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DEVELOPMENT OF AN AUTOMATIC HEIGHT CONTROL SYSTEM FOR WIG CRAFTS

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Abstract: A WIG craft takes advantage of the ground effect phenomenon, where this kind of craft are designed to fly at low altitudes close to the ground (between 0.05 – 0.5 of the wing cord) to experience an increase in lift, while drag decreases, this result in an enhanced lift-to-drag ratio and hence greater flight efficiency. However to achieve an ideal flying altitude and a safety low flight is necessary to implement an automatic height control system capable of sustaining the WIG craft stable. The concept is to take out the "hand of the man" from the control of the altitude, so that the system will take over the control of the elevator and correct the flying altitude until the ideal level is reached and maintain it there. In addition, this system can also be used to provide accurate flight altitude. *Copyright© 2008 IFAC.*

Keywords: low altitude flight, flight control, marine landing, sea waves, ultrasonic sensors, sensors integration.

1. INTRODUCTION

The development of the WIG Crafts has been growing worldwide. Its advantage and efficiency can provide a new way of transport in the 21st century which can be used to communicate coastal cities, islands and even continents at a very high velocity and less fuel than others kind of transportation systems, and even its use for military proposes can give to an army force the opportunity to have a good "defense weapon".

A WIG craft is designed to fly at low altitudes to take benefit from the ground effect which is understood as an increase in the lift-to-drag ratio of a wing moving close to an underlying surface. It means that this craft can have more capacity for cargo and passengers while consuming less fuel per kilometer. The lift increase is produced because of the presence of the ground that forms a high pressure cushion under the wing, and the drag decrease is produced by the compression of the vortices when the wing approaches to the ground and there is not enough space for the vortices to fully develop, therefore the amount of "leakage" of pressure from the lower side to the upper side is less and the vortices becomes weaker.

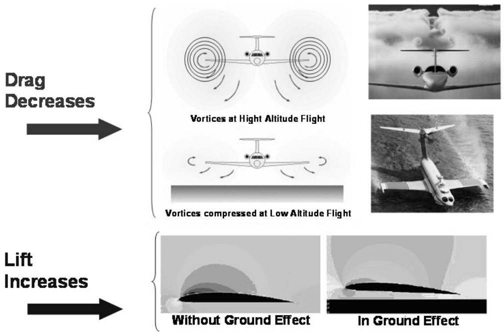


Fig. 1. Ground Effect Phenomenon

For the essential action of ground effect the altitude of the WIG flight has to be less than a half of the wing chord. At the certain size of WIG craft it is possible at the limited height of sea waves. However it is necessary to choose the extremely low flight altitude, permissible as to criterion of flying safety at the definite height of sea waves. Even if the vehicle has the natural properties of self-positioning as to the altitude and the inclination angles, only the facilities of an automatic height control can ensure the required functional characteristics under the circumstances of rough sea. Unfortunately, WIG craft has the essential instability of motion in the longitudinal plane, so perfect automatic control system is necessary first of all for providing good flight stability.

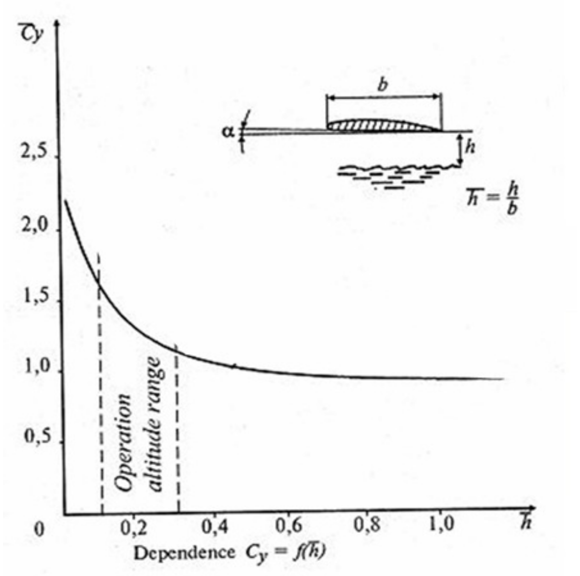


Fig. 2. Coefficient of Lift (Cy) vs height/cord (h/b)

