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Analysis of Wing-in-Ground-Effect Vehicle with regard to Safety Ensuring Control

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Abstract: Due to the efficiency and their classification as fast vessels, wing in ground crafts have the potential to become favored transport vehicles for mean distances in coastal regions. However, up to now, this potential could not be realized, because the safe operation of WIG crafts fails in view of the challenging control problems. The nonlinear character of the aerodynamics close to the ground, the constraints for actuators and states, as well as the need for high performance call for advanced control concepts. The paper will contribute to the solution of the control problem by providing appropriate mathematical models. On basis of a theoretical analysis, the paper describes the applied methods and results for the experimental process identification at a scaled 5:1 WIG craft. Apart from the effect of the actuators, the influence of wind and surface disturbances is investigated. The achieved nonlinear MIMO models have been verified at different experiments, and have already proven to be very useful for the design of first basic controllers.

Keywords: Marine system analysis, identification and modelling; Nonlinear and optimal marine system control; Wing-in-ground effect Vehicle

1. INTRODUCTION

The phenomenon of increased lift and reduced lift-induced drag experienced by a wing, operating close to a ground plane, is called wing-in-ground (WIG) effect. A WIG craft is a particular type of watercraft that exploits this benefit by being designed to maintain a small and constant gap between the water surface and the trailing edge of the wing in cruising flight. Fuel economies in relation to speed is considerably more efficient than traditional waterborne and airborne means of transportation.

Safe operation of WIG crafts means cruising flight with maximum reliability never to touch the water surface. With the presence of disturbances, stability problems arise that make a stabilizing control system an essential part of the WIG craft (Nebylov, 2009). Stability was first investigated by Staufenbiel (1978). To improve stability, the huge Russian WIG crafts (ekranoplan) had been equipped with analog controllers at that time (Diomidow, 1996; Shukow, 1997). Up to the present, new techniques in control design as well as in real-time implementation are grown up. On the other hand energy resources became scarce good. With the altered perspective, the WIG craft's scope has undergone a radical change. In this regard we need to start all over again and enhance the WIG craft set-up with respect to fuel efficient and primarily safe means of transportation.

Efforts in performing height control were made by Daniel (2008). A complex real-time flight simulator to train WIG drivers was developed by Kolewe et al. (2010). WIG craft behavior at the presence of disturbances have been investigated by Kornev and Groß (2013).

IMO (2003) certifies as follows: *A WIG craft is a high speed vessel. The WIG craft principal mode of operation is flying through the atmosphere over water in the zone of aerodynamic influence of the surface. WIG crafts operate with other waterborne crafts and must utilize the same collision avoidance rules as conventional shipping.*

Actual WIG crafts are designed to close the gap between slow economical watercrafts and fast fuel consuming aircrafts at operational distance of 100 km to 1000 km and cruising speed of about 200 km/h. WIG crafts make use of the same infrastructure like other marine vessels. As a consequence they have to maneuver between landing stage and runway which requires adequate maneuverability in displacement mode with presence of rough sea and wind.

It is widely believed that the problem of safely operating WIG crafts cannot finally be solved by mechanical engineering design features only but by modern control methods. Since an entire control system is not available yet, this paper is devoted to the analysis and modeling of a scaled WIG craft with respect to robust and reliable stabilization of the ground clearance.

2. PROBLEM AND APPROACH

From control design point of view WIG crafts have a tricky behavior in some respects that follows from aerodynamics in ground effect. Below the rear part of the wing, the close ground creates a ram pressure that results in an additional force $\boldsymbol{F}_{ge}$ and moment $\boldsymbol{M}_{ge}$ depending on the ground distance, Fig. 1. The effect is experienced by the pilot as pitch up tendency during ascent. The shift of the aerodynamic center is an inherent danger during flight in ground effect because it potentially leads to longitudinal instability. In

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case of flight regime changes or disturbances such as acting wind gusts, a properly performed corrective action could be required immediately. Applying an automatic control system is prerequisite to ensure safe operation. To gain good handling qualities, modeling and control system synthesis has to focus on watercraft qualities as well as on aircraft qualities of the WIG craft.

