N/m$^3$ (0.02 lb/ft$^3$), i.e. about 28% of that of hydrogen or 30% of the helium figure. Despite this low lift, necessitating relatively large envelopes, hot air has many operational and economic advantages over either gas for sporting balloons and certain types of small airship, in which categories it is now very widely used.