The process of design of WIG craft incorporates, as a necessary element, an investigation of stability of motion and dynamic properties of the WIG craft under development. The estimations of dynamic properties, performed by conducting corresponding calculations, are carried out at every stage of the project development and serve as a guideline for selecting an appropriate variant of the designer's solutions. A necessity in performing the aforementioned investigations is due to complexity of the problems of dynamics of the ground-effect flight. The latter is stipulated by the fact that dynamic qualities of WIG craft change with variation of its kinematical parameters: "pitch angle" and "flight height". The same applies to characteristics of stability. As a result, there exists in the coordinate system a certain domain of stability of motion of the WIG craft. The problem consist of maximally widening dimensions of this domain, thus securing the stability of motion of the WIG craft in the wider possible ranges of variation of pitch angle and flight heights.

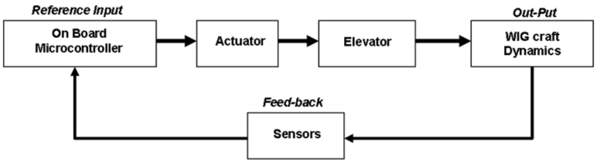
As the peculiarities and complexities of providing the stability of WIG craft fully exhibits themselves during its motion in vertical plane.

Strong dependence of dynamic properties of WIG craft on parameters of its motion, which distinguish WIG craft from Air craft, is stipulated by complex dependencies of its aerodynamic characteristics upon the said kinematical parameters. Therefore, if automatic control system is not used for ensuring stability of the WIG craft, its stability can only be reached for quite certain quantitative relationships between the magnitudes of aerodynamic characteristics, resulting in appearance of stability domain in the parametric space. Therefore, the problem consists of determining a correspondence between the domains, which is of finding the magnitudes of the aerodynamic characteristics required to ensure stability of the craft. This can be done, for example, by considering linear mathematical models of flight dynamics of WIG craft.

2. DESIGN OF THE AUTOMATIC HEIGHT CONTROL SYSTEM

The objective is to implement an automatic height control system capable of sustaining the WIG craft at the ideal flying altitude, so that the required L/D ratio and a stable flight motion are achieved, giving a safety low flight. The concept adopted is that during the initial take off, this system will take over the control of the elevator and correct the flying altitude until the ideal level is reached and maintain it there. In addition, this system can also be used to provide accurate flight altitude data. The whole system requires various hardware components, written algorithm control logic and the understanding of the flight motion dynamics.

A schematic diagram of the overall height control system is as follows:



2.1 Components

All the components of this system involve the consideration of important factors such as performance, reliability, weight, compatibility, availability, ease of use and cost. All selected components must to be integrated for their functionability under various conditions.

2.1.1 Sensors And On Board Microcontroller

A sensor has to be implemented to provide accurate altitude measurements and feedback to the control loop. As the WIG aircraft is designed to fly at low altitude (between 10cm to 10m) and at a maximum speed of approximately 70m/s, the sensor chosen must have a sensing range capable of operating within this altitude and speed limits, and a blind zone of less than 5cm. In addition, the sensor must be able to function accurately over water surface and must be compatible with the other hardware components.

After considering several sensors, operating under different principles such as capacitive, photoelectric and ultrasonic mode; as well as sensors with different scan techniques such as thru-beam, retro-reflective and diffuse scan, the Parallax PING ultrasonic range finder SRF08 is ultimately chosen. The sensor detects objects by emitting a 40kHz short ultrasonic burst and then "listening" for the echo. It has a sensing range of between 2.5cm to 10m with a resolution of 2.5cm and as such, provides good coverage for the distance required.