For achieving the coming objective of high-performance and fully integrated control system for automatic procedure of takeoff and alighting, reliable control of ground clearance that is robust to disturbances and also the ability to fly a sharp control system guided emergency turn while still preventing fatal touch down of the wingtip several steps have to be processed:

(1) preliminary study of process behavior with scaled prototype
(2) analysis of particular characteristics of WIG craft with respect to modeling, identification and control
(3) wind-tunnel investigation of WIG craft to determine specific model parameters
(4) inspect available WIG craft models for applicability in control system design
(5) identification tests with scaled prototype
(6) design of WIG craft models with the aim that identification can be achieved by utilization of collected measurements
(7) identification of WIG craft models for different operational modes, different operating points/ranges
(8) Control system synthesis
(9) evaluation of control system by running real-time simulation of alternative complex WIG craft model
(10) real testing of scaled prototype with activated control system

In this paper mainly steps (1) – (7) are dealt with.

3. PROCESS DESCRIPTION

The design of a controller for such a complex process typically requires a hierarchy of different models:

- A basic models which can easily be fitted to measurements and build the origin for first basic controllers.
- A more complex model which can be applied for more realistic controller modifications and verification.

3.1 Basic model

The Basic model can be derived from Kirchhoff's equations (rigid body in ideal fluid, (Fossen, 1994))

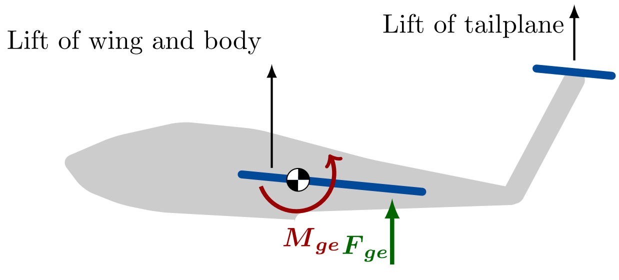

Fig. 1. Force $\boldsymbol{F}_{ge}$ and moment $\boldsymbol{M}_{ge}$ acting on a WIG craft in ground effect

$$\boldsymbol{F}_{b,\text{water}} + \boldsymbol{F}_{b,\text{aero}} + \boldsymbol{F}_{b,\text{thrust}} + \boldsymbol{F}_{b,g} = \mathbf{m}\dot{\boldsymbol{v}}_b + \boldsymbol{\omega}_b \times \mathbf{m}\boldsymbol{v}_b \quad (1)$$

$$\boldsymbol{M}_{b,\text{water}} + \boldsymbol{M}_{b,\text{aero}} + \boldsymbol{M}_{b,\text{thrust}} = \mathbf{J}\dot{\boldsymbol{\omega}}_b + \boldsymbol{\omega}_b \times \mathbf{J}\boldsymbol{\omega}_b + \boldsymbol{v}_b \times \mathbf{m}\boldsymbol{v}_b \quad (2)$$

where $\boldsymbol{m}$ is the mass of the vehicle, $\boldsymbol{J}$ is it's inertia matrix, $\boldsymbol{v}_b$ is the translational velocity, and $\boldsymbol{\omega}_b$ is the angular velocity. Note that the mass matrix $\boldsymbol{m} = \begin{bmatrix} m_{xx} & 0 & 0 \\ 0 & m_{yy} & 0 \\ 0 & 0 & m_{zz} \end{bmatrix}$ includes the hydrodynamic mass at low speed in displacement mode. The applied forces $\boldsymbol{F}$ and moments $\boldsymbol{M}$ on the left sides of (1), (2) have been transformed to body fixed frame (subscript b). They arise from water, aerodynamics, thrust and gravity.

Under the assumption of quasisteady flow the aerodynamic force and moment are expressed in vector forms as

$$\boldsymbol{F}_{b,\text{aero}} = \mathbf{C}_w^b \begin{bmatrix} -C_D \\ C_S \\ -C_L \end{bmatrix} \cdot \frac{1}{2}\varrho A \cdot |\boldsymbol{v}_{b,w}|^2 \quad (3)$$

$$\boldsymbol{M}_{b,\text{aero}} = \begin{bmatrix} bC_R \\ \bar{c}C_P \\ bC_Y \end{bmatrix} \cdot \frac{1}{2}\varrho A \cdot |\boldsymbol{v}_{b,w}|^2 \quad (4)$$

where ϱ is the air density, A is the wing reference area, $\boldsymbol{v}_{b,w}$ is the air-relative velocity (wind fixed frame), b is the wing span, and $\bar{c}$ is the mean aerodynamic chord of the wing. $\mathbf{C}_w^b$ is transformation from wind fixed to body fixed frame.

