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Strategies for reduction of energy consumption during ascending and descending process of modern telescopic HAPS aerostats

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Abstract. In this article, the authors propose and investigate a new concept of HAPS aerostat design in a modular form, which allows for sequential increasing or decreasing of the total volume, up to the desired size. In its initial form, the aerostat has relatively small dimensions but its central cylindrical part is multi-segmented and can be easily extended. The application of controllable construction couplings enables precise control of the aerostat expansion process and significantly improves its vertical mobility. The paper describes details of telescopic aerostat construction, presents a mathematical model of its vertical motion and investigates numerically two volume control strategies aimed at maximization of operation efficiency and minimization of operation cost. The results obtained reveal the main problems that have to be addressed and the factors that play a key role in design of such telescopic aerostats and control of their vertical mobility.

Key words: helium airship, control of vertical mobility, reduced energy consumption, optimum ascending and descending path.

1. Introduction

Over the last 30 years, a few projects have been conducted in different parts of the world whose purpose was to build numerous objects operating in the stratosphere in order to carry communications and monitoring equipment for intelligence, surveillance and reconnaissance missions (so-called HAPS – High Altitude Pseudo Satellites). Currently, more and more companies, mainly those specializing in telecommunications or remote monitoring, are working on development of technologies enabling applications of flying objects located 20–30 km above the sea level, cf. [1], [2] and [3]. Ultimately, they are intended to be unmanned aircrafts powered by solar energy, having the ability to move both in the vertical and horizontal directions, which may persist in space between several months and 1–2 years without landing on the ground. In parallel to development of stratospheric airplanes (e.g. Zephyr S, [4]), many countries are working on a new generation of airships filled with hydrogen or helium, also with electric drive.

Such airships are usually built as classical systems, i.e. as systems where the external volume of the airship is constant and does not change during its ascent from the ground level to the level of the stratosphere. Examples of such solutions include: the Russian concept of Berkut (see Fig. 1a), Lockheed Martin's ISIS (see Fig. 1b) and the French Stratobus (see Fig. 1c).

As a rule, these are objects with very large dimensions – from approx. 100 m to approx. 300 m in length, with diameters ranging from approx. 30 m to approx. 50 m. In this type of construction, the required flight altitude is obtained by changing pressure of the gas inside internal tanks, which causes a change in their volume.

Another solution, where the external volume of the airship is changing during increasing the ceiling is, for example, the US construction of HiSentinel80, in which at the low altitude the

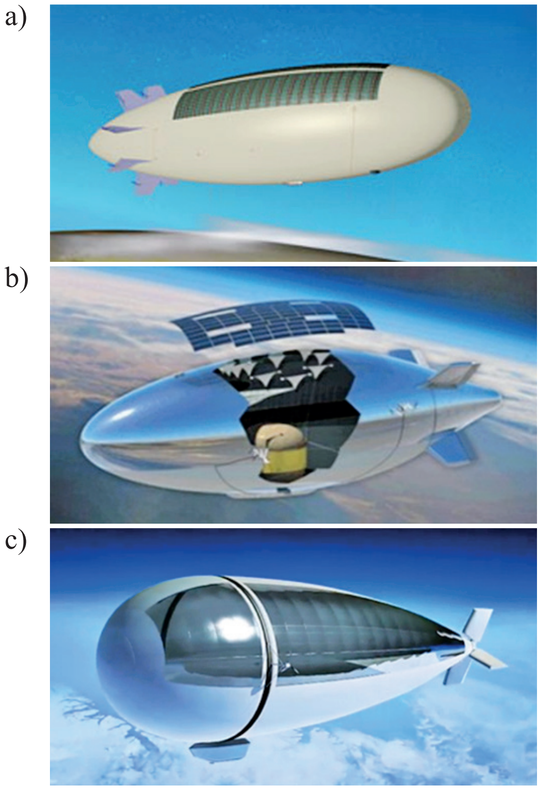

Fig. 1. a) The concept of the HAA Berkut [5], b) – Lockheed Martin's airship ISIS [6], c) The airship of Thales Alenia Space – Stratobus [7]

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Fig. 2. HiSentinel 80 airship [8]

airship has the smallest volume (Fig. 2a), and in the stratosphere its volume is about 12 times larger (for H = 20 km) – Fig. 2b. In this case, the elevation control is carried out by changing the gas pressure (helium or hydrogen) inside the airships.

There are also objects operating in the stratosphere in the shape of a classic balloon (sphere). In order to reach a height of about 20 km, they must increase their volume approximately 12–15 times in order to obtain aerostatic buoyancy force providing the required lift.

Despite the large number of programs currently implemented in the world and huge expenses related to the construction of stratospheric airships, a number of technical problems remain unresolved, which affects the desirable utility of such a platform [9]. In Europe, the first HAPS4ESA workshop took place at ESA Netherlands: "HAPS4ESA – Towards an ESA Stratospheric High Altitude Pseudo-Satellites (HAPS) Program for Earth Observation, Telecommunications and Navigation", organized by the European Space Agency and dedicated to the stratospheric HAPS, in October 2017 [10].

Construction of diverse types of airships and development of control strategies for their vertical and horizontal motion was also the subject of many academic research works. In particular, a review of research and development of various types of standard non-rigid, semi-rigid, and rigid airships as well as unconventional airships with unique shape design, operation mode, or payload capability is presented in papers [11] and [12], which also review techniques of modelling, structural analysis and optimization of the airship or plane body.

Among more detailed research works it is worth to mention paper [13], devoted to detailed investigation of airship aeroelastic behavior using fluid-structure interaction approach. In turn, amid papers dedicated to optimization of the airship bodies one should distinguish the sophisticated approach based on aerodynamic design and genetic algorithms presented in [14], as well as multi-objective optimization of the envelope with imperfections described in [15].

Another branch of research concerns development of the control strategies for vertical and horizontal motion of the airship. The fundamentals for development of the control strategies are papers dedicated to modelling and simulation of dynamics of airship motion in the stratosphere. Simpler approaches are applied for rigid heavy-lift airships [16], while more sophisticated methods are adopted for flexible deformable airships – see e.g. [17] for a description of general modelling methodologies and [18] for application of the analytical rules and method of differential pressure gradient for simulation of compression and wrinkling during the ascent process. Moreover, general benefits of optimization of the trajectory of airship flight are described in [19].

Substantial research efforts are dedicated to individual technical solutions and development of control algorithms for ascents and descents of the airships. In particular, a guidance-based path-following control system with cascaded structure consisting of a guidance loop, attitude stabilization loop and velocity tracking loop, dedicated to an under-actuated stratospheric airship was proposed in [20]. Moreover, the problem of trajectory tracking in the presence of wind gusts was approached by applying Lyapunov theory and universal stabilizing feedback, leading to robust control laws with respect to uncertainties of the model and external parameters [21]. In addition, optimum ascent trajectories using wind energy in order to achieve minimum-time and minimum-energy flights were determined by defining an optimum control problem with terminal and path constraints and using the direct collocation method to solve the parameter optimization problem [22]. In paper [23], nonlinear compensation introduced into the control loop allowed to decouple the nonlinear system of equations of airship motion, while an adaptive law based on feedback linearization was used to execute autonomous tracking of desired time-varying trajectory of an airship.

In paper [24], a non-adaptive controller for a class of an airship is proposed. The velocity tracking controller is expressed in terms of the transformed equations of motion, in which the dynamics of the system is taken into account and can be applied for controlling a fully actuated airship. Paper [25] proposes an adaptive trajectory tracking controller for fully-actuated robotic airships with parametric uncertainties and unknown wind disturbances by applying dedicated adaptive control strategy ensuring the asymptotic decrease of trajectory tracking errors. Finally, paper [26] introduces integrated guidance and control path following for the stratospheric airship based on redundant control systems, including the planar position tracking controller, velocity regulator and altitude stabilizations.

