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MODELLING OF PHYSICAL PHENOMENA IN THE VERTICAL VELOCITY MEASURING CIRCUIT FOR PROCESS OF DESIGNING THE SWPL-1 HELMET-MOUNTED DISPLAY SYSTEM

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Abstract

The article presents the selected methods of identifying static and dynamic properties of the measuring paths to the extent necessary for the proper integration of on-board systems with the helmet-mounted flight parameter display system. It presents the methods of identifying static and dynamic properties of the WR-10MK on board variometer as one of more difficult identification elements. Its identification was carried out on the basis of the basic dependencies of the International Standard Atmosphere and the instruments construction's parameters. It built a mathematical model describing the physical phenomena associated with vertical speed measurement. This model differs from the models found in the literature in terms of detail and description accuracy. On this basis, in the Simulink environment, it built a simulation model corresponding to its mathematical model. The non-linear model was the starting point for the construction of the linearized model based on the operator transmittance. The developed models were evaluated for errors of vertical speed's dynamic indications. This allowed assessing the usefulness of the individual models for further works on ensuring the correlation of indications of the on-board variometer and the SWPL-1 helmet-mounted flight parameter display system. The presented simulation models include design details, as well as the characteristics of technological errors and disturbances of a stochastic nature. Another approach to the issue of identification is to use the characteristics provided by the manufacturer in the form of approximate characteristics of a module.

Keywords: *transport, avionics, helmet-mounted display systems, errors of the vertical velocity measurement*

1. Introduction

The article presents the selected methods for the identification of static and dynamic properties of measurement chains to the extent that is necessary for the correct integration of on-board systems with a SWPL-1 helmet-mounted flight parameter display system. The SWPL-1 helmet-mounted flight parameter display system is dedicated to crews of the following helicopters: Mi-17-1V, Mi-17 T/U, Mi-17 AE and other versions of the Mi-17 helicopter. It allows for observation of the area while controlling the helicopter's flight parameters [2]. The SWPL-1 system receives and processes information from on-board systems and presents them on helmet-mounted displays in the form of graphic symbols or in digital form.

The article presents the selected methods for the identification of static and dynamic properties of the WR-10MK on-board variometer as one of more difficult identification elements. The identification was carried out on the basis of the basic relationships of the International Standard Atmosphere [3] and the variometer's design parameters. A mathematical model describing the physical phenomena associated with vertical speed measurement was built. This model differs from the models found in the subject literature (e.g. [4]) in terms of details and description accuracy. On this basis, in the *Simulik* environment, a simulation model corresponding to its mathematical model was built. The non-linear model was a starting point for the construction of a linearised model based on the transfer function. The developed models were assessed from the perspective of dynamic indications of vertical speed errors under conditions of dynamic transitional states. This allowed assessing the usefulness of individual models for further integration works of the on-board variometer and the SWPL-1 helmet-mounted flight parameter display system.

The identification of measurement chains is a key problem of integration of the SWPL-1 helmet-mounted parameter display system with on-board systems. The accuracy of mapping the parameters displayed in the helmet-mounted system, both in static and dynamic states, depends on the identification correctness. The identification of measurement chains of the on-board systems is also a starting point for the design of measurement chains of the helmet-mounted system.

The measurement chain term is understood as a system consisting of the following elements: a measuring element, an information processing system and an information imaging system. The measurement chains occur both in the on-board systems, as well as in the helmet-mounted flight parameter imaging system. The SWPL-1 helmet-mounted system, in some cases, uses information from the measurement chains of the on-board systems, processing it and imaging on the helmet-mounted display. It provides great savings and significantly simplifies the system. If there is no information processed to the electrical form (e.g. classic membrane devices) on the helicopter board, the measurement chain of such parameters is entirely built in the SWPL-1 system.

The identification is a quite complex problem and it depends on the available information on the object (e.g. provided by its manufacturer).

In case of the parametric identification, on the static and dynamic properties, its task is to determine the parameters of the mathematical model describing the static and dynamic properties. It may be, for example, determination of coefficients of differential equations or transfer function coefficients. For linear systems, as we have access to input and output signals, it is possible to use the classic identification methods determining the parameters of the transfer function or differential equation describing the physical phenomena occurring in the system. A more difficult problem is to identify the measurement chains, in which there are non-linear elements. In case of non-linearity described by continuous functions, this problem can be solved by making linearisation by the function development into a Taylor series and taking into account only linear components of the expansion.