To design a WIG craft aerodynamic model, the force and moment coefficients for drag C_D, side force C_S, lift C_L, roll C_R, pitch C_P, and yaw C_Y have to be characterized as functions $C(h, \boldsymbol{v}, \dot{\boldsymbol{v}}, \boldsymbol{\omega}, \dot{\boldsymbol{\omega}}, \delta \ldots)$ that depend on the WIG craft states, inputs δ and especially on height h.

$\boldsymbol{F}_{b,\text{water}}$ has to involve hydrostatic as well as hydrodynamic effects where the latter is crucial for capturing take-off and landing. This paper focuses on flight mode.

3.2 Vortex lattice method

The more complex model is obtained by an approach that applies vortex lattice method (VLM) to compute aerodynamic coefficients and their derivatives. Based on that way pre-generated lookup tables, dynamic simulation of aircraft coefficient model is executed. It was shown that WIG craft behavior is captured fairly good for selected operating points by developed software AUTOWING. (Kornev and Matveev, 1993)

In real flight test, there are flight regimes that are not practicable to reach without hazard but need to be mastered by control system. Therefore we utilize the dynamic model resulting from VLM.

3.3 Multi-component multiple-point model

The approach divides the WIG craft into functional components. For each, the generated force and moment is calculated separately for different operating points (i. a. displacement mode, ground effect mode). The model considers influence of wind and waves as well as streaming between the functional components and deformations of airfoils. (Kolewe et al., 2010)

Because a wide range of non-linear effects (including touchdown of wing tip) is captured by the model we adopt it for evaluation of controllers in real-time testing.

4. OBJECT OF INVESTIGATION

This paper investigates the control capabilities of WIG crafts utilizing a 5:1 scaled model; specifications are outlined in Tab. 1. The full-scale WIG craft HYDROWING was build and tested in Germany, see Ebert and Meyer (1998).

The scaled WIG craft is equipped with low range radio altimeters, pitot tube, magnetometer, GPS, fiber optic gyroscope, accelerometer. On board, the flight control computer processes all sensor signals and pilot inputs before they are directed to the actuators. It allows for rapid prototyping by running MATLAB/SIMULINK models in real-time.

Wind tunnel tests, shown in Fig. 2, were done to determine aerodynamic parameters of the scaled WIG craft e. g. thrust of propellers as functions of airspeed and rotational speed of propellers.
Captive WIG craft experiments, shown in Fig. 3, were done to identify parameters of static cruising flight conditions and of dynamic response to input steps.
Flight tests over water, shown in Fig. 4, were done to determine remaining parameters and to verify previous results.

Tab. 1. Specifications of scaled WIG craft

Property	value
vehicle weight	30.1 Kg
mean chord	0.85 m
wing reference area	1.98 m^2
wing span	2.34 m

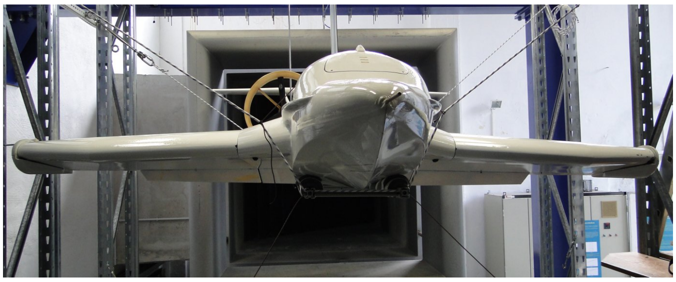

Fig. 2. Scaled WIG craft in wind tunnel

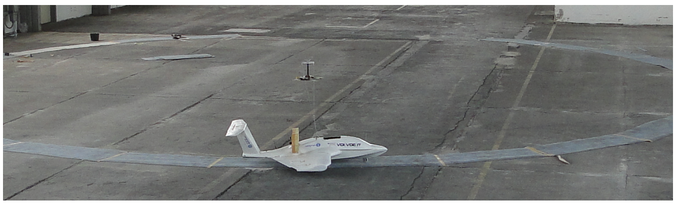

Fig. 3. Scaled WIG craft rebuilt as captive plane and tested in a large, empty storage hall

5. IDENTIFICATION OF THE CAPTIVE WIG CRAFT

Below, some results of investigating the flight behavior of the scaled WIG craft as captive plane are presented.

