

Continuous-Positional Automatic Ballonet Control System for Airship

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ABSTRACT

This paper is devoted to a method of creating of the automated ballonet system for pressure control inside an airship envelope. Along with the study of the effects of the positional control system parameters, the authors develop novel control scheme. It is based on a new hybrid controller, which combines positional approach to forming the output control signal with a contour of continuous correction of input signal, which defines the pressure drop on the surface of the envelope as a function of the flight altitude. This approach allows reducing the effect of self-oscillations of airship envelope internal pressure on the flight altitude. In order to prove the new approach the mathematical model is being obtained. The results of the derivation and simulations of the control system operation are presented in this paper.

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INTRODUCTION

Most rigid and semi-rigid airships need regulation of pressure of buoyant gas (BG) in envelope while changing of altitude of flight. The main instruments of this pressure regulation are devices called ballonets, which form ballonet system (BS). Ballonets are air bags with flexible shell. The volume of these bags depends on the total volume of the airship hull and maximum altitude of flight. BS is especially important for soft airship designs due to the following reasons. It firstly creates overpressure in the hull, and secondly provides rigidity of hull by creating internal tension. Thirdly BS protects material of the hull from excessive stress and burst. In some airship designs BS influences the parameters of the buoyancy of the whole airship and could be used to control angles of attack or roll. BS of these airships has two or more ballonets.

Because of such critical functions of BS, it cannot work without automatic control of its parameters. For the purpose of the construction of the automatic control system (ACS) a mathematical model of the BS as the control object is required. The task of controlling of BS, despite its apparent simplicity, is associated with a number of constraints that depend nonlinearly on the parameters of the flight of the

airship, and the parameters of the environment. Mathematical model of BS should be most adequate to properly take into account all the constraints necessary. This makes the task of construction of mathematical model (MM) and studies the properties of this model extremely crucial and urgent.

ORGANIZATION OF BS AND PROCESSES IN BALLONETS

Stability and operational safety of inflated airship is provided by excess pressure in the hull. When using BS this overpressure is created by inflation of ballonets with additional air (see [Figure 1](#)). Using of flexible ballonets as containers, storing the air, provides this effect. Ballonet envelope is airproof and isolates airship hull containing the BG from the outer air.

While ballonet system controls the pressure in the hull of airship, it produces disturbance on work of flight control system of airship. This is due to the fact that the change of air amount in ballonets changes the overall airship mass, as well as the distribution of mass within it. Consequently, inertia of the airship and its moment of inertia change. This fact requires the dynamic identification of the parameters of the BS, which is impossible without MM. A more complex

problem arises in multi-ballonet systems because mass redistribution due to the different amount of air in each ballonet should be considered (Fig. 1).

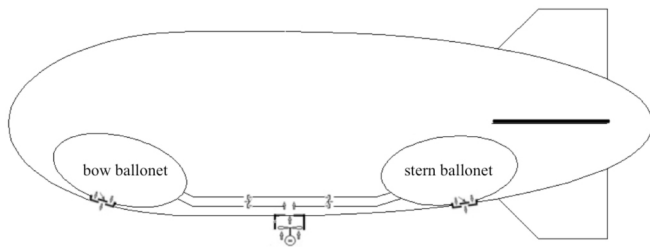


Figure 1. Airship with double-ballonet system and additional pitch control function

Scheme of airship as a controlled object (CO) is shown in Fig. 2.

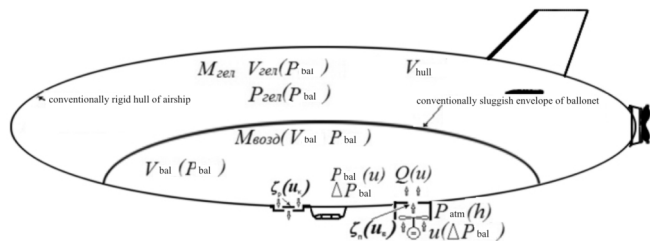


Figure 2. The scheme of the airship ballonet system

Airship envelope is a multi-layer composite of polymeric materials. It is very strong and is almost non-stretchable. So when inflated or anchored on a rigid frame envelope is almost rigid. With this structure, stability and operational safety of inflated airship is provided by varying of the amount of air, and hence pressure, in ballonets. Ballonets interconnect to the atmosphere through the intake and exhaust valves (labeled InpV and OutV at Fig. 2). Air input channels of ballonets are equipped with fans. Valves and fans are controlled with automated control system that keeps necessary (defined based on envelope material properties) overpressure ΔP_{bal} in ballonet relative to the ambient air pressure P_{atm} .