Fig. 3. PING ultrasonic sensor SRF08

An integral component in this system is the onboard microcontroller, which is used to store the algorithm logic, receive signals, store data and send out control commands to the actuator. In selecting this microcontroller, important factors of consideration includes: power consumption, processing speed, compatibility with other electronics, weight and cost. After careful consideration, Parallax's 2SX (BS2SX-IC) module is selected for this application. The microcontroller is somewhat like a single board computer, as it has its own processor, memory, clock, and interface (via 16 I/O pins). It serves as the 'brains' inside electronics applications, and is able to control and monitor switches, timers, motors, sensors, relays, etc.

Programming is performed using the PBASIC language. BS2SX-IC shows improved speed, larger program memory, faster serial I/O and higher resolution for time sensitive command when compared with many other available models. Furthermore, it comes with serial PC interface, which provides enhanced debug features, via an in-house editing software.

The board allows for easy integration with other control components and the downloading of the programming codes. It serves as an ideal development platform for various control applications. In addition, the Parallax 2SX microcontroller is designed by the same company that develops the ultrasonic sensor and as such, offers good hardware compatibility and easy integration.

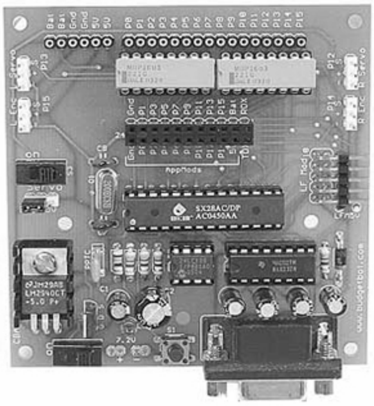


Fig. 4. Parallax 2SX Microcontroller on Board

The various hardware components are then interconnected to ensure compatibility, and verify that the microcontroller is able to send precise signal pulses to the actuator at regular interval. Different signal pulse widths will result in the actuator turning at different angles.

A simple experiment is also designed to verify that the sensor is able to take multiple readings, over both ground and water surface, and ensure its accuracy. The setup shown below explains how the sensor is tested to take readings over water surface at different height and across varying forward velocity.

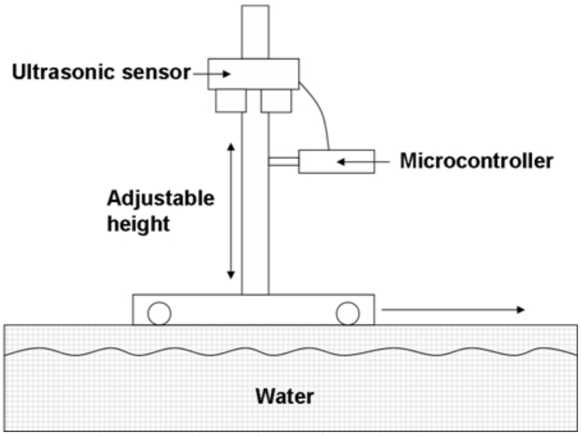


Fig. 5. Experimental setup for testing the sensor

2.2 Establishing the Aerodynamics Transfer Function.

The basic logic of this automatic height control system is to control the angle of deflection of the elevator, in order to generate the required change in moment on the tail. This change in tail moment will result in a change in the angle of attack of the WIG craft and in turn produce a change in the height, to compensate for any deviation from the ideal flying altitude, as stipulated by the control logic program.

To accomplish this function, it requires the calculation of the transfer function that represents the WIG craft dynamics.

To understand the motion dynamics of the WIG craft, it is important to first determine its moment of inertia about the C.G. since the objective is to implement an automatic height control system, pitch angle is the most crucial parameter, and the focus is thus to determine the moment of inertia along the pitch axis (X-axis).