The utilized WIG craft shows only weak stability at particular operating points. Challenge of performing flight tests with difficult handling qualities is solved by assistance of simple controllers. As a consequence of this, identification approaches have to consider the activated controllers, which again can be challenging.

Interaction between ground distance, angle of attack and air speed

In steady flight, lift is equal to weight. The most influential process variables to generate lift are air speed, angle of attack and height. If ground effect decreases during ascent, lift has to be maintained by increasing angle of attack or speed. All three variables captured at different steady flight conditions and plotted in Fig. 5 show a surface that represents possible cruising flight conditions.
Knowledge about possible flight conditions can be adopted for computing flight path. User demands for desired height requires the control set-points to be determined according to Fig. 5.
Recorded flap/elevator deflection, propulsion etc. for several steady states provides required data for developing feed forward control.

Fig. 6 demonstrates how to manipulate height of WIG craft by fixing speed and pitch-angle. The corresponding height should be readable from Fig. 5, too.

Fig. 4. Scaled WIG craft flying over water

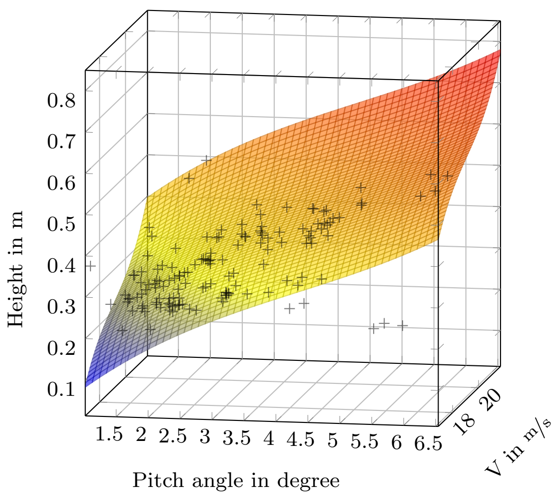

Fig. 5. Surface of static flight conditions

Lift generated by ground effect

Capturing angle of attack at constant speed but various heights is used to explore effect of ground distance (Fig. 7).

Ground effect increases extremely when WIG craft approaches the ground. When ground distance exceed chord, ground effect approaches zero.
When modeling lift coefficient of WIG craft with

$$C_L\left(\delta_{\text{flap}}, \alpha, h, \ldots\right) = K_0 + K_{\text{flap}}\delta_{\text{flap}} + K_\alpha \alpha + f\left(h\right) + \ldots \quad (5)$$

at least one term $f(h)$ has to appear that captures dependence on ground distance.
For control design, WIG craft model has to be chosen as simple as possible. Linearization is a common approach but as mentioned before, with transition to free flight ground effect tends to zero. Exponential function of the form $f(h) = k_{h1}\exp\left(-{}^{h}/_{k_{h2}} + k_{h3}\right)$ fulfills the requirements. We have to explore how to deal with such a term in control design.

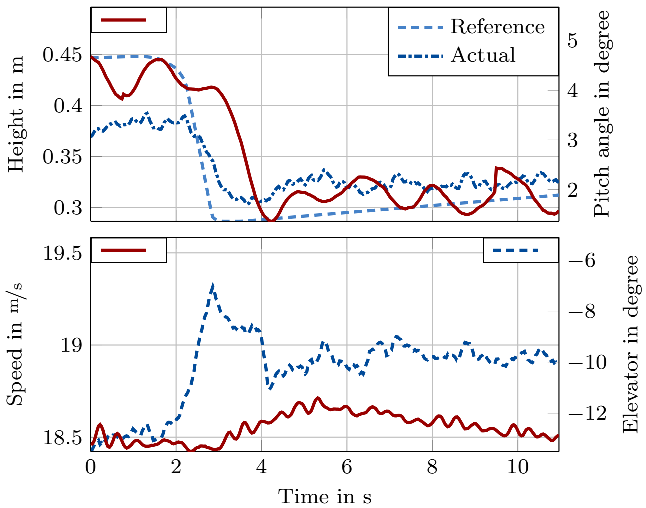

Fig. 6. Basic PD-control of pitch-angle and PID-control of speed to manipulate height related to Fig. 5 (Left legend corresponds to left axis and vice versa.)