The problem strongly connected with control of airship motion is the optimum design of the propulsion system. Such problem is addressed e.g. in paper [27], which presents optimization-based development of the power unit for a high-altitude airship providing the largest effectiveness of propulsion and minimum system weight. Another important issue is the amount of external energy required to obtain the desired airship trajectory. For example, paper [28] proposes high-altitude platforms utilizing solar cells as novel radio transmission systems, while paper [29] introduces application of HAPS as a platform for providing third generation (3G) mobile services. Both the above-mentioned platforms are expected to be relatively stable or follow the desired trajectory over a long period of time. Therefore, zero- or low-energetic control of actual HAPS location is required in both these applications.

The above presented literature review reveals that one of the main problems related to application of stratospheric variable-volume HAPS aerostats is the lack of technical solutions providing exact tracking of the assumed vertical path while simultaneously ensuring low energy consumption and minimization along with required helium usage. The first challenge in this field is the development of the system for changing the actual volume of the aerostat and independent modification of its internal pressure, which enables precise control of generated buoyant force and reduction of stresses in the aerostat envelope. The other unresolved problem is the development of strategies for volume and pressure control aimed at realization of the assumed vertical path either with maximum efficiency or minimum energetic cost.

The paper addresses the above formulated challenges by proposing an adaptive telescopic aerostat, which is equipped with a coupling mechanism enabling arbitrary pressure-induced volume modifications and additional pressure tank with a compressor and valve allowing to obtain the desired pressure difference between the aerostat and atmosphere. The results of the simulations presented in the paper concern the altitudes of up to 5 km, which may correspond to monitoring ecological changes in the environment beneath aviation-free areas but requires only 1.6 times the volume change. However, the proposed design of the aerostat can be potentially used also at distinctly higher altitudes. This requires limiting the payload as well as ensuring the possibility of more than 12 times the volume change to reach the altitude of 20 km. Such goal may be achieved by increasing the number of aerostat segments or connecting the aerostats into a larger construction, as presented in the further part of the paper.

The remaining part of the paper is organized as follows. The second section presents the general idea of telescopic Heli-Caps, while the third section describes technical details of the aerostat design. The fourth section presents a mathematical model of the vertical motion of the aerostat and formulation of the corresponding control problems aimed at realization of the assumed altitude path. Two different control strategies, providing maximum control efficiency and minimum control cost, are proposed and precisely analyzed in the sixth section. The paper finishes with general conclusions and expected further stages of telescopic HAPS development.

2. General idea of telescopic HAPS

The proposed concept for vertical air mobility is based on the reversible, telescopic option for the aerostat volume modifications, where the crucial feature is a system composed of structural sections connected via linear guideways and of a clamping mechanism (fixing or releasing relative movement between guideways of telescoping sections) and an additional helium tank (ballonet), allowing for controllable release or absorption of gas inside the aerostat [30].

The above Heli-Caps concept offers also a new approach to the HAPS aerostat design in a modular form, allowing for sequential increasing or decreasing of the volume, up to the desired size. In its initial form, an aerostat has relatively small dimensions and its central, cylindrical part can be multi-segmented. Such telescopic construction of an aerostat allows for folding and unfolding of the individual sections and precise adjustment of the total aerostat volume. Additionally, in order to take control over the repeatability of the aerostat shape during different phases of its ascending/descending and to become less vulnerable to the wind drift, the controllable construction couplings allowing for blocking and releasing the clamping mechanism for changing the volume of the aerostat are intended to be applied (cf. Fig. 5).

Various potential applications for the proposed Heli-Caps flying objects are the following:

- Stratospheric aerostats HAPS, ascending from the ground / descending to the ground,
- Deployment of large stratospheric aerostat HAPS via attaching numerous Heli-Caps modules,
- Distribution of Heli-Caps via a jet-aircraft (caps ascending from the level of 13 km),
- Capsules supplying stratospheric HAPS aerostats with additional helium, making use of auto-docking (distributed via a jet-aircraft),
- Safe, no parachute, emergency dropping capsules (distributed via drone or general aviation aircraft), slowing down velocity before touching the ground.

Distribution of stratospheric Heli-Caps via a jet aircraft (13 km) provides for an important structural difference, as only 4-times volume scaling up (instead of 12 times) is needed to reach the desired stratospheric level of 20 km.

In this article, the authors present results of numerical analyses of the vertical motion for the model of aerostat telescopic design, which illustrate the issues and problems that need to be addressed while building a real object of this kind. The results of the presented analyses, even though regarding the low-altitude aerostat, not only reveal the complexity of the problem, but also indicate the factors that play a key role during developing the telescopic aerostats. In the proposed HAPS design, one of the issues to be addressed is the minimization of the total cost required for controlling vertical HAPS mobility, understood as the total amount of energy required for transfer of helium, its maximum mass flow rate or the required amount inside the additional storage tank. Our numerical simulations show that the amount of energy needed can be significantly reduced by means of controlling the volume of HAPS and helium flow in a proper way. In this manner, it is also possible to reduce the mass of helium and masses of electric batteries and solar panels needed for operation of the Heli-Caps (which increases operational payload).

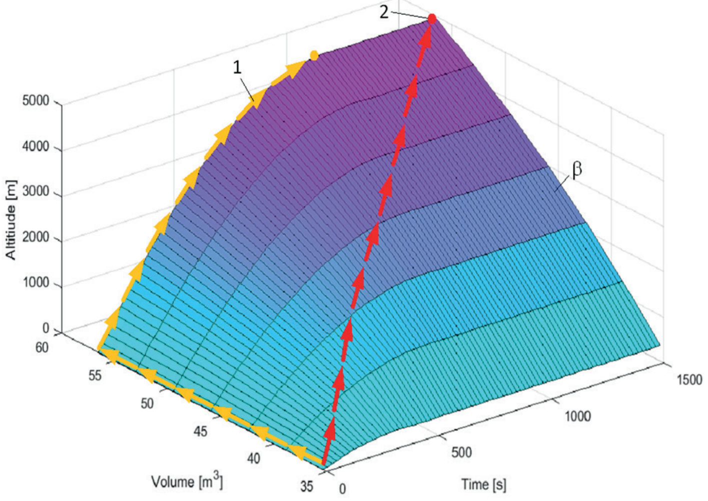


Fig. 3. The buoyant surface of the telescopic Heli-Caps: 1 – fast path, 2 – energetically efficient path

The buoyant surface β (in the 3D space: the aerostat volume, its altitude and time, cf. Fig. 3) determining actual, natural equilibrium position for the aerostat with properly tuned volume will play a crucial role in optimization of the ascending / descending path in vertical mobility strategy. The left part of the plot indicates natural dynamic equilibrium positions (ascent at constant volume), while the right side of the plot indicates natural static equilibrium positions (final altitude for given constant volume). In general, faster vertical mobility (path No. 1) requires faster change of volume and more intensive helium transport between ballonet and the aerostat itself (from the ballonet going up to the ballonet going down). This, however, can be costly due to higher technical requirements for the compressor applied.

Smooth volume modifications extended over time (path No. 2) translate into reduced vertical velocity, accelerations and requirements for the compressor effectiveness. Both types of paths will be precisely determined and analyzed in later parts of the paper.

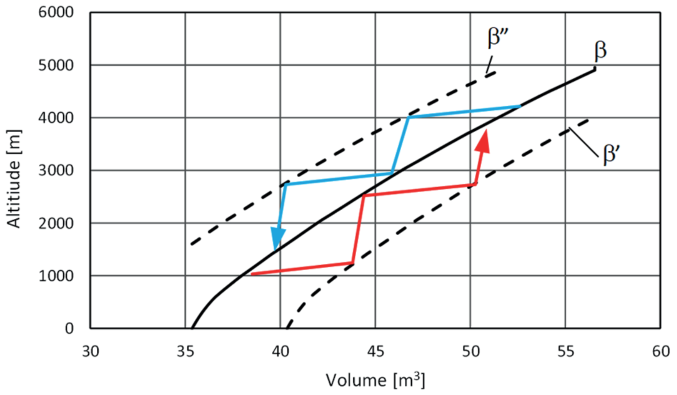


Fig. 4. Example of ascending / descending path with constraints β' and β" resulting from the assumed required over- / underpressure and compressor maximum helium mass flow rate

However, permissible changes of aerostat volume during the process are affected by the required pressure difference between the aerostat and its environment and by the maximum mass flow rate of helium between the internal tank and the aerostat, resulting from the compressor applied. As a consequence, one can introduce two approximately parallel surfaces β' and β", indicating constraints imposed on vertical motion of the aerostat resulting from requirements concerning over- / underpressure and helium flow. These surfaces are schematically illustrated in Fig. 6, which shows exemplary non-ideal realization of path No. 2 in two dimensional space composed of the aerostat volume and its altitude. In this case, the path on natural buoyant surface is not exactly followed, but instead the obtained aerostat path is confined by the lower or upper constraint surface during the ascent and descent process, respectively.