Moment generated due to $\Delta\alpha$ = ΔLift on the tail x moment arm, l_t
$M(\alpha) = -\, l_t\,(\Delta \mathrm{Lift}) = -l_t\,(C_{L\alpha t}\,\alpha\, Q\, S_t) = C_{M\alpha t}\alpha Q S_t$ (1)
Where
$Q = 0.5\,\rho\, V^2$
S_t = area of the tail
l_t = distance between the C.G. and a/c of tail

Taking derivative with respect to α:

$dM/d\alpha = C_{M\alpha t}\, Q\, St$ (2)

Note that the change in angle of attack, $\Delta\alpha$ on an aft surface can be approximated using small angle approximation:

$\tan\Delta\alpha = q\, l_t/V$
Therefore for small angle, $\alpha \approx q\, l_t/V$

Now consider the moment contribution due to pitching velocity (pitch rate) q:

$M(q) = -l_t\,(C_{L\alpha t}\,\Delta\alpha\, Q\, S_t) = -l_t\,[C_{L\alpha t}\,(q\, l_t/V)\, Q\, S_t]$ (3)

Taking derivative with respect to q:
$dM/dq = -lt[_{L\alpha t}\,(l_t/V)\, Q\, S_t]$ (4)

The equation of motion governing the pitching motion can be derived as follows:

$M = I_y\,\Delta\ddot{\alpha}$ (5)

Generally, pitching moment, M can also be expressed as a function of change in angle of attack, rate of change of angle of attack, change in pitch rate and change in elevator deflection as shown below:

$M = f(\Delta\alpha, \Delta\dot{\alpha}, \Delta q, \Delta\delta_e) = (dM/d\alpha)\,\Delta\alpha + (dM/d\dot{\alpha})\,\Delta\dot{\alpha} + (dM/dq)\,\Delta q + (dM/d\delta_e)\,\Delta\delta_e$ (6)

Equating equation (5) and (6),
$\Delta\ddot{\alpha} - (Mq\dot{\alpha} + M)\Delta\dot{\alpha} - M_\alpha\,\Delta\alpha = M_{\delta e}\,\Delta\delta_e$ (7)
where $Mq = (dM/dq)/Iy$ $M\dot{\alpha} = (dM/d\dot{\alpha})/Iy$ $M_\alpha = (dM/d\alpha)/Iy$ $M_{\delta e} = (dM/d\delta_e)/Iy$ and $\Delta q = \Delta\dot{\alpha}$

Note that the moment contributions from the wings are neglected in the formulation of the above equation. This is because all moment calculations are taken with respect to the C.G position of the aircraft, which is very close to the aerodynamic centre of pitch of the wings and thus, the moment arm for the wings is very small, leading to negligible moment contributions.

Now taking Laplace Transform of equation (7),

$s^2 F(s) - sf(0) - \dot{f}(0) - (M_q + M_{\dot{\alpha}})(sF(s) - f(0)) - M_\alpha F(s) = M_{\delta e}\,\Delta\delta_e$ (8)

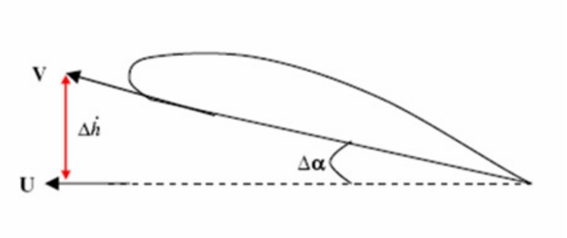
Note that $f(0) = \dot{f}(0) = 0$. Also, the contribution due to $M_{\dot{\alpha}}$ in equation (8) is ignored because this term is primarily due to the interaction of the wing wake on an aft surface. This effect is negligible in this WIG craft configuration because the tail is mounted at a high vertical location such that it is exposed to little downwash.
Rearranging equation (8) yields:

$F(s)[s^2 - M_q s - M_\alpha] = M_{\delta e}\,\Delta\delta_e$
$\Delta\alpha(s)\,[s^2 - M_q s - M_\alpha] = M_{\delta e}\,\Delta\delta_e$

$$\frac{\Delta\alpha(s)}{\Delta\delta_e} = \frac{M_{\delta e}}{s^2 - M_q s - M_\alpha} \qquad (9)$$

Let the change in height due to the pitching moment be Δh. For small angle, $V \approx U$

$\Delta\dot{h} = V\sin(\Delta\alpha) = U\Delta\alpha$ (10)



Now taking Laplace Transform of equation (10),

$s\Delta h(s) = U\Delta\alpha(s)$

Dividing by de throughout, the transfer function becomes:

$$\frac{\Delta h(s)}{\Delta\delta_e} = \frac{U}{s}\,\frac{\Delta\alpha(s)}{\Delta\delta_e} = \frac{U}{s}\left(\frac{M_{\delta e}}{s^2 - M_q s - M_\alpha}\right)$$

By modeling the control surfaces under ideal flight conditions and deflecting them at various angles, a series of simulations are done to compute the change in force and moment generated about the hinge. This is to determine the load torque acting on the respective control surfaces at various angle of deflection, and will help to determine the moment specifications required on the actuator controlling the surface (elevator).