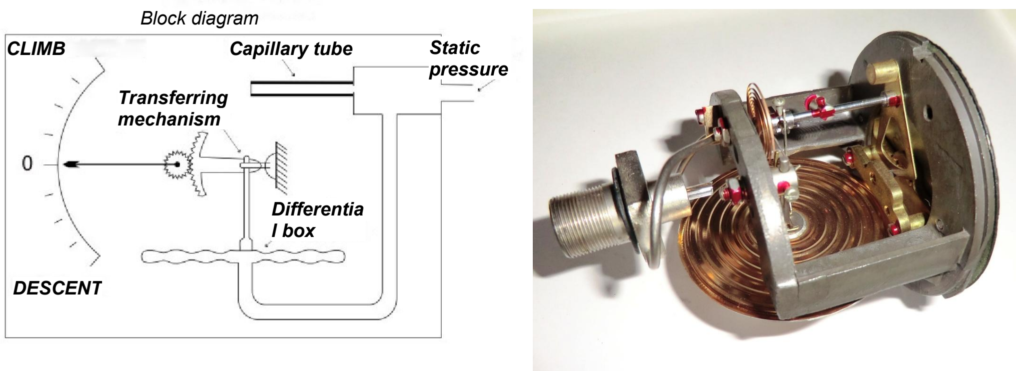
In order to draw closer to the solution in the entire range of the parameter changes, it is important to make linearisation in many points of the work (for non-linear characteristics). The non-linear problem is replaced with linear ones in specific operating points. Another approach may be to identify the non-linear characteristics and to solve problems with the use of non-linear differential equations describing the physical phenomena occurring in the measurement chains. Even more complex will be the situation, when we do not have direct access to the input or output signals. Such a situation occurs, among others, in case of the WR-10MK variometer built in the Mi-17 helicopter. While the static pressure applied to the variometer input can be measured by installing the relevant converters, the values indicated by the variometer are not processed to the electrical form. In such a situation, for the identification purposes, there is only a method of filming the changes of the measured parameter with the known force, and at a further stage, a method for reading the indications of vertical speed measured by the variometer from individual film frames. It is a tedious method; however, it is necessary for verification of mathematical models describing the physical phenomena in the measurement chain.

In this article, the example identification methods (for static and dynamic properties) of measurement chains, taking into account their specific properties, on the example of the WR-10MK variometer, were presented. The WR-10MK variometer identification is based on mathematical models that describe the physical phenomena in the measurement chains. On the basis of these models, the simulation models that reflect the properties of the measurement chains were built. These models were verified for accuracy of reconstruction of the measured parameters using the actual WR-10MK system.

2. Identified object

The object, in which the static and dynamic properties were identified, included the WR-10MK variometer of the Mi-17-1V helicopter. It is a typical, classic aviation variometer, with the use of a membrane box, as a measuring element, operating in the differential circuit [1].

In the WR-10MK variometer (Fig. 1), the measurement of the climbing and descending vertical speed is carried out by measuring the pressure difference between the pressure inside the variometer housing and pressure in the membrane box. Air flows to the housing space through the capillary tube.



a) block diagram b) view of the construction

Fig. 1. WR-10MK aviation variometer

The relationships between the helicopter vertical speed and the pressure difference were derived under the following assumptions:

- air is a Newtonian fluid (Newton's hydrodynamic law concerning static stress and a velocity gradient of air layers is applicable),
- air is an ideal gas (ideal gas state equation is applicable),
- air flow through the capillary tube is laminar (Reynolds number is lower than the critical value of the capillary tube $\mathrm{Re}_{kryt} = 2100$),
- we omit the losses at the capillary inlet and outlet,
- at the inlet and outlet of the capillary tube, there is a small pressure difference.

3. Mathematical and simulation models of the object

It develops original, not occurring in the subject literature, theoretical models of physical processes, which take place in the on-board avionic systems of the Mi-17 helicopter, and on their basis, I build the corresponding simulation models. One of the examples presented in the monograph was my developed mathematical model of physical phenomena in the WR-10MK on-board variometer, which takes into account the occurrence of a number of non-linearity and is characterised by high precision of reflection of the processes in it, not only in static states, but also in dynamic ones, during the performance of the helicopter's manoeuvres.

