Proceedings of the 1998 IEEE
International Conference on Robotics & Automation
Leuven, Belgium • May 1998

Airship Dynamic Modeling for Autonomous Operation

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ABSTRACT

Robotic Airships have an enormous, yet untapped, potential as low-speed, low-altitude platforms for aerial exploration, monitoring, and surveillance, as well for transportation and telecommunication purposes. We present in this paper a comprehensive description of the physical principles of airship operation, along with their dynamic model in a form suited for controller design and computer simulation. Based on the dynamic model, airship response modes are analyzed and control challenges are pointed out. The present work provides a starting point for robotics and control researchers interested in utilizing airships as robotic aerial vehicles.

1. INTRODUCTION

Interest on the utilization of unmanned aerial vehicles, has grown in the past few years, due to their potential utilization in surveillance, exploration, monitoring, and transportation tasks. In this context, efforts, have been directed to the development of semi-autonomous vehicles with on-board control and navigation systems capable of planning and executing trajectories based on high level human-planned missions. Despite the progress in this area, there is still an untapped potential in the form of airships, also known as blimps or lighter-than-air (LTA) vehicles, as unmanned robotic platforms. In fact, airships outperform airplanes and helicopters in low-speed, low altitude applications. It is against this background that the Automation Institute started the AURORA project, within which airship control and navigation systems for semi-autonomous operation are being developed, towards an ultimate goal of environmental monitoring [1]. The success of this project depends, on one hand, on reliable vehicle state estimation from INS and GPS sensor data, and, on the other hand, on an accurate dynamic model of the airship

As the basis for the development of performant control and navigation strategies, we present in this paper the physical principles of operation and a comprehensive 6 degrees-of-freedom dynamic model of a non-rigid airship, a class that includes all of the currently existing airships and indoor blimps. The model is based on that of a remotely operated underwater vehicle (ROV), upgraded to suit the airship itself. The model includes all inertial, dynamic, aerodynamic, gravitational, buoyant, and propulsion forces. While most of these terms are relatively easy to obtain, the ones related to aerodynamics are usually very hard to be determined. Our model, therefore, is based on data collected during 600 hours of wind tunnel testing, and is considered the most comprehensive airship aerodynamics database existing today [2].

The paper is divided as follows: in section 2 we present the physical principles of airship operation, and in section 3 the complete airship dynamic model. Based on this model we present in section 4 the airship response modes and challenges to be dealt with by an automatic control system. Finally, in section 5 we present our conclusions and directions for future work.

2. PHYSICAL PRINCIPLES OF AIRSHIP OPERATION

2.1 'Floating' in the Air: Aerostatic Lift

The airship, being a direct descendant from balloon technology, has as its main source of lift what is called aerostatic lift, i.e., lift that is independent of flight speed. Unlike the lift force generated over a wing surface which is directly proportional to the square of the flight speed, aerostatic lift comes from Archimedes' Principle: it can be calculated by multiplying the volume of air displaced by the lifting gas, by the difference in density between such gas and air. That is also why such force is still known today as buoyancy. Therefore, only gases that are lighter than air, i.e., whose densities are lower than air at a given temperature and pressure, can be used. First and foremost among those stands hydrogen. Since the spectacular accident with the Hindenburg over Lakehurst, NJ, in 1937, however, it is only used as a lifting gas under very restricted conditions.

Helium is the most commonly used lifting gas. When humans are carried aboard, it has become mandatory by the certification authorities. Under sea-level ISA conditions (15°C, 1013.25 mbar, 1.225 kg/m^3 air density), its lifting capacity is 1.06 kg/m^3, i.e., some 8% lower than hydrogen.

Next in terms of wide spread use comes hot air. But, due to the volume required for any practical payload, its use is essentially restricted to advertising balloons or manned airships of considerably limited performance.

2.2 Going Up in the Atmosphere: Ballonets

The discussion presented in the previous section is valid for a vehicle restricted to a certain height. As it ascends through the atmosphere, air gets less dense due to the decrease in the ambient pressure. In order therefore to retain the same buoyancy force upwards, the lifting gas needs to expand to proportionately higher volumes. This is achieved by letting air out of the ballonets (Fig. 1), which are simply bags of air inside the main (lifting gas) envelope.