3. Basic features of telescopic HAPS design

3.1. Aerostat construction. The design of the HAPS adopted for further analyses regarding its ascending and load-carrying capacity is schematically presented in Fig. 5. In Fig. 5a, the HAPS is in its initial and extended form. The construction consists of a cylindrical housing (e.g. reinforced by axial and circumferential ribs) of diameter D and length D, multi-layered, similarly to the telescopic cylinder. At the ends of the cylindrical section, there are two parts in the shape of a hemisphere with diameter D. The HAPS offers a possibility of volume change by means of changing the length of the cylindrical section from the dimension of D to the maximum dimension of 2D. This is possible due to the construction (cf. Fig. 5a) of this section, consisting of the inner (1) and outer segments (2), which are sliding along linear guideways (7) whose relative motion can be blocked by the piezoelectric or electric piston actuator (3). The linear guideways and the piezoelectric actuator create the clamping mechanism (cf. Fig. 5b), which can be used for precise control of the aerostat main tank volume. In the case being considered, the construction of the clamping mechanism can be based, for example, on amplified piezoelectric actuator APA 120ML produced by CEDRAT, which allows to generate adequate values of friction forces. Instead of the above-described mechanism, another solution can be used, such as linear motors or other linear mechanical devices.

One of potential problems of the described aerostat design can be gas leakages occurring between inner and outer segments. To prevent leakages, it is possible to apply rubber sealing (e.g. in the form of elastic membrane) or a thin internal balloon filling the space between outer and inner segments. Although the reliability of the clamping system, including precise control of friction between linear guideways and the piezoelectric actuator, can be treated as a potential problem, a similar system based on friction control by piezoelectric actuators was successfully applied in [31]. Moreover, only a general idea of the clamping system is proposed and other solutions, e.g. those based on rotational clutches, can be considered.

In the case of a maximum expanding of the HAPS, its overall length, together with both hemispheres at the ends, amounts

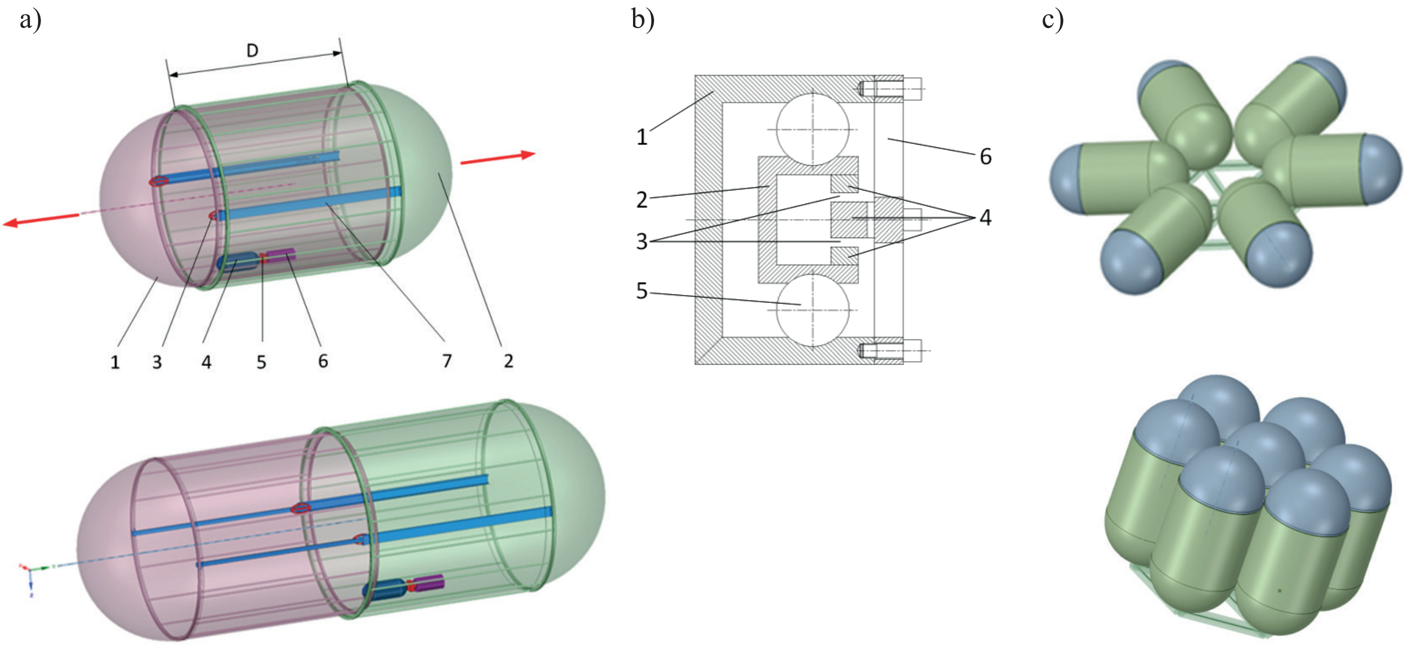


Fig. 5. Scheme of HAPS design: a) aerostat in initial and extended form: 1 – inner segment, 2 – outer segment, 3 – piezoelectric actuator, 4 – additional helium tank, 5 – valve controlling helium flow, 6 – compressor; lower drawing – aerostat in extended form, 7 – linear guideway; b) clamping mechanism: 1 – external linear guideway, 2 – internal linear guideway, 3 – clearance, 4 – friction lining, 5 – bearing balls, 6 – amplified piezoelectric actuator (APA), c) HAPS assembled from numerous Heli-Caps modules

to 3D, and its diameter – to D. In order to achieve proper mobility, aerostat is equipped with an additional gas storage tank (4) with an additional amount of pressurized helium. This additional tank serves the purpose of balancing the pressure difference outside and inside the aerostat, if such a need arises. The value of overpressure and underpressure can be used to generate the proper value of internal or external forces needed to fold and unfold Heli-Caps. Additionally, too large value of differential pressure can lead to damage of the aerostat's envelope. In order to reduce helium losses caused by its release into atmosphere, the HAPS is equipped with a compressor (6) and a valve (5) controlling the flow of helium between the main and additional gas tanks. Application of the additional storage tank, the compressor and the valve allows to increase or decrease the pressure difference between the aerostat and the atmosphere according to the assumed control strategy.

3.2. Assumed aerostat parameters. In the course of the analyses presented in this work, the following data of the aerostat model (HAPS – see Fig. 7) were adopted:

- diameter and length of the cylindrical part D = 3 m,
- maximum length in the contracted state 2D = 6 m,
- maximum length in the expanded state 3D = 9 m.

At these dimensions, the utility volume of the HAPS equals to:

- in the contracted state $V_{g0} = 35.34\ \text{m}^3$,
- maximally, in the expanded state $V_{ge} = 56.55\ \text{m}^3$,
- initial mass of the helium filling the aerostat under the conditions of the aerostat take off (atmospheric pressure and density corresponding to the altitude of 0 m) – 5.97 kg.

To conduct the analyses, it is also necessary to adopt initial parameters related to the aerostat's framework design and its envelope. The following parameters were adopted:

- unit mass of the aerostat envelope surface – 0.15 kg/m^2,
- unit mass of the structure framework – 0.56 kg/m^3 (for the expanded structure),
- total mass of the aerostat structure with the volume changing mechanism – 31.7 kg,
- the assumption was made that the maximum permissible mass of the aerostat's model with the equipment and additional gas storage tank amounts to $m_{ac} = 41.6$ kg.