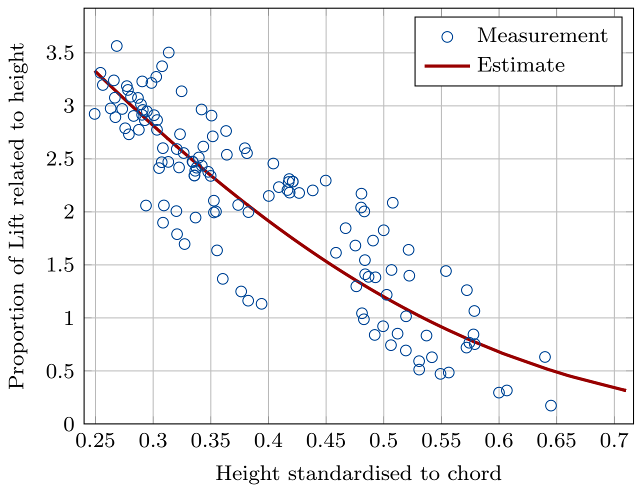

Fig. 7. Aerodynamic lift force in relation to ground-distance

Effect of elevator

Comparing various steady flight conditions at different heights, shows that elevator is folded down with increased height.
The influence of ground-effect decreases with height. Same holds for the related moment. To keep height in steady flight, elevator is utilized to trim pitch/height.
Trim of pitch by shifting center of mass has to be adjusted such that clearance to limits of elevator is ensured in extreme ground-effect as well as out of ground-effect for any speed. If impossible, effect of elevator is insufficient – operation in flight mode is hazardous. In case of limits come into effect pitch-up or touch down crash is the consequence. A larger control surface might be required than for a corresponding air craft.

Trim of pitch by shifting center of mass is quite delicate; referred to scaled WIG craft (Tab. 1), position of center of mass has to be adjusted with accuracy of about $\pm 1.5\,\text{cm}$ to ensure sufficient handling qualities.
Distribution of passengers or cargo load in WIG craft is highly relevant for operability. Inappropriate adjusted center of mass has to be compensate with tailplane or elevator deflection – large control surface is required to avoid above-mentioned issue of limitations.

Pitch angle with respect to elevator deflection is presented in Fig. 8. Reaction in pitching shows absolutely sufficient dynamics.

Effect of flaps

Short time period of height with respect to flap deflection is presented in Fig. 9. Height-response shows non-minimum-phase behavior.
Flap deflection not only enhances lifting force but also generates pitch down moment that lets decrease angle of attack and hence height. Angle of attack has greater effect to lifting than flap deflection.

Long time period of height with respect to flap deflection is presented in Fig. 10. Flap deflection leads to **de**creasing height.

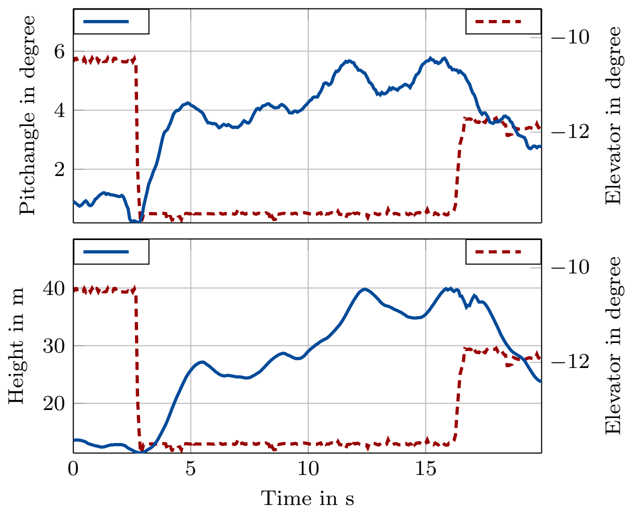

Fig. 8. Elevator step response. (Left legend corresponds to left axis and vice versa.)