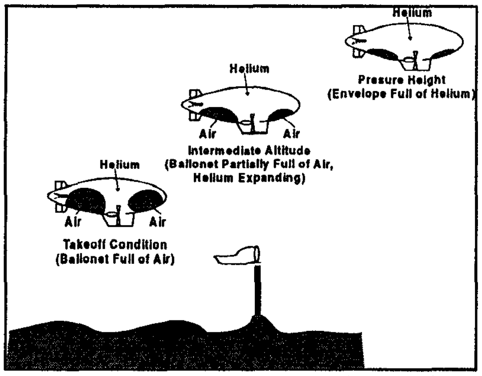

Fig.1- Ballonet operation in a traditional non-rigid airship.

At this stage it is important to note that all current airships are the so-called non-rigid or pressure airship type. They keep their streamlined shape through pressurization, the internal gas pressure being only 0.5 to 1% higher than that of the surrounding air ambient pressure. Only extremely large gas envelopes justify - in fact require - the weight penalty represented by rigid structural elements, the Hindenburg being the largest such vehicle ever built (and in fact, the largest aerial vehicle of all times)

When air is let out of the ballonets in climbs or is pumped into them in descents, the associated amounts are those just adequate to keep the prescribed pressure differential range mentioned above. Once an altitude is reached at which there is no more air to be expelled from the ballonets, then further ascent would only be possible by valving off the lifting gas, an expensive and usually forbidden operation in the case of helium. It is therefore said that the vehicle has attained its pressure height, i.e., its operational ceiling.

This top limit is designed-in from the start. Most airships are designed with a ballonet volume of 25% of the total envelope volume at sea-level, i.e., only 75% of the envelope volume is filled with helium. Considering typical values for the weight of the gondola, engines, other systems, crew, and payload of manned airships, that means a typical pressure height of around 9,000ft (3,000m) under ISA conditions. If the airship operational requirements establish a lower pressure height then more envelope volume can be filled with helium at sea-level and, everything else staying the same, proportionately more payload can be carried from the ground up. This explains why airships are essentially vehicles for the lower parts of the atmosphere.

2.3 Getting Hot: Temperature Effects

Temperature affects LTA vehicles in two different ways:

Firstly, aerostatic lift, like any quantity directly proportional to gas density, decreases as the temperature increases (and vice-versa) if everything else stays the same. As a consequence, an airship designed to have a certain pressure height under ISA conditions may find it is short on performance if suddenly required to operate from hot and high airfields. This is, incidentally, similar to the effect on conventional aircraft.

Secondly, in a way unique to LTA, the lifting gas can acquire a temperature significantly higher (or lower) than that of its surrounding air. Called superheat, this is a phenomenon which can occur, for example, after long exposure to direct sunlight and/or a rapid ascent through the atmosphere. The resulting lifting gas expansion usually generates a relatively fast increase in the buoyancy force. This in turn can sometimes become quite a nuisance for the steady control of the vehicle.

2.4 The Quest for Slimming: Heaviness and Lightness

When the airship is powered by fuel-burning engines, it will undergo a mass decrease over a given period of operation. If not properly accounted for, it can come to land with the buoyancy force far exceeding the weight of the complete vehicle. In that case, the landing operation can become quite a hazardous activity, to be avoided at all costs, since it could ultimately mean valving off expensive helium gas. To prevent such occurrence, three means are usually resorted to. Firstly, the most common of all which is to take off with the vehicle carrying enough ballast. This results in the vehicle weight being higher than the buoyancy force on landing, even after the burning of the trip's fuel. Secondly, using vectored thrust, i.e., deflecting the thrust propulsors downwards so as to help bring the airship down when such mechanical facility is available. And thirdly, replacing the mass of fuel burned along the way by increasing the amount of water ballast through the use of heat exchangers placed in the exhaust gas stream out of the propulsion engines.

The first method is the most commonly used, even in airships fitted with vectored thrust. In this way, the vehicle operates in a heavy condition all the time, returning to land with a residual amount of heaviness left. Then, and only if the amount of fuel burned exceeded the pre-flight forecast or anything causing relative lightness (like superheat) is present, vectored thrust is employed in earnest.

The amount of heaviness thus integrated into normal operation is dealt with by flying with the vehicle at a slight angle of attack to the oncoming air, i.e., generating an amount of aerodynamic lift with the hull which is just enough to compensate for the degree of heaviness. As the flight proceeds and fuel is continuously burned, the angle of attack is decreased since less aerodynamic lift is progressively required. But this does mean that constant flight altitude cannot be maintained below a certain speed and unless vectored thrust is available (see next item) the airship has to take off and land like a conventional aircraft. Usually, however, an angle of attack of one to two degrees is all that is required, and the penalty paid in terms of a drag force higher than otherwise required is not a significant factor.