The mathematical model of physical phenomena inside the variometer's housing and in the measuring element was presented below:

$$\frac{dp_1}{dt} = \frac{\pi \cdot d_k^4 \cdot (p_s - p_1)\cdot(p_s + p_1)}{256 \cdot \eta \cdot L \cdot v_1} = \frac{\pi \cdot d_k^4 \cdot (p_s^2 - p_1^2)}{256 \cdot \eta \cdot L \cdot v_1} = \frac{\pi \cdot d_k^4 \cdot p_s^2}{256 \cdot \eta \cdot L \cdot v_1} - \frac{\pi \cdot d_k^4 \cdot p_1^2}{256 \cdot \eta \cdot L \cdot v_1}, \tag{1}$$

$$\frac{dp_m}{dt} = \frac{\pi \cdot d_p^4 \cdot (p_s - p_m)\cdot(p_s + p_m)}{256 \cdot \eta \cdot L_p \cdot v_m} = \frac{\pi \cdot d_p^4 \cdot (p_s^2 - p_m^2)}{256 \cdot \eta \cdot L_p \cdot v_m} = \frac{\pi \cdot d_p^4 \cdot p_s^2}{256 \cdot \eta \cdot L_p \cdot v_m} - \frac{\pi \cdot d_p^4 \cdot p_m^2}{256 \cdot \eta \cdot L_p \cdot v_m}, \tag{2}$$

$$m \cdot \frac{d^2 y}{dt^2} + \mu_y \cdot \frac{dy}{dt} + c_y \cdot y = q \cdot S_m \,, \tag{3}$$

where:

p_s – air pressure at the capillary tube inlet,

p_1 – air pressure inside the variometer housing (equal to the pressure at the outlet of the capillary tube),

η – air dynamic viscosity coefficient,

v_1 – air volume inside the variometer housing,

v_m – membrane box volume,

$q = p_1 - p_m$ – pressure difference,

L – length of the capillary tube,

d_k – diameter of the capillary tube,

L_p – length of the thin-walled cable connecting the membrane box with the variometer's inlet port,

d_p – inner diameter of the thin-walled cable connecting the membrane box with the variometer's inlet port,

p_m – pressure inside the membrane box,

m – mass of moving elements of the kinematic system of transferring the motion to the variometer's indicator brought to the beginning of the kinematic system (membrane box); it is related to the kinematic ratios,

μ_y – friction coefficient of the viscous kinematic system,

c_y – a constant of spring elements (membrane box and spiral spring),

S_m – membrane surface,

y – linear movement of the membrane box.

The variometer's simulation model, which takes into account non-linear differential equations of a mathematical description of WR-10MK variometer's dynamic properties, was presented below:

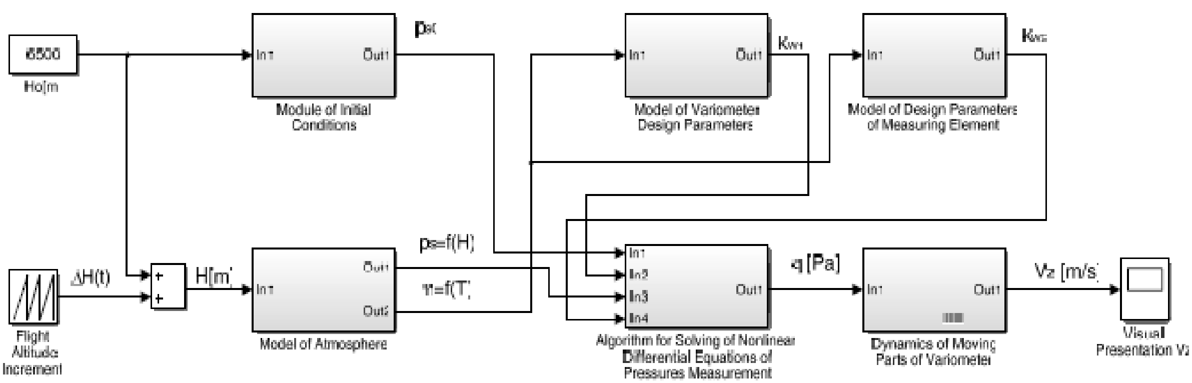


Fig. 2. WR-10MK variometer's simulation model in transition states

4. Integration problems of the helicopter's on-board systems with a helmet-mounted flight parameter display system

Original methods for integration of the helicopter's on-board systems with the helmet-mounted flight parameter display system were developed. In the integration process, we solved a number of problems, which can be presented in the following way in synthetic terms:

- analysis of the user’s requirements for the integration of systems,
- identification of on-board systems and devices,
- analysis of the form of signals in the integration place of systems,
- synthesis of the structure of designed measurement chains,
- synthesis of parameters of the designed system structure,
- design and implementation of calculation algorithms in the digital signal processing section,
- ensuring the reliability of indications in the SWPL-1 helmet-mounted system,
- ensuring the compliance of the SWPL-1 flight parameter display system’s indications with on-board systems under static and dynamic conditions,
- protection of on-board signals against distortion and interferences during integration with the helmet-mounted flight parameter display system,
- protection of the helmet-mounted flight parameter display system against interferences from the helicopter’s on-board systems and installations,
- ensuring the immunity and resistance of the designed system to environmental conditions in the place of mounting on the helicopter’s board.