Although we discuss the above-mentioned data in the article, in Fig. 5c we show that scaling of the aerostat and adjustment to actual needs (e.g. payloads) can be achieved by increasing the number of Heli-Caps modules and connecting them into one large HAPS.

3.3. Additional storage tank. The already mentioned additional helium storage tank, with the system (i.e. valve and compressor) for adjusting the pressure balance between the main tank and the atmosphere surrounding the aerostat, plays the key role in the strategy of controlling HAPS vertical mobility and ensuring the appropriate stresses generated in the aerostat envelope through controlling the helium overpressure / underpressure in the aerostat, depending on the external pressure. At the assumed low mass of the structure and the aerostat's envelope, it is not permissible for the aerostat structure and the envelope elements to convey large forces. Thus, maintaining the overpressure of 200 Pa inside the aerostat at the time of rising aims at protecting its structure from excessive overload. It also has the purpose of creating the adequate force at the mechanism adjusting the aerostat volume changes, with the controlled coupling, which allows for controlled increasing of the aerostat volume. Similarly, during aerostat descending, keeping the underpressure inside, relative to the pressure outside, will provide the force necessary to reduce the aerostat volume, thus decreasing the buoyant force. Additionally, it will protect the aerostat structure from excessive overload.

To maintain the proper values of overpressure or underpressure inside the aerostat, it is crucial to apply the additional gas storage tank, which has already been mentioned, with the properly selected initial amount of helium. The amount of gas in the additional tank depends on the way the aerostat volume change is controlled, and on its altitude. The altitude of the aerostat determines the external pressure, and the internal pressure is maintained by letting more helium in or dropping helium from the aerostat inside from / into the additional gas storage tank. In order to minimize the mass of the additional tank and the helium contained therein, the algorithm for controlling aerostat altitude and the assumed values of overpressure or underpressure are of vast importance. While the ascend algorithm will assume slow changes in altitude, the additional tank size and the initial amount of helium therein can be quite limited. For example, in the case of the analyses conducted, the smallest obtained volume of the additional storage tank ranged between 0.2–2.4 m^3, whereas the initial mass of helium in this tank ranged between 0.036–2.8 kg. Large size of the additional gas storage tank and the initial mass of helium therein decrease the payload, thus limiting the additional tank's size as well as the mass of helium is purposeful.

3.4. Compressor for helium pumping. If a proper initial value of the pressure and helium mass in the additional storage tank is assumed, it is possible to feed helium into the aerostat freely (pressure in the additional tank higher than pressure inside the aerostat) during the whole operation of ascending and descending. Recovering helium from the aerostat interior requires it being compressed into the additional storage tank; and this process requires delivering the energy necessary for the compressor to pump helium. The amount of helium in the additional storage tank is closely related to the assumed scenario of the aerostat going up and down, as well as the assumed values of underpressure and overpressure. While the changes in altitude will be slow and occurring continuously, initially, the amount of helium in the additional storage tank, and also the amount of helium pumped from the aerostat to the additional storage tank may be significantly limited. The values of assumed overpressure and underpressure have a similar influence – the greater the difference, the greater the initial mass of helium that should be present in the additional storage tank. The adequate algorithm for controlling changes in volume and the difference in pressure assures lowering the energy demand for compressing helium into the additional storage tank.

3.5. Mechanism for aerostat expansion. Another key element in controlling the aerostat volume is the above-mentioned technological solution of the controlled coupling, which blocks or enables the movement of the mechanism expanding the aerostat, and leads to increasing / decreasing the aerostat volume. The concept of operation of the mechanism expanding the aerostat is based on the fact that the maintained overpressure or underpressure will result in automatic increasing or decreasing of the aerostat volume by means of employing the sliding outer and inner cylindrical parts. Meanwhile, employment of the coupling, and more precisely – of the clamp – will enable the blockage of mutual movement of the aerostat parts. Thanks to the appropriate control of the coupling, the aerostat volume change will be possible due to the operation of external forces (e.g. red arrows marked in Fig. 5). Controlling this coupling is vital for achieving the assumed scenario of the aerostat ascending and descending over time. Depending on the control variant and the aerostat altitude changes, the control may take place at specified time points, or it can be performed continuously. At the assumption of continuous control, the coupling operation can take place during the whole process of ascending and descending of the aerostat.

4. Mathematical model of aerostat vertical motion and corresponding control problems

4.1. Mathematical model of vertical motion. In the course of the numerical analysis of the aerostat's model in the MATLAB / Simulink software, a series of assumptions aimed at simplification of the initial computations were adopted – cf. Fig. 6. The function of volume control and the function of under- / overpressure in the main tank were considered the main input for the aerostat model.

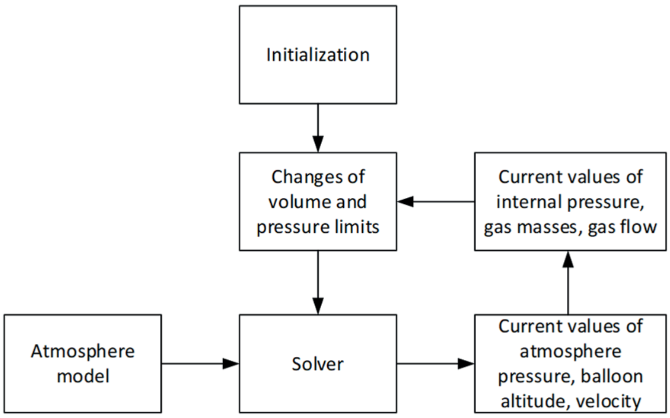


Fig. 6. Diagram of the computation algorithm using the Matlab / Simulink software

Assumption of the function defining aerostat volume change allows to formulate the equation governing its vertical motion, which contains weight of the aerostat, volume-dependent buoyant force and velocity-dependent air resistance force:

$$m_{ac}\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -Q_{ac}(x) + Q_{aw}(x) - Q_{aa}\,\mathrm{sign}\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right), \qquad (1)$$

where:

- x is the spatial variable describing the height of the aerostat,
- $Q_{ac} = m_{ac}g(x)$ is the weight of the aerostat at height x,
- $Q_{aw} = \rho_{atm}(x)g(x)V_g$ is the buoyancy of the aerostat at height x, where $\rho_{atm}(x)$ describes air density at height x and V_g describes the current value of the aerostat volume,
- $Q_{aa} = \frac{1}{2}c_x\rho_{atm}(x)A_a\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2$ is the absolute value of drag force during ascending or descending, where c_x is the drag coefficient approximated in the same way for the ascending and descending processes due to symmetry of the aerostat and A_a is the area of the horizontal cross-section of the aerostat.

The drag coefficient c_x is related to the velocity and the Reynolds number of the considered processes of ascending and descending. Although for the small velocities (and Reynolds numbers) the drag coefficient is larger, the value of drag force is small due to quadratic dependence on aerostat velocity. In contrast, for large velocities the drag coefficient is smaller but the drag force assumes larger values and is significant for the motion of the aerostat. It is worth mentioning that the exact value of the drag coefficient in relation to the Reynolds number can be estimated experimentally after building the aerostat, so on this stage of investigations, approximation of the c_x value is based on literature data concerning objects of quite similar shapes [32].

Solution of the above equation allows to determine the actual position, velocity and acceleration of the aerostat as well as the time-history of the buoyant, air resistance and lift forces. Apart from the function of the aerostat volume change, the function of overpressure (during ascending) and underpressure (during descending) Δp_{gb} relative to the external atmospheric pressure at the given altitude, which allows for realization of the volume change process, also has to be considered. On this basis, it is possible to calculate the pressure in the main tank of the aerostat:

$$p_g(x) = p_{atm}(x) + \Delta p_{gb}, \tag{2}$$

where $p_{atm}(x)$ describes the air pressure at height x.