2.5 Taming the beast: Propulsion and Actuation

Unlike what happened with conventional aircraft, whose technology evolved over many decades of continuous improvement, the airship's maneuverability had a very definite historical landmark: Paris, 1901, when the Brazilian born Alberto Santos-Dumont won the Deutz prize with his "No.6" airship. He took off from Saint-Cloud, outside Paris, went around the Eiffel Tower, and returned to Saint-Cloud within the prescribed time. The significance of that feat can hardly be fully comprehended even to this day: humans which had been taking to the air for the past 120 years (in balloons, gliders, etc.), essentially under the will of the winds, were now assured that flying and navigating through the air was possible. That must truly have marked the beginning of the science of Aeronautics in its most literal sense.

Operation of an airship starts, from a theoretical point of view, with what is available to its forerunner, the balloon: release of gas, affecting the buoyancy force, and release or addition of ballast, affecting the total mass of the vehicle. In practice, helium is not usually released for the reasons previously discussed and the following features are used:

- *aerodynamic control surfaces* like rudders and elevators attached to the empennage surfaces (Fig. 2). Deflection of the former controls the yaw movements (going to the left or right) whereas the latter controls the vehicle's altitude (going up or down).

- *vectored thrust*, which is simply a rotation of the propulsion units about a horizontal axis so as to provide thrust in the direction required. This usually means having the engines, and their associated propellers, being able to swivel up or down, with reverse thrust being sometimes also possible.

- *bow and/or stern thrusters* have also become widely used, since they provide fine control features for the landing and docking operations, dispensing the large ground parties normally required for ground handling.

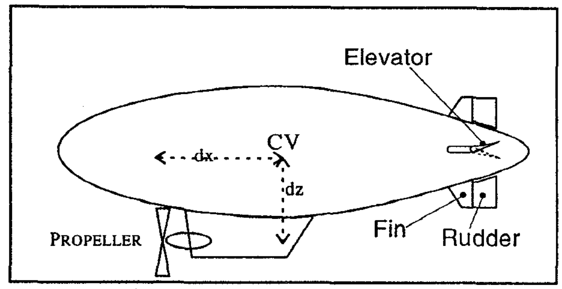

Fig. 2 - Airship vertical and horizontal tail fins and control surfaces.

The simple conclusion from the previous points is that the airship uses the same aerodynamic controls as conventional aircraft plus its power units for the same purpose. In fact, like any buoyant vehicle, below a certain speed, aerodynamic controls do not work at all and control reversal, i.e. a non-minimum phase behavior, is quite a reality. At very low speeds, going up or down is then achieved by vectored thrust and going left or right demands the use of differential thrust in the right and left hand side propulsors.

2.6 Pride and Prejudice: Airship Operations

Much has been said about an airship's apparent lack of maneuverability under strong winds or in the face of weather fronts. This usually derives from a wrong perception: a buoyant vehicle, whose overall mass is very close to that of the displaced air would behave like a bubble of soap, floating and drifting away carried by the elements.

In fact, that may happen to an airship that is strongly underpowered as it does with conventional aircraft as well. And flying through weather sometimes means - as it did with the Graf Zeppelins of the past - flying around weather fronts in such a way that the tail winds push compensated for the extra mileage incurred and the timetable was kept to within a few minutes.

Realistically, the airship is vulnerable to winds much in the same circumstances as conventional aircraft are, i.e., during take-off and landing operations when the speed is low and the winds are described as light and variable. A steady wind provides all that is required for any airship to align itself against and proceed with full aerodynamic and power controls to either disengage from the mast and take-off or come back to land. Once moored to the mast, it swivels around it weathercocking like a windsock.

In fact, the ground handling of airships is traditionally regarded as their weak point. In the past, parties of up to 200 people were required to walk a Zeppelin out of its hangar and hold it prior to take-off. The application of vectored thrust and reverse thrust to the modern (small) blimp has resulted in 10-15 people being the normal ground crew size. Bow and/or stern thrusters are designed to reduce that to one to three people at the most, before a completely automatic docking operation (using infra-red or ultra-sonic technology) is implemented doing away with the ground crew altogether. But quite a few airships have been seriously damaged by striking (rather than gently docking to) their mooring masts or have hit disaster while being moved in or out of a shed. Definitive solutions to those problem situations are part of research programs currently in progress both in Europe and the USA [3].