Assuming that flaps should enhance lift and increase height it is found that flap deflection provokes a quite contrary effect. Because of the relatively large chord, flaps are placed far behind center of mass and thus have effect similar to elevator as reasoned above.

Height control with exclusive use of flaps is not suitable. An option to benefit from flaps is to compensate the undesirable moment with appropriate elevator deflection in feed forward control.

Wind gust disturbance

To safely control a WIG craft, adequate knowledge about it's behavior in case of windy weather is required. Therefore the response to a wind gust (up to 5 knots) is investigated as captive plane (Fig. 11). .

The steady flight is disturbed by a wind gust that acts tangential to the circular flight path. This is realized by flying through the air flow of a fan. When the wind gust

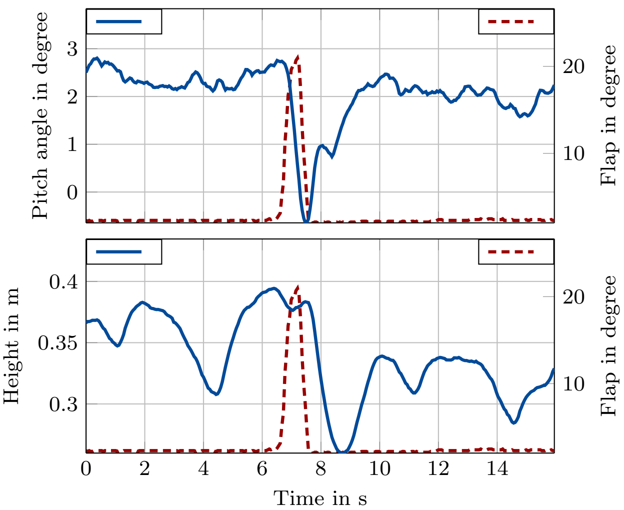

Fig. 9. Deflection test signal response to height and pitch angle. (Left legend corresponds to left axis and vice versa.)

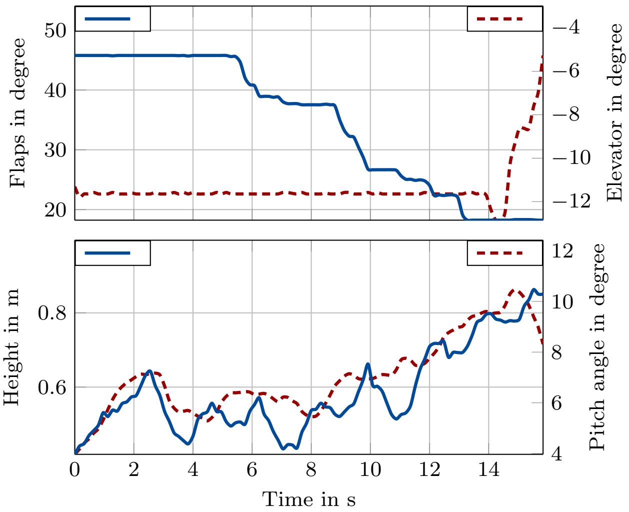

Fig. 10. Long time period response of flap deflection shows contrary effect than required. (Left legend corresponds to left axis and vice versa.)

comes into effect, the WIG craft undergoes a temporary ascent and afterwards returns to the initial height.
The stronger the gust of wind relative to ground speed the higher the jump. Significant change in pitch angle with tendency to pitch up was not observed in the experiments but this should not be generalisable.
Increasing speed in cruising flight minimizes influence of wind gust disturbance. Minimizing oscillation in height arising from wind and wave disturbance is not only objective of a stabilizing controller but also the goal of the passenger's perspective.

6. IDENTIFICATION FROM REAL FLIGHT EXPERIMENTS

Real flight measurements are used to identify the aerodynamic submodels C in (3), (4). These models are assumed to have the form of

$$C(\alpha, \delta, h, \ldots) = K_0 + K_\alpha \alpha + K_\delta \delta + \mathrm{f}(h) + \ldots \tag{6}$$

where α is the angle of attack, δ is a pilot input, h is the height, and K_0, K_α, K_δ, ... are scalar parameters which have to be identified.