Based on the above-estimated pressure, the helium mass in the main tank (which should be present in the aerostat so that the assumed overpressure or underpressure is maintained) can be computed (for the current aerostat's altitude) from the following formula:

$$m_{hg}(x) = \frac{p_g(x)V_g M_A}{RT(x)}, \tag{3}$$

where:

- R – the gas constant,
- $T(x)$ – is the temperature inside main tank, which is assumed to equal the air temperature,
- M_A – the mass of one mole of helium.

While analyzing ascending and descending of the aerostat, the NASA atmospheric model [33], which is used by organizations designing high-altitude aerostats and which comprises the altitudes of up to 90 km, was employed. The adopted model defines atmospheric pressure $p_{atm}(x)$, temperature $T(x)$, air density $\rho_{atm}(x)$ and acceleration due to gravity $g(x)$ at a given altitude. Moreover, it was assumed that the temperature of the helium inside the aerostat changes identically as the temperature of the surrounding environment. This assumption results from the fact that ascending and descending of the aerostat is relatively slow and the thermodynamic process of temperatures equalization occurs within single time-steps of the analysis. A more detailed model of thermodynamic transformations accompanying the gas flow inside the aerostat would require identification of the data regarding the heat exchange between the environment, aerostat and the additional storage tank.

The proper value of pressure difference Δp_{gb} can be maintained via application of the additional pressure tank. The initial overpressure of helium inside this additional tank allows to replenish the helium stock in the aerostat by opening the valve controlling the flow of helium. In turn, the transfer of gas from the aerostat interior to the additional storage tank is accomplished by compressing the gas using the compressor. On the basis of the computed required mass of helium in the aerostat, it is possible to determine the mass flows of the helium flowing from or to the additional storage tank:

$$\frac{\mathrm{d}m_{hg}}{\mathrm{d}t} = \dot{m}_{hg} \approx \frac{\Delta m_{hg}}{\Delta t} = \frac{m_{hg}(x_t) - m_{hg}(x_{t-1})}{\Delta t}. \tag{4}$$

Furthermore, it is also possible to calculate the amount of helium which is inside the additional tank:

$$m_{hb}(x_t) = m_{hb}(0) - \int_0^t \dot{m}_{hg}\,\mathrm{d}t, \tag{5}$$

and the helium pressure in the additional tank:

$$p_{hb}(x) = \frac{m_{hb}}{M_A}\frac{RT(x)}{V_b}, \tag{6}$$

where V_b is the constant volume of the additional tank. As it was already mentioned, the flow of helium from the additional tank to the main tank is realized without the compressor and is done only due to the adequate difference of pressures. Therefore, it is important to adequately choose the proper values of the initial volume and pressure in the additional tank, which allows for overpressure in the additional tank during the whole process of ascending and descending of the aerostat.

After determination of helium parameters in the main and additional tank, it is possible to determine the amount of energy needed to charge the compressor:

$$E_h = \left| \int_0^t \frac{\dot{m}_{hg}}{\rho(x)}\left(p_{hb}(x) - p_g(x)\right)\mathrm{d}t \right| \quad \text{for} \quad \dot{m}_{hg} < 0. \tag{7}$$

where $\rho(x)$ describes the helium density at height x. Adopting the above formulae and assumption of the required construction parameters allowed for building, in the Matlab/Simulink software, a discrete model of the aerostat which uses, in individual time steps, analytical relationships connected with gas transformations inside the aerostat and the additional storage tank, presented in Fig. 6.

4.2. Formulation of the problem of aerostat vertical motion control. We will analyze the process of aerostat ascending and descending of total duration of 12 000 s. During the first part of the process, the aerostat should ascend from the ground level to initial equilibrium position located at $h_1 = 350$ m, then float to the target altitude of $h_3 = 5000$ m with an intermediate stop at the altitude of $h_2 = 3000$ m. Later, in the second part of the process, the aerostat should descend from the altitude of $h_3 = 5000$ m back to the altitude of $h_5 = 350$ m, with the intermediate stop at the altitude of $h_4 = 3000$ m.

Two separate control problems are considered in this study. In both the objective of controlling vertical movement is to find the change of aerostat volume $V(t)$ which enables realization of the above-defined aerostat ascending and descending sequence, while simultaneously providing:

1. the shortest time of aerostat motion between the assumed altitudes,
   or
2. the minimum total cost of aerostat motion understood as required work of the compressor.

The above statement constitutes a standard formulation of the control problem, which is typically aimed either at maximization of control efficiency or minimization of control cost required for realization of the assumed dynamic process.

The problem of minimization of the time of aerostat motion between the assumed altitudes can be defined mathematically as follows:

$$\text{Minimize} \quad T_{\text{transfer}} = \Delta t_{h_1-h_2} + \Delta t_{h_2-h_3} + \\ + \Delta t_{h_3-h_4} + \Delta t_{h_4-h_5};$$

With respect to $V(t)$;
Subject to:

- $|V_{h\_min}| \leq |V(t)| \leq |V_{h\_max}|$,
- $|\dot{V}_{min}| \leq |\dot{V}(t)| \leq |\dot{V}_{max}|$,
- Eqs. 1–6 (equations governing system response),
- $\{(h_1, 0), (h_2, 0), (h_3, 0), (h_4, 0), (h_5, 0)\} \subset \{x(t), \dot{x}(t)\}$, $\mathrm{t} \in \langle 0, \mathrm{T} \rangle$.

The objective function is defined as total duration of two phases of aerostat ascents and the two phases of aerostat descents that follow. The objective function is minimized with respect to the volume of the aerostat, which constitutes a design variable of the optimization problem. The constraints of the optimization problem are bounds imposed on volumes of the aerostat (corresponding to its minimum and maximum altitudes (V_{h_min}, V_{h_max})) as well as minimum and maximum rates of aerostat volume changes. The minimum aerostat volume change rate results from the requirement of obtaining volume corresponding to the assumed altitude at the desired time intervals. In turn, the maximum aerostat volume change rate results from the limitations of the operational mass flow of the compressor applied and of the pneumatic installation (valves, diameters of pipes, etc.), and it depends on direction of the flow between aerostat interior and the additional tank. Additional constraints of the optimization problem are previously introduced equations governing system dynamics. Finally, the last constraint is the requirement of successful realization of the assumed ascending and descending scenario, which includes reaching the subsequent altitudes h_1–h_5 and making intermediate stops at these altitudes (indicated by zero value of aerostat velocities).

In turn, the problem of minimization of the required work done by the compressor can be formulated as follows:

$$\text{Minimize} \int_0^t \frac{\dot{m}_{hg}}{\rho(x)} \big(p_{hb}(x) - p_g(x)\big) \mathrm{d}t;$$

With respect to $V(t)$;
Subject to:

- $|V_{h\_min}| \leq |V(t)| \leq |V_{h\_max}|$,
- $|\dot{V}_{min}| \leq |\dot{V}(t)| \leq |\dot{V}_{max}|$,
- Eqs. 1–6 (equations governing system response),
- $\{(h_1, 0), (h_2, 0), (h_3, 0), (h_4, 0), (h_5, 0)\} \subset \{x(t), \dot{x}(t)\}$, $t \in \langle 0, T \rangle$.

The objective function is defined as time integral of the power used by the compressor during helium transfer from the main aerostat to the additional tank, which is a function of required mass flow of helium, its actual density and pressure difference between the additional storage tank and the aerostat. The objective function is minimized with respect to the volume of the aerostat. The constraints for the optimization problem are defined exactly in the same manner as previously and they include bounds imposed on aerostat volume and its derivatives, equations governing system response as well as the requirement of successful realization of the assumed ascending and descending path.