3. Airship Dynamic Modeling

In the attempt to establish a workable mathematical model of airship flight a number of considerations have to be taken into account, as it differs from the usual conventional aircraft models:

- the LTA vehicle displaces a very large volume and its virtual (added) mass and inertia properties become significant, i.e., it behaves as if it had a mass and moments of inertia substantially higher than those indicated by conventional physical methods;

- the airship's total mass can change considerably in a very short time. In a climb or descent maneuver for example, this is due to ballonet deflation or inflation respectively;

- in order to reasonably accommodate the constantly changing Center of Gravity (CG) position, a characteristic which is unique to airship flight, the airship motion has to be referenced to a system of orthogonal body axes fixed in the vehicle with the origin at the Center of Volume (CV) as shown Fig. 3. The CV is also assumed to coincide with the gross Center of Buoyancy (CB).

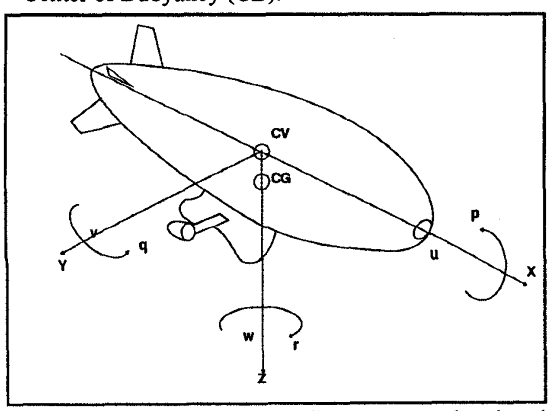

Fig. 3 - Airship body axes coordinate system showing the Center of Volume, Center of Gravity and linear (u,v,w) as well as angular (p,q,r) velocities around the X, Y, and Z axes respectively.

The dynamic model was derived originally for a buoyant ROV [4]. Later, it was modified to reproduce the peculiarities of airships, such as the Westinghouse's YEZ-2A [2].

In building the full non-linear 6DOF mathematical model only two limiting assumptions were made at the outset for practical reasons:

1. the airship forms a rigid body such that aeroelastic effects can be ignored;
2. the airframe is symmetric about the XZ plane such that both the CV and the CG lie in the plane of symmetry.

The dynamic model can be stated as:

$$M\,\dot{x} = F_d(x) + A(x) + G\,(\lambda_{13}, \lambda_{23}, \lambda_{33}) + P$$

where each of the components is described in the sequence.

- Velocity vector, x

The 6x1 velocity vector contains the three linear velocities
u, v, w and three angular velocities p, q, r, all written with respect to the body-fixed reference frame XYZ. For control and navigation purposes, they must be transform to an earth fixed (NORTH-EAST-UP) inertial reference frame, via a direction cosine matrix (DCM):

$$\begin{bmatrix} V_{NORTH} \\ V_{EAST} \\ V_{UP} \end{bmatrix} = DCM \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

- Mass matrix, M

The 6x6 matrix M incorporates all masses and inertias of the airship, including the virtual terms associated with the fact that we are dealing with a buoyant vehicle, plus the variable ballonet mass. For the YEZ-2A or similar aiships it is given by:

$$M = \begin{bmatrix} m-X_{\dot u} & 0 & 0 & 0 & m\,a_z-X_{\dot q} & 0 \\ 0 & m-Y_{\dot v} & 0 & -m\,a_z-Y_{\dot p} & 0 & m\,a_x-Y_{\dot r} \\ 0 & 0 & m-Z_{\dot w} & 0 & -m\,a_x-Z_{\dot q} & 0 \\ 0 & -m\,a_z-L_{\dot v} & 0 & I_x-L_{\dot p} & 0 & -J_{xz} \\ m\,a_z-M_{\dot u} & 0 & -m\,a_x-M_{\dot w} & 0 & I_y-M_{\dot q} & 0 \\ 0 & m\,a_x-N_{\dot v} & 0 & -J_{xz} & 0 & I_z-N_{\dot r} \end{bmatrix}$$

where :

- m is the airship mass;
- $m_x = m - X_{\dot u}$ $\quad m_y = m - Y_{\dot v}$ $\quad m_z = m - Z_{\dot w}$
- $X_{\dot u}$, $Y_{\dot v}$, $Z_{\dot w}$ are the virtual mass terms for X, Y and Z axes respectively;
- I_x, I_y and I_z are moments of inertia about OX, OY and OZ respectively;
- $L_{\dot p}$, $M_{\dot q}$, $N_{\dot r}$ are the virtual inertia terms respectively about OX, OY and OZ respectively;
- $J_x = I_x - L_{\dot p}$ $\quad J_y = I_y - M_{\dot q}$ $\quad J_z = I_z - N_{\dot r}$