The particular attention should be paid to my developed original methods for ensuring the compliance of the SWPL-1 flight parameter display system’s indications with on-board systems under static and dynamic conditions. The provision of the compliance of indications under static conditions was obtained by the semi-automated calibration method of measurement chains.

The user-friendly calibration interface, for an example measurement chain of vertical speed, is presented below:

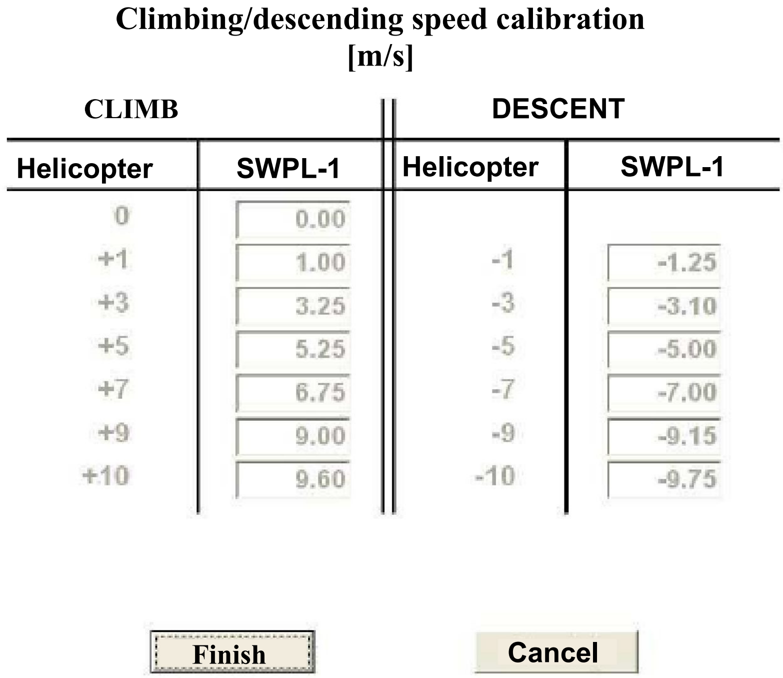


Fig. 3. View of the user’s interface for calibration of the measurement chain of vertical speed

The measurement chain calibration is made to compensate for static errors, understood as a difference in indications between the real WR-10MK on-board variometer and the SWPL-1 helmet-mounted flight parameter display system. The calibration should be performed for the selected points of the variometer scale. These points will be treated, in the computing algorithms of the SWPL-1 system, as interpolation nodes for calculating the intermediate values between individual points of the scale.

There were developed original methods for ensuring the compliance of indications of the helmet-mounted system with on-board instruments under dynamic conditions of changing flight parameters, and also systems for the assessment of dynamic errors with the use of non-linear models of the dynamics of measurement chains. On the basis of the measurement chain of vertical speed, the system is as follows:

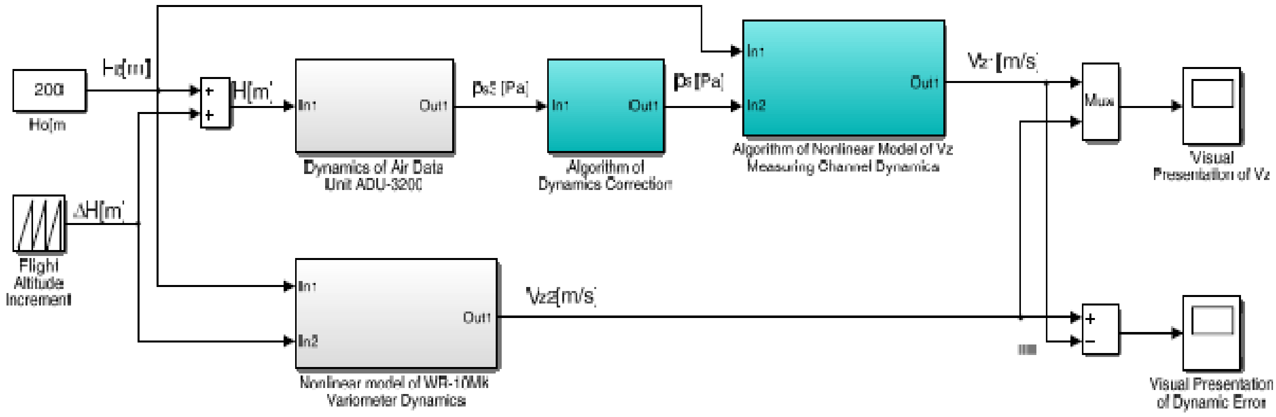


Fig. 4. System (model) for the assessment of a dynamic error with the use of the non-linear dynamics of the measurement chain of vertical speed

The minimisation of dynamic errors was obtained with the use of a criterion function, as a criterion for adjusting the indications, based on the integral of the square of the difference between the standard course, and the one obtained in the helmet-mounted imaging system.