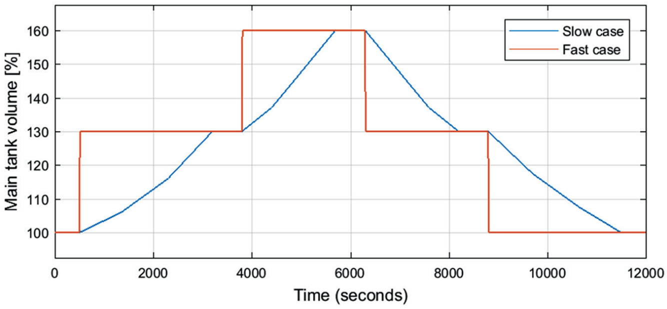
In both optimization problems the searched quantity $V(t)$ is the unknown function of time, which indicates that the optimization domain is a functional space and the formulated problem of aerostat vertical mobility belongs to the class of variational problems. Exact mathematical solution of this problem is relatively complex due to the large number of various parameters influencing the dynamic process being analyzed.

In order to find an approximate solution to the first optimization problem, we will take advantage of general properties of the solutions of optimum control problems of the above class, which are typically of "bang-bang" type and utilize either extreme values of the control functions or extreme values of their derivatives. Therefore, the solution of the problem of minimization of the total time of aerostat motion comprises maximally fast increase of aerostat volume at the beginning of each ascending or descending and then keeping it constant until the end of the stage. In turn, the approximate solution to the second problem can be simplified to finding the minimum value of mass flow from the main to additional tank forced by the compressor needed to achieve the assumed altitude in the desired time interval.

5. Comparison of control strategies

The presented numerical example concerns control of a vertical motion scenario involving float of the aerostat from the ground level to the equilibrium position at 350 m, ascent to altitude of 3000 m, further increase of altitude to 5000 m and final descent to initial equilibrium position of 350 m. In the strategy aimed at maximization of vertical mobility efficiency, the objective of the control applied was to achieve possibly fastest change of aerostat altitude, regardless of the corresponding energy consumption and required mass flow rate of helium. In turn, in the strategy aimed at minimization of the control cost, the changes of aerostat altitude are implemented in a possibly slowest manner in order to minimize the energy consumption and mass flow rates. Simultaneously, the maximum time of reaching the altitude of 3000 m was limited to 4000 s, while the maximum time of reaching 5000 m was limited to 6000 s. The process of descending was assumed to be symmetrical to the process of ascending such that total duration of the process was equal to 12000 s. Maximization of the efficiency of vertical motion and shortening the time of transfer between subsequent altitudes requires application of step change of aerostat volume. The relationship illustrating the adopted function of volume change is shown in Fig. 7a in a red line (so-called fast case). The subsequent changes in volume of the aerostat are determined with the use of static equation of equilibrium of the aerostat at assumed altitudes. Adoption of the assumed change of aerostat volume can be used to determine the control signal of the aerostat expansion/contraction mechanism. Unlocking the mechanism of the aerostat volume change is obtained by releasing the coupling of the mechanism blocking the mutual movement of external and internal parts of the cylindrical aerostat section. The plot in Fig. 7b marked by the red line shows the corresponding assumed function of overpressure or underpressure in the aerostat during ascending or descending. Due to the adequate values of overpressure and underpressure, it is possible to use the difference in pressure to generate forces necessary to expand the aerostat (overpressure) and contracting it (underpressure). An assumption was made that the process of step change in the aerostat volume lasts approx. 10 s and the process of obtaining the overpressure and underpressure lasts 40 s.

a)



b)

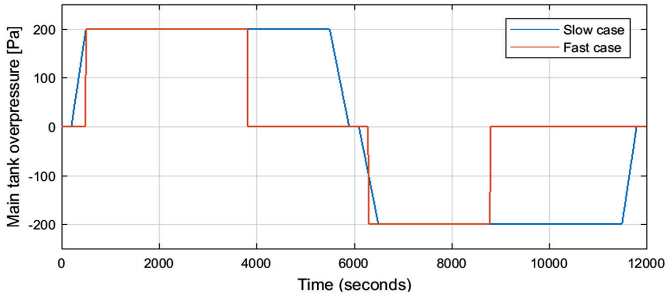


Fig. 7. Comparison of control strategies – determined functions defining: a) change of aerostat volume in time, b) difference of pressure in the aerostat and external atmosphere in time

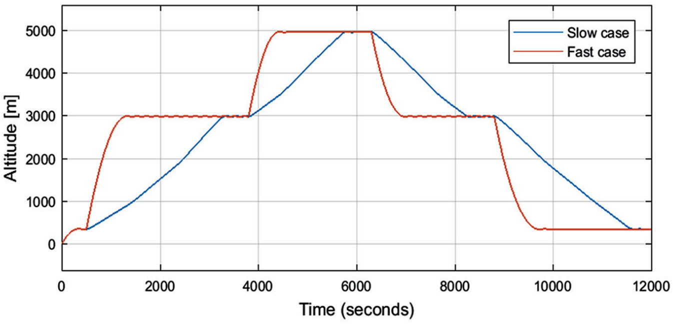


Fig. 8. Comparison of control strategies – change in aerostat altitude as a function of time

In turn, the change of aerostat volume corresponding to minimum energy consumption and mass flow rate of helium is presented in Fig. 7a in a blue line (so-called slow case). The graph in Fig. 7b shows the assumed function of overpressure or underpressure in the aerostat during ascending or descending. Also, the values of permissible overpressure and underpressure in the aerostat were the same as in the previous strategy and were limited to 200 Pa.

The resulting changes of the aerostat altitude over time in both control strategies are shown in Fig. 8 in the red and blue line, respectively. The aerostat total mass together with the load is selected so that the aerostat of initial volume rises to the altitude of approx. 350 m. In the case of the first control strategy (marked by the red line), the applied step change in volume corresponds to generation of the buoyant force, which induces acceleration and vertical velocity of the aerostat. However, the decrease of buoyant force due to decrease of atmosphere density and substantial air-resistance force causes the vertical velocity of the aerostat to gradually decrease, and eventually the aerostat stops at the equilibrium position at desired altitudes of 3000 m and 5000 m, respectively. The time instants when aerostat motion starts correlate clearly with the time instants of volume changes in the control function. The curve defining the change of aerostat altitude is less steep than the curve defining change of aerostat volume due to effect of aerostat inertia and air resistance force being effective while ascending and descending. In turn, in the case of the second control strategy (marked by the blue line), the adopted functions of volume change and pressure difference cause the aerostat to ascend and descend more smoothly than in the previous control strategy.

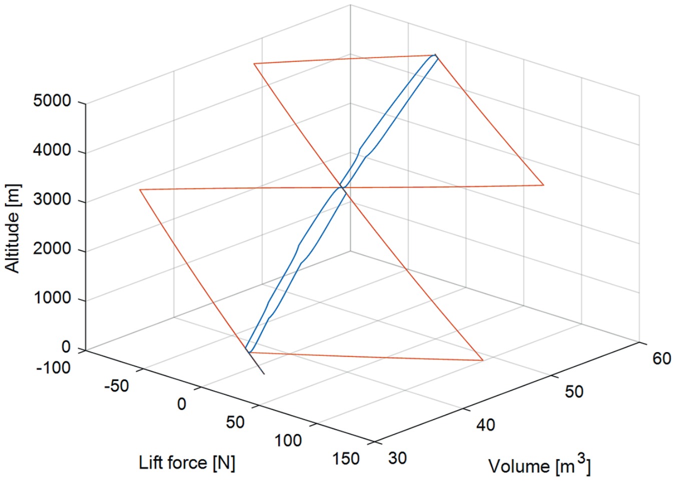


Fig. 9. Comparison of control strategies – the relationship between the aerostat lift force and the aerostat altitude as a function of time and as a function of volume (blue – slow case, red – fast case)

The aerostat reaches the required altitude slightly before the assumed maximum time, which indicates that change of volume could be performed even slightly more smoothly.