- $J_{xz} = I_{xz} + N_{\dot p} = I_{xz} + L_{\dot r}$
  where I_{xz} is the product of inertia about OY, and $N_{\dot p}$ and $L_{\dot r}$ are virtual inertia terms;
- a_x and a_z are the coordinates of CG relative to CB;
- $X_{\dot q}$, $Y_{\dot p}$, $Y_{\dot r}$ and $Z_{\dot q}$ are virtual mass terms;
- $L_{\dot v}$, $M_{\dot u}$, $M_{\dot w}$ and $N_{\dot v}$ are virtual inertia terms;

The virtual masses and inertia can be estimated as [6], [7]:

$X_{\dot u} = -k_1\, B/g \qquad Y_{\dot v} = -k_2\, B/g \qquad Z_{\dot w} = Y_{\dot v}$

$M_{\dot q} = -k'\, [B/g]\ [(l^2 + d^2)/20] \qquad N_{\dot r} = M_{\dot q}$

where B is the buoyancy force, g the gravitational acceleration, k_1 and k_2 are Lamb's inertia ratios for movements along the longitudinal (OX) and lateral (OY) axes respectively, k' is Lamb's inertia ratio for rotation about the lateral axis (OY), and l and d are the airship length and maximum diameter respectively.

- Dynamic forces vector, F_d

The force vector contains the Coriolis and centrifugal terms of the dynamic model, and is given by:

$F_d = [f_1\ f_2\ f_3\ f_4\ f_5\ f_6]^T$

where:

$f_1 = -m_z\, w\, q + m_y\, rv + m\, [a_x\, (q^2+r^2) - a_z\, r\, p]$

$f_2 = -m_x\, u\, r + m_z\, p\, w + m\, [-a_x\, p\, q - a_z\, r\, q]$

$f_3 = -m_y\, v\, p + m_x\, q\, u + m\, [-a_x\, r\, p + a_z\, (q^2+p^2)]$

$f_4 = -(J_z-J_y)\, r\, q + J_{xz}\, pq + m\, a_z\, (u\, r - p\, w)$

$f_5 = -(J_x-J_z)\, p\, r + J_{xz}\, (r^2-p^2) + m\, [a_x\, (v\, p-q\, u) +$
$\quad - a_z\, (w\, q - r\, v)]$

$f_6 = -(J_y-J_x)\, q\, p - J_{xz}\, q\, r + m\, [-a_x\, (u\, r - p\, w)]$

- Aerodynamic forces vector, A

The force vector A contains the aerodynamic terms of the model, arising from the aerodynamics of the airship's hull and control surfaces. It is computed from the non-dimensional coefficients of lift (C_L), drag (C_D), side(C_Y) forces, as well as pitching (C_m), yawing (C_n) and rolling (C_l) moments, as:

$A = F(C_i) = [A_X\ A_Y\ A_Z\ A_L\ A_M\ A_N]^T$

The non-dimensional coefficients C_i, can be obtained from either of the following methods:

- direct measurement in a wind tunnel;
- from the geometrical characteristics of the vehicle [8];
- from aerodynamic stability derivatives.

The non-dimensional coefficients of forces and moments follow the standard convention for airships:

$C_D = A_X / (0.5\, \rho\, U^2\, V^{2/3})$

$C_Y = A_Y / (0.5\, \rho\, U^2\, V^{2/3})$

$C_L = A_Z / (0.5\, \rho\, U^2\, V^{2/3})$

$C_l = A_L / (0.5\, \rho\, U^2\, V)$

$C_m = A_M / (0.5\, \rho\, U^2\, V)$

$C_n = A_N / (0.5\, \rho\, U^2\, V)$

where: A_X, A_Y and A_Z are the drag, side and lift forces (in N); A_L, A_M and A_N are the rolling, pitching and yawing moments (in N.m); V is the airship model volume (in m^3), U is the air speed in wind tunnel test section (in m/s) and ρ is the air density (in Kg/m^2).