In case of ground effect we have to deal with a non-linear term $\mathrm{f}(h)$ that involves ground distance dependent lift and drag respectively. Early investigations by Wieselsberger (1921) assume exponential decrease of resistance of a wing approaching ground.

For the purpose of identification, dynamic model (1), (2) is rearranged to obtain aerodynamic coefficients (Klein and Morelli, 2006)

$$\begin{bmatrix} -C_D \\ C_S \\ -C_L \end{bmatrix} = \mathbf{C}_b^w \left(m \left(\frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{v}_b + \boldsymbol{\omega}_b \times \boldsymbol{v}_b \right) - \boldsymbol{F}_{b,\text{thrust}} - \mathbf{C}_e^b \cdot \boldsymbol{F}_{e,G} \right) \cdot \left(\frac{1}{2} \rho A \cdot |\boldsymbol{v}_w|^2 \right)^{-1} \tag{7}$$

$$\begin{bmatrix} bC_R \\ \bar{c}C_P \\ bC_Y \end{bmatrix} = \left(\mathbf{J} \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{\omega}_b + \boldsymbol{\omega}_b \times \mathbf{J} \boldsymbol{\omega}_b - \boldsymbol{M}_{b,\text{thrust}} \right) \cdot \left(\frac{1}{2} \rho A \cdot |\boldsymbol{v}_w|^2 \right)^{-1}. \tag{8}$$

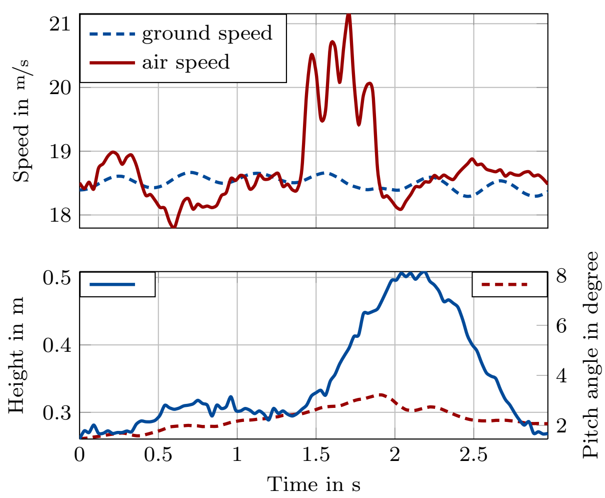

Fig. 11. Wind gust disturbance. (Left legend corresponds to left axis and vice versa.)

This way the right hand sides of (7), (8) can be determined from measurement data. The left hand side of (7), (8) are the coefficients in the form of (6). Note that mass and inertia are known from laboratory measurements, propulsion is known from wind tunnel tests, force/moment caused by water contact is excluded.

In case of aerodynamic submodel (6) is linear in the parameters, linear regression can be applied. Therefore (6) is evaluated at discrete time steps $t = 1$, $t = 2$, ... of a dynamic flight test and written in vector form

$$\underbrace{\begin{bmatrix} 1 & \alpha_1 & \delta_{\delta,1} & \cdots \\ 1 & \alpha_2 & \delta_{\delta,2} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}}_{\boldsymbol{X}} \cdot \underbrace{\begin{bmatrix} K_0 \\ K_\alpha \\ K_\delta \\ \vdots \end{bmatrix}}_{\boldsymbol{\theta}} = \underbrace{\begin{bmatrix} C_1 \\ C_2 \\ \vdots \end{bmatrix}}_{\boldsymbol{Z}} + \underbrace{\begin{bmatrix} \nu_1 \\ \nu_2 \\ \vdots \end{bmatrix}}_{\boldsymbol{\nu}}$$

where $\boldsymbol{\nu}$ are measurement and model errors. Now, all K are directly found by

$$\hat{\boldsymbol{\theta}} = \left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\boldsymbol{X}^T\boldsymbol{Z}. \quad (9)$$

This method gives initial estimates for the coefficients K_0, K_α, K_δ, ... that are required to apply non-linear optimization of WIG craft model.