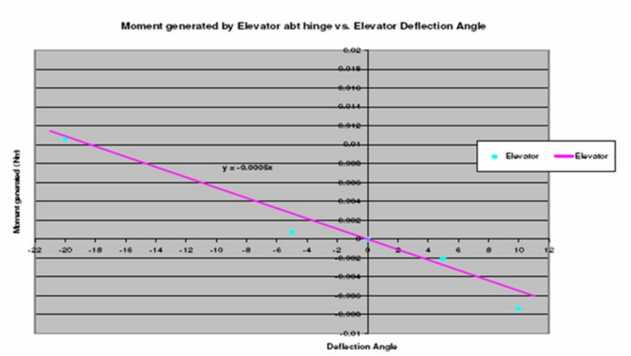


Fig. 6. Moment generated about the hinge against angle of deflection.

2.3. Implementation of the System

After selecting the necessary hardware components, writing the control algorithm and determining the overall transfer function, the system is installed on board the WIG craft, ready for testing.

The first stage of testing the system involves a static test. The sensor is attached to the underside of the WIG craft and height readings are taken at varying altitude to test for the range of the sensor and accuracy of the measurements. The deflection of the elevator is also monitored to ensure that the control logic is functioning properly. The results of this experiment show that the sensor is able to measure and provide accurate height readings over the range of 2.5cm to 3m, and is very responsive to any sudden height changes. The corresponding response of the elevator deflection angle is also very fast and precise. As such, it is concluded that the static performance of the height control system is satisfactory.

Flight test are conducted over water surface to verify the ground effect characteristics of the WIG craft, and measure its flight performance. This also helps to prove the accuracy of earlier simulation results. The automatic height control system is also tested to verify its performance and effectiveness and is evident that the craft is capable of achieving Ground Effect.

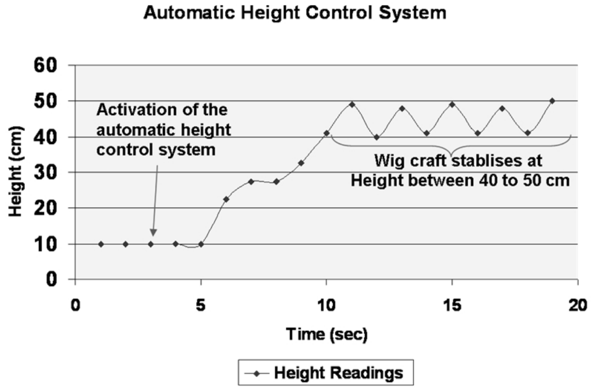


Fig. 7. Graphics of Height Readings of the Sensors.

3. CONCLUSION

For a WIG craft, which is designed to fly very close to the surface at a very high velocity, the use of an automatic height control system is essential to maintain a safety flight and a good effectiveness of the ground effect. The design of this system requires taking in account the varying of the environmental conditions and the state of the sea so that the height can be achieved without disturbance of the motion of the WIG craft.

At the time of a real use of the WIG craft technology is important to understand the average of the sea state in the operation area where this "flying ship" will be in service. The knowledge of this parameter provides the necessary information for the designing of the automatic height control system principally in the parameters of the control algorithms and the program coding, so the altitude of flight will be specified according to the average height of the sea waves.

This system was developed to be installed in an experimental WIG craft which is being tested to prove the principles for an ideal control system that allows to the pilot to maneuver the ship without having to control the height at the same time, which can turn into a factor of danger for the application of the WIG technology.

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