- Gravity and buoyancy vector, G

The vector G is simply the difference between the airship's weight, W, and the buoyancy acting upwards on it, B, resolved into airship body axes by the direction cosine parameters λ_{ij}, and simplified by the vehicle symmetry about the XZ plane:

$$G = W - B = \begin{bmatrix} \lambda_{31}\,(W-B) \\ \lambda_{32}\,(W-B) \\ \lambda_{33}\,(W-B) \\ \lambda_{32}\, a_z\, W \\ (\lambda_{31}\, a_z - \lambda_{33}\, a_x)\, W \\ \lambda_{32}\, a_x\, W \end{bmatrix}$$

where:

λ_{ij} are the elements of the DCM - Direction Cosine Matrix, W is the airship weight acting at the CG, B is the buoyancy force acting at the CV, a_x and a_z are CG coordinates on the X and Z axes respectively.

- Propulsion vector, P

This vector contains the terms associated with the propulsive forces and moments, and it is a function of the geometrical arrangement of the propulsive units around the body axes. For a typical arrangement with two propellers on each side of the airship, P is expressed as:

$P = [X_{prop}\ Y_{prop}\ Z_{prop}\ L_{prop}\ M_{prop}\ N_{prop}]^T$

where: X_{prop}, Y_{prop} and Z_{prop} are the total thrust along the OX, OY and OZ axes respectively; L_{prop}, M_{prop} and N_{prop} are the total thrust moments along the same axes; and, considering the distances shown in Fig. 2 :

$X_{prop} = (T_{ds} + T_{dp})\cos(\mu)$

$Y_{prop} = 0$

$Z_{prop} = -(T_{ds} + T_{dp})\sin(\mu)$

$L_{prop} = (T_{dp} - T_{ds})\sin(\mu)\, d_y$

$M_{prop} = (T_{ds} + T_{dp})\, [d_z \cos(\mu) - d_x \sin(\mu)]$

$N_{prop} = (T_{dp} - T_{ds})\cos(\mu)\, d_y$

T_{ds} the Thrust of starboard side

T_{dp} the Thrust of port side

μ the vectorization angle

d_x the horizontal distance from CB to propeller along the airship's main axis

d_y the horizontal y distance from CB to propeller perpendicular to the airship's main axis

d_z the vertical distance from CB to propeller

The mathematical model described above, including the aerodynamic database [2], corroborated by flight test data collect in 1991, is being used in one of the first Internet based airship simulators [9] and also in the Bedford Advanced Flight Simulator [5].

4. AIRSHIP RESPONSE MODES AND CONTROL

Based on the dynamic model presented, a computer simulation [9] was implemented to verify the response modes of the YEZ-2A or similar airships. Four interesting control challenges were found:

- at very low speeds or during hover, airships can only be put in motion by acting on the propellers' speed and vectorization. On the other hand, during cruising, maneuvers are performed by acting on the control surfaces or by exchanging air between the ballonets. An automatic control system should cope with both situations and generate smooth transition between them;
- the airship is a time-varying system, as a consequence of large mass variations during flight due to ballonets contraction and expansion with altitude/temperature fluctuations and fuel consumption;
- airships present a non-minimum-phase behavior for aerodynamic pitch commands at low speeds. In other words, when the control surfaces are used to make the airship gain altitude, it starts going down, before initiating climbing, as shown in Fig. 4;

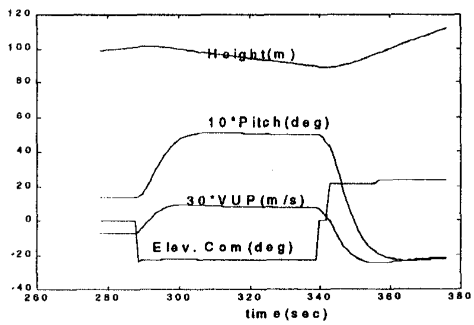

Fig. 4 - Non-minimum-phase behavior at low speeds

- finally, airships present lightly damped oscillation behavior in the lateral and longitudinal modes, mainly during hover. Mathematically, this is due to a system pole close to the imaginary axis at low speeds [2]. The physical explanation has long been known by balloonists, and is based on the fact that the CG is located some distance below the CB.

5. CONCLUSIONS

We presented in this paper a comprehensive description of the physical principles of airships, along with their dynamic modeling in a form suited for computer controller design simulation. Response modes and control challenges were analyzed based on the model presented. This work is hoped to be useful to foster the development of control and navigation systems for autonomous airships.

6. ACKNOWLEDGMENTS

The authors wish to thank Marcel Bergerman, Samuel Bueno, Alberto Elfes, and all the AURORA team for their support.

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