Ballonet system regulatory process proceeds as follows. With increasing altitude the external pressure of the atmosphere decreases. In this case, there is a gradual replacement of the air, accumulated in ballonet, with expanding buoyant gas. When airship descending external pressure of the atmosphere on the contrary increases, which leads to a gradual compression of BG. This requires replenishment of air in ballonets. Thus, when changing altitude airship pressure difference between the BG in airship envelope and the atmosphere changes and this difference must be restored. In addition, it is necessary to limit the vertical rate of climb or descent of the airship. This is due to the limited capacity of valves and the limited capacity of the fans.

This process is possible until the pressure outside the airship hull not becomes so small that expanding buoyant gas

in the hull displaces all the air from ballonets. In this condition, the pressure produced by the fan ΔP_{fan} cannot resist the pressure P_{BG} . Formulate the condition corresponds to the case when the air amount in ballonet becomes zero. Emptying ballonets is very dangerous to the integrity of the airship hull. Airship's further rise could lead to an unacceptable increase of pressure difference and burst of its envelope. Therefore, the problem of reliable tracking of pressure in ballonets $P_{bal}(h)$ and pressure of BG $P_{BG}(h)$ arises. This operation is carried out by means of so-called dynamic estimators (identifiers), which are based on the mathematical model of the BS.

Thus, mathematical model, applicable for calculations and defining control to actuators of BS, is needed.

PROBLEM FORMULATION

The goal is developing a mathematical model of the multi-ballonet system with minimal assumptions associated with the idealization of the properties of materials, airship construction and gas involved in the process: buoyance gas and air. We have considered only the following assumptions (of many other possible):

a. Inflated airship hull is assumed rigid due to the internal pressure, so airship hull volume does not change, $V_{hull} = const$;

b. Ballonets walls, separating internal air from buoyance gas in the airship envelope, are considered as not resisting any action, no matter how small the difference in pressure between the BG and air in ballonets is;

c. At steady-state of volumes of BG and air and non-zero reserve of air in ballonet, their pressures are equal: $P_{ball}(h) = P_{balj}(h) = \dots = P_{BG}(h)$, which is result of nonresistance of ballonets walls;

d. Due to the pressurization system (fan at Fig. 2), $P_{bal}(h)$ in the equilibrium state is the sum of the atmospheric pressure $P_{atm}(h)$ and excess pressure, which is provided by the fans $\Delta P_{bal} = \Delta P_{fan}$, $P_{bal}(h) = P_{atm}(h) + \Delta P_{fan}$;

e. The above assumptions a), c) and d) together result in the fact that the volume of ballonet could be calculated by the difference between V_{hull} and the volume occupied by BG at the current $P_{bal}(h)$, ie $V_{bal} = V_{hull} - V_{BG}$;

f. Transition process, caused by opening of the intake valves and turning on fans or closing the exhaust valves with fans off, is significantly faster than the transition process of filling ballonets and pressure change during airship ascent and descent;

Based on the assumptions made, it is possible to construct a sufficiently adequate mathematical model of the ballonet system and whole airship.

MATHEMATICAL MODEL OF THE BS

Building a Static Mathematical Model of the BS

Taking into account assumptions c) and d) and assuming presence of some nonzero amount of air in BS, for the equilibrium state of airship,

$$P_{bal}(h) = P_{atm}(h) + \Delta P_{bal}(h) = P_{BG}(h), (M_{bal}(h) > 0) \quad (1)$$

where $M_{bal}(h)$ - the mass of air contained in ballonnet at a given height, and $P_{atm}(h)$ denote pressure dependence on altitude.