The graph shown in Fig. 9 illustrates the relationship between the aerostat lift force (difference between the buoyant force and the aerostat weight), and the aerostat altitude as a function of volume during the ascending and descending process in both control strategies being considered. To facilitate the graph analysis, the curve of the lift force was additionally shown as a function of time in Fig. 10. In the case of the strategy aimed maximization of vertical mobility efficiency, the rapid changes in the aerostat volume correlate with rapid changes in the resultant buoyant force responsible for the aerostat ascending. These forces gradually decrease along with the increasing aerostat altitude, which is the result of change of density of the atmosphere. In order to avoid too large pressure difference, which could be generated as the aerostat ascends, an assumption was made that helium flow takes place between the aerostat and the additional storage tank, if required. Lowering the pressure in the aerostat is possible through pumping helium from the main aerostat volume to the additional storage tank with the use of a compressor. In turn, in the case of the control strategy aimed at minimization of the control cost, the assumed function of volume change is smoother than in the previous control strategy, which results in distinctly smaller values of the lift force in terms of time and in terms of aerostat volume. The lift force does not have significant peaks at time instants of volume change but has a more uniform positive value during the ascending and descending process, respectively.

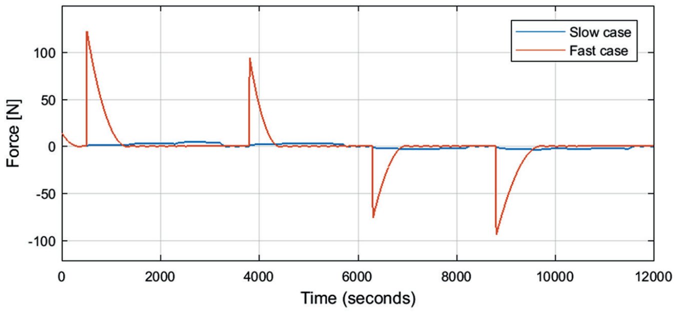


Fig. 10. Comparison of both control strategies – lift force affecting the aerostat as a function of time

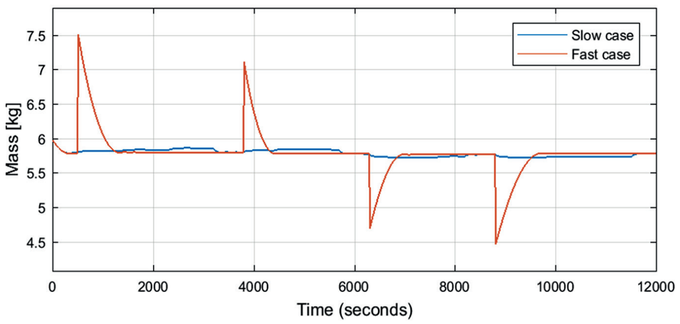


Fig. 11. Comparison of control strategies – amount of helium in the aerostat as a function of time

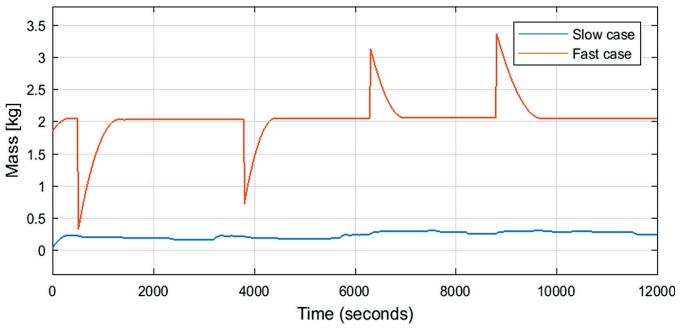


Fig. 12. Comparison of control strategies – amount of helium in the storage tank as a function of time

The mass of gas in the additional storage tank and in the aerostat resulting from the assumed pressure difference is shown in the graphs in Fig. 11 and 12. In the first control strategy the initial volume of the additional storage tank was assumed as 0.7 m^3 (which provides that initial pressure is below 17 atm and during the process it does not drop below atmospheric pressure). The initial gas mass (1.85 kg) in the additional storage tank was selected in such a manner that there is always overpressure in the tank relative to the pressure of helium in the aerostat (regardless of ascending or descending of the aerostat), with its purpose being filling up helium into the aerostat. In turn, in the second control strategy the volume of the storage tank was selected as 0.25 m^3 (almost three times smaller than in the previous control strategy), while the initial mass of helium in this tank providing overpressure with respect to aerostat was equal to 0.043 kg. Thus, it can be clearly seen that adopting smoother and prolonged change of volume allows for significant decrease in volume of the additional storage tank as well as decrease of the helium mass located inside. Let us note that the previously occurring requirement of rapid transfer of helium to the aerostat after the first expansion and further pumping of helium back to the storage tank is now almost completely eliminated. Decreasing the helium mass in the additional storage tank, decreasing the size of the tank as well as reducing the pressure all allow for potentially increasing the aerostat permissible load capacity as compared to the first control strategy by over 1.807 kg.

Figure 13 illustrates the graph of the pressure of helium in the storage tank. In the case of the first control strategy, the pressure of helium inside the additional storage tank reaches remarkable values, rising to approx. 2.7 MPa. In order to decrease the pressure values in the additional tank, it is possible to assume its greater volume but then a greater mass of gas will be required in order to provide automatic replenishing of the aerostat. For example, at the volume of the additional storage tank of 2 m^3, the maximum pressure in the tank can be decreased to approx. 1.03 MPa. However, in such case the mass of the gas inside the tank should be substantially larger (approx. by 2.1 kg), which significantly affects the total payload of the HAPS. In the case of the second control strategy, the maximum pressure amounts to approx. 0.8 MPa and it is distinctly lower than in the previous control strategy.

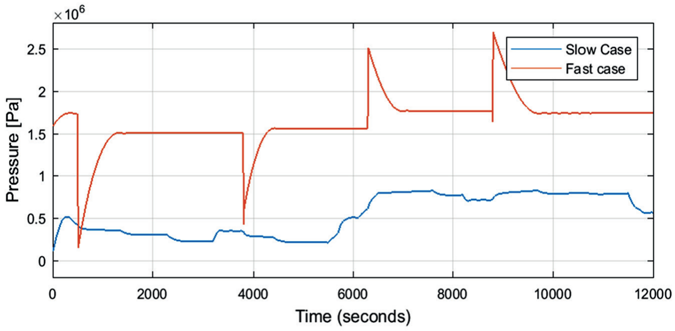


Fig. 13. Comparison of control strategies – pressure of helium in the storage tank as a function of time

The above figures show how the control process can be executed. Let us assume that we have installed the gas valve controlling the spontaneous flow (with no energy consumption costs) from the additional storage tank to the main tank and a forced flow (generated by the compressor) in the opposite direction. The flow of helium between the tanks is shown in Fig. 14. Sections with the mass flow greater than zero indicate the periods during which the compressor pumping helium from the aerostat into the additional storage tank must be used in order to maintain assumed pressure balance between the main tank and the aerostat surroundings. It is evident that in the case of the second control strategy the compressor work will take place only at the selected time points, and not during the whole course of the aerostat ascending and descending cycle. This will result in reducing the demand for the energy to supply the compressor.

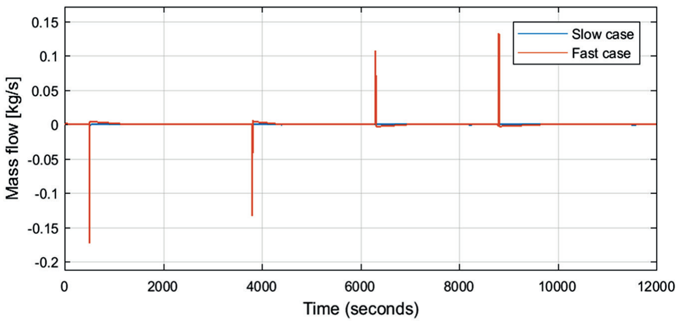


Fig. 14. Comparison of control strategies – helium mass flow between the main tank and additional storage tank, as a function of time

Given the mass flow and the pressure values in the main tank and the additional storage tank, computation of the energy needed to supply the compressor for squeezing the gas in the additional storage tank in case of applied volume changes is possible (Fig. 15). In the case of the fast control strategy, the conducted process requires a large amount of work performed by the compressor. The work is executed during the ascending of the aerostat when helium is pumped back to the storage tank in order to maintain constant pressure difference between the aerostat and the atmosphere (two initial stages of work increase). Moreover, rapid decrease of aerostat volume requires a certain value of underpressure, which is obtained by rapid pumping of helium from the aerostat to the tank, associated with a large amount of executed work (two final short periods of work increase). The amount of energy needed to maintain the given function of volume change (and thus the altitude), and to maintain the given difference in the pressure values, requires a significant amount of energy at step changes in the aerostat volume. Additionally, in the periods of rapid growth of work the compressor will need to be fed considerable power necessary to compress the gas. In turn, in the case of the slow control strategy, more zero-energetic valve openings (picks below the 0-line in Fig. 14) and more valve opening synchronized with the compressor are necessary to smooth down the aerostat ascending / descending process. In other words, the requirement for extensive mechanical work and mass flow rates of the compressor are significantly reduced by application of more complex and more effectively tuned control strategy.