7. CONCLUSION

Analysis of a scaled WIG craft was done with respect to two primary objectives of control design:

(1) high performing ground clearance control to be save not to touch the sea-surface with the wing-tip which potentially leads to air crash
(2) robustness against wind gust disturbance and wave disturbances (fast changing height).

Results of analysis and involved challenges of control design are summarized as follows:

(1) In case of disturbed flight, we expect transient through a broad range of height. The ground effect dependent lifting force is non-linear with respect to ground distance. Therefore single operating point design might be impractical.
(2) Especially in case of insufficient trimmed center of mass, elevator limitations may take effect. Controller has to deal with that.
(3) There is a strong coupling between speed and height and there are two inputs: elevator and flap to control height (see Fig. 12). These circumstances may require to treat WIG craft as MIMO-system and to reflect about an approach for control allocation.
(4) It is important from safety aspects as well as for comfort of passengers to observe certain specified limits in height, angle of attack, acceleration, speed, propulsion and other. These constraints form the flight envelope that has to be protected by controller.

Control system design, i. e. evaluation of control structure, determination of parameters as well as verification of controllers is subject of current research.

REFERENCES

Daniel, D. (2008). Development of an Automatic Height Control System for Wig Crafts. In *17th IFAC World Congress*. Seoul, Korea.

Diomidow, V. (1996). *Automatic Control of Ekranoplan Motion*. Central Scientific and Research Institute ELEKTROPRIBOR State Research Center of the Russian Federation, St. Petersburg.

Ebert, J. and Meyer, M. (1998). Hydrowing – a New Efficient Wing-in-Ground Effect Craft. In *International workshop WISE up to ekranoplan GEMs*, 267–273. The University of New South Wales, Sydney, Australia.

Fossen, T. (1994). *Guidance and Control of Ocean Vehicles*. John Wiley & Sons, Chichester (UK).

IMO (2003). Wing-in-Ground (WIG) craft. International Maritime Organization, `http://www.imo.org/OurWork/Safety/Regulations/Pages/WIG.aspx`. Accessed: 2013-10-15.

Klein, V. and Morelli, E. (2006). *Aircraft System Identification: Theory and Practice*. American Institute of Aeronautics and Astronautics.

Kolewe, B., Drewelow, W., Dewitz, D., and Lampe, B. (2010). MARSPEED - Modelling and Real Time Simulating the Motion of a Wing-in-Ground-Effect Vehicle. In *8th IFAC Conf. on Control Applications in Marine Systems*, 219–224.

Kornev, N. and Groß, A. (2013). Investigations of the Safety of Flight of WIG craft. *Journal of Marine Sciences and Technology*.

Kornev, N. and Matveev, K. (1993). Complex Numerical Modeling of Dynamics and Crashes of Wing-in-Ground Vehicles. In *American Institute of Aeronautics and Astronautics (AIAA)*.

Nebylov, A. (2009). New Generation of Automatic Control Systems for WIG-craft. In *IFAC Workshop "Aerospace Guidance, Navigation and Flight Control Systems"*. Samara, Russia.

Shukow, W. (1997). *Aerodynamics, Stability and Controllability of Ekranoplan (russian)*. Central Aerohydrodynamics Institute (TsAGI).

Staufenbiel, R. (1978). Some nonlinear effects in stability and control of wing-in-ground effect vehicles. *Journal of Aircraft*, 15(8), 541–544.

Wieselsberger, C. (1921). Wing Resistance Near the Ground. *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, 10.

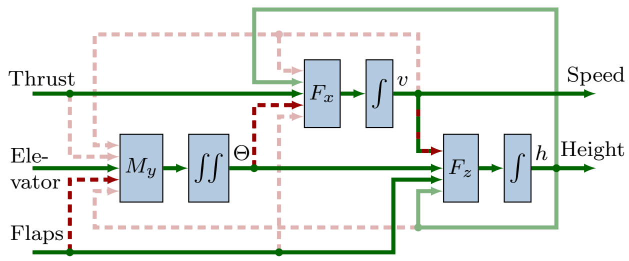

Fig. 12. MIMO structure of the process

green	positive effect
red (dashed)	negative effect
opacity	impact of effect