For tropospheric altitudes this dependence is good described by known "barometric formula" [1]

$$P_{atm}(h) = P_0 \cdot e^{-\frac{\mu_a \cdot g \cdot h}{R \cdot T(h)}} \quad (2)$$

$$T(h) \approx T_0 + t_0 - 0.0065 \cdot h, \quad (3)$$

where P_0 is pressure at sea level (usually $P_0 = 101325 \text{ Pa}$); μ_a - the molar mass of air (at sea level $\mu_a \approx 0.029 \text{ kg/mol}$, but at large tropospheric and stratospheric altitudes μ_a deviates from this value, and should be calculated accordance to standard atmosphere formula; $R = 8.31 \text{ J/mol} \cdot \text{K}$ - universal gas constant; $T(h)$ - temperature, varies with altitude and weather conditions; $T_0 = 273 \text{ K}$ - temperature in Kelvin degrees corresponding to 0 Celsius degrees; t_0 - the calculated temperature at sea level; $h(t)$ - current airship altitude in meters; $g = 9.807 \text{ m/s}^2$ - acceleration of gravity (dependence of g on the height of the flight can be neglected because of its incompatibility with the radius of the Earth).

Condition correctness of formula (1) is the following constraint on h :

$$h \leq h_{crit} : M_{bal}(h) = 0 \quad (4)$$

This is due to the fact that in-hull pressure (1) depends from h , according to (2). In-hull pressure is formed by two different reasons - pressure self-leveling according to Pascal law and the automatic overpressure control. This relationship persists until BG (filled before airship start) fills entire airship envelope. As a result, all the air will be replaced from ballonnet.

Airship state at height of flight h_{crit} is critical because

$$\forall h \geq h_{crit} \rightarrow P_{BG} = const. \quad (5)$$

Condition (5) appears from assumption a). Consequently, pressure of BG in the constant volume of airship hull V_{hull}

would not be changed according to the laws of thermodynamics, when climbing upper then h_{crit} . Since $P_{atm}(h)$ decreases when lifting, the pressure difference between envelope and atmosphere

$$\Delta P_{hull}(h) = P_{BG}(h) - P_{atm}(h) \quad (6)$$

will increase.

Achieving critical value $\Delta P_{hull} = \Delta P_{crit}$ leads to the destruction of the envelope.

This is unacceptable so MM of BS describes the state of the airship under restriction

$$h \leq h_{crit} \rightarrow \Delta P_{hull}(h) = \Delta P_{bal}(h) \quad (7)$$

Thus, using the basic physics laws, we obtain the following system of equations describing the static model of BS:

$$\begin{cases} P_{BG}(h) = P_{atm}(h) + \Delta P_{bal}; \\ V_{BG}(h) = \frac{M_{BG} \cdot R \cdot T(h)}{\mu_{BG} \cdot (P_{atm}(h) + \Delta P_{bal})}; \\ V_{bal}(h) = V_{hull} - V_{BG}(h); \\ \Delta P_{hull} = \Delta P_{bal}; \\ M_{bal}(h) = \frac{\mu_a \cdot V_{bal}(h)}{R \cdot T(h)} \cdot P_{BG}(h). \end{cases} \quad (8)$$

To identify a whole state of airship two parameters are the most important. For operation safety it is important to know pressure difference $\Delta P_{hull}(h)$, which is determined by the expression (6), or by equations 1 and 4 and the system (8). To estimate the dynamic properties of the airship we need to know total weight, which varies only with the change of air mass in ballonets. Model of change of air mass in ballonets with height is given by the following expression:

$$M_{bal}(h) = \frac{\mu_a \cdot (V_{hull} \cdot \mu_{BG} \cdot (P_0 \cdot e^{-\frac{\mu_a \cdot g \cdot h}{R \cdot T(h)}} + \Delta P_{bal}) - M_{BG} \cdot R \cdot T(h))}{R \cdot T(h) \cdot \mu_{BG}}, \quad (9)$$

which is obtained by the transformation of the system (8).

At constant during flight body mass M_{hull} (we don't take into account mass change due to atmospherically condensation and cargo weight change here) and weight of lifting gas M_{BG} , expression for the total mass of the airship, which is necessary to know when constructing of airship dynamics equations, takes the form:

$$M_{aircr}(h, \Delta P) = M_{hull} + M_{BG} + M_{bal}(h, \Delta P) \quad (10)$$

$$M_{bal}(h, \Delta P) = \sum_n M_{bali}(h, \Delta P) \quad (11)$$