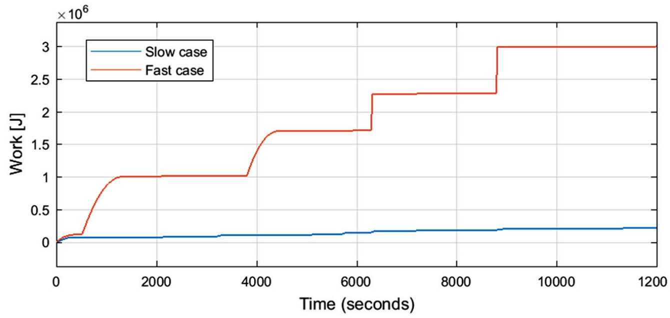


Fig. 15. Comparison of control strategies – work performed during gas compression in the additional storage tank

Analysis of the plots of energy consumption for both strategies allows to conclude that energy required during ascending of the aerostat, consumed for maintaining constant overpressure value, is now significantly smaller (see increases of work before the intermediate and maximum altitude). Similarly, energy required during descending of the aerostat, consumed for obtaining underpressure, is distinctly smaller and more distributed in time (see the increases of work during the second part of the process). As a result, the amount of work needed to compress the gas in the additional storage tank is now nearly 12 times smaller than in the previous control strategy. In the current control strategy, the application of a compressor of relatively small capacity and smaller maximum mass flow, is possible. Such a solution potentially allows for applying a lighter pneumatic fitting and for limiting the energy supply for the aerostat.

The presented results of the strategy aimed at minimization of control cost indicate significant advantages as compared to the results of the strategy aimed at control efficiency maximization. For example, adoption of smoother curves of changes in volume, as well as overpressure and underpressure values, allows for applying a distinctly smaller additional gas storage tank, limiting the total amount of helium (by nearly 25%), and thus ensuring greater HAPS load capacity. With the adoption of a similar threshold of maximum pressure values, almost a threefold reduction in the additional tank volume was obtained, and the initial mass of gas was reduced 40 times. Nevertheless, it is evident that optimization of the HAPS aerostat construction parameters as well as improvement of the control strategies aimed at overall cost of the control applied (compressor energy and mass flow rate requirements) is still possible via continuous monitoring of HAPS parameters.

An additional word of comment is required with regard to providing adequate energy sources to supply the HAPS appliances. In the project of designing the HAPS, it is possible, for example, to consider the use of alternative energy resources, including ultralight photoelectric cells providing the necessary energy for the compressor and couplings operation.

6. Final remarks – adaptive pressure balance strategy for control of HAPS mobility

Analysis of the results of the already discussed variants of the HAPS aerostat ascending indicates that solving a series of problems connected with construction, control, and ensuring the energy needed for the HAPS operation will be necessary within the framework of the HAPS developing project. These problems can be divided into the following categories:

- minimization of the HAPS mass and developing the efficacious design of the aerostat expanding mechanism – the aerostat mass is predominantly the envelope weight and the expandable HAPS framework. That is why employing the ultralight construction materials as well as the ultralight and airtight external aerostat envelope, resistant to UV rays, are the key factors. A decisive element of the potential HAPS aerostat construction is the mechanism for its expanding and contracting realized thanks to obtaining the adequate difference in pressure values between the main tank and the external pressure. Design of such a mechanism makes it possible to use the precisely controlled construction coupling discussed in detail in [31]. The possibility of switching on/off the coupling, controlled over time, along with the controllable helium flows between the aerostat compartment and the additional gas storage tank, allows for designing the optimum adaptive pneumatic balance (APB) strategy of the aerostat's ascending/descending;
- developing rules of the HAPS control – the results of analyses indicate that HAPS functional characteristics are influenced to a large extent by, apart from its mass, the way the aerostat ascends and descends. Reduction of pressure peaks resulting from changes in the aerostat volume plays the key role. The small values of overpressure and underpressure applied during ascending or descending can be used to obtain forces necessary to change the aerostat volume and to protect its supporting structure from excessive loading. This challenge also requires performing a crucial task of designing the system to control the gas flow (valves with low-energy demand) that will enable a precise pressure balance between the aerostat and the additional tank. As the results of numerical analyses show, application of adequately efficient algorithms for the volume control may also result in reduction of the HAPS aerostat mass;
- minimization of energy consumption during vertical transport – the results of analyses indicate that allowing zero-energy and costless flow of gas based on pressures equalization between the additional storage tank and the aerostat is possible, while forcing the gas flow in the opposite direction is energy-consuming and expensive. Searching for new energy sources to control and operate the HAPS aerostat internal appliances is necessary, for example through employment of the new-generation photovoltaic cells.

The results of the analyzed cases indicate potential paths to be chosen in the process of solving the above-mentioned problems. They show, for example, that the extended time of transport and limiting the magnitudes and rates of changes in the aerostat underpressure and overpressure are the cost of the more advantageous path. The time of vertical transport in the slow case of the control could be reduced approximately twofold, if such a need arose, but that would involve four-times greater peaks of the buoyant force, with the mass of required helium (in the additional tank) increasing three-fold. This corresponds to the requirement of covering rapid, energy-consuming expenditures of the compressor pumping helium from the main to the additional tank at the greater pressure values of helium.

The results obtained indicate that the recommended rational strategy of vertical transport is that of aerostat ascending at minimum required overpressure values, necessary to obtain the adequate force enabling expansion of the HAPS as well as its descending while underpressure is maintained in the aerostat, which should allow for folding the aerostat's cylindrical section. Such a strategy of maintaining the pressure difference combined with the smooth control mode of the aerostat volume change guarantees smooth ascending and descending, with no rapid accelerations or envelope's stress peaks. This can be achieved by assumption of the exemplary precisely tuned scenarios of vertical transport and by adjusting the resultant helium flows between the additional tank and the aerostat.

A series of simplifications were adopted in numerical analyses, because of the lack of correspondence to the already-existing results of experimental research of the discussed type of HAPS aerostats. For this reason, the results of numerical analyses require further experimental tests making evaluation of the operation of the adopted HAPS aerostat model possible. For example, empirical research may explain if the adopted minimum values of overpressure/underpressure in the aerostat compartment are sufficient, so that the construction coupling could be actuated, triggering increasing/reducing the aerostat volume.

Another comment concerns development of the aerostat adequate design, allowing for continuous change of volume. The demonstrator of the HAPS structure is intended to be built by using the adaptive, telescopic system based on implementation of sliding linear guideways into the aerostat construction. By means of adjusting the number of segments in the Heli-Caps module reaching the altitude of approx. 20 km by the aerostat could be possible. Alternatively, higher altitude can also be achieved by increasing the number of HAPS modules.

A key factor in the precise HAPS volume change is the employment of precise control of the actual pressure value [34] and the controlled construction couplings in telescopic connections [31]. Previously conducted research indicates that the final solution aimed at obtaining high efficiency and vertical mobility of the HAPS aerostats will depend on using the adaptive pressure balance system based on controlled construction couplings and precise balance of pressure values inside and outside the aerostat. In the next, continuation paper, the smart, telescoping connections controlling shape modification development will be discussed. In such case the morphing effect achievable in this manner will play a crucial role in effective control of aerostat vertical mobility.

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