The criterion function on the basis of adjusting the vertical speed courses is described by the Q functional specified by the following equation:

$$Q(D_{k1}) = \int_{t=0}^{t=t_k} \left[V_{Z2}(t) - V_{Z1}(t, D_{k1})\right]^2 \cdot dt, \tag{4}$$

where: t – current time, t_k – final time (time to reach the steady state), D_{k1} – parameter of adjusting the non-linear algorithm of the dynamics model of the measurement chain, $V_{Z1}(t, D_{k1})$ – course of changes in the vertical speed in the measurement chain of the SWPL-1 system, $V_{Z2}(t)$ – course of changes in the vertical speed measured with the use of the WR-10MK on-board variometer.

In this system, the input quantities include initial height H_0 of the helicopter's flight, a change in the height ΔH and parameter of adjusting the algorithm of the non-linear dynamic model of the measurement chain. A change of the flight height is made in a linearly increasing way with a gradient providing a certain rate of climb or descent. The minimisation of dynamic errors is performed for the specific initial height H_0, when changing the parameter of adjusting the algorithm of the non-linear dynamic model of the measurement chain. For the specific initial height H_0 and a derivative barometric altitude $\dot{H}$ (carried out by $\Delta H(t)$), D_{k1} parameter is changed in such a way as to minimise the functional Q. In this way, we obtain optimal adjustment and minimisation of the dynamic errors.

Figure 5 shows the relationship of the functional Q on the initial height H_0 and the parameter D_{k1}. The detailed research of the Q functional show that the optimum value of the D_{k1} adjusting parameter slightly depends on the H_0 initial height of the stroke of the rate of climb $\dot{H}$.

This functional reaches the minimum value for the optimum value of the adjustment parameter D_{k1}. For this value, the best compliance of the helmet-mounted system's indications with the on-board instrument is obtained (for vertical speed measurement).

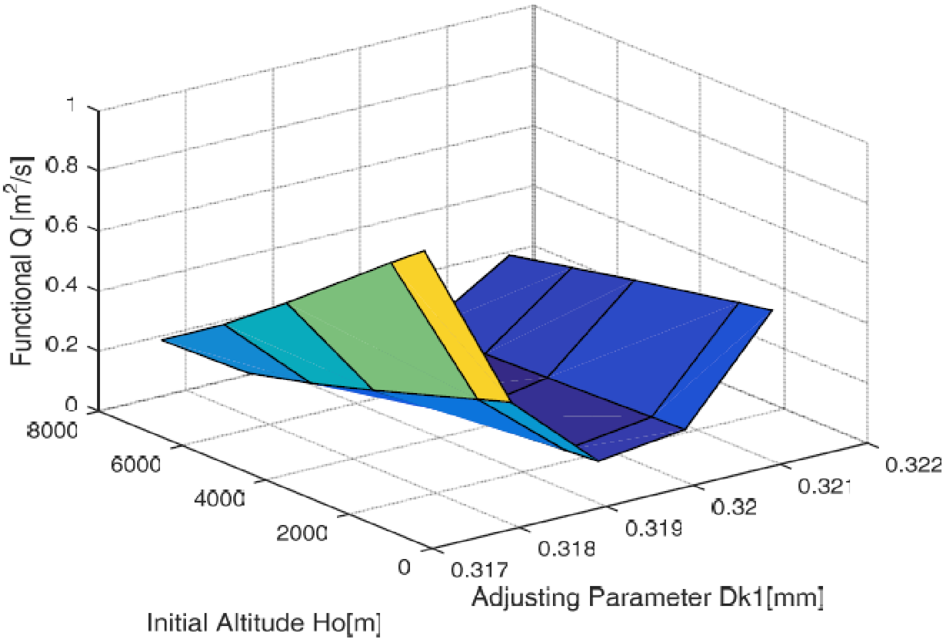


Fig. 5. Example relationship of Q functional from the H0 initial height and the parameter of adjusting the non-linear algorithm of the dynamics model of the Dk1 measurement chain

5. Summary

One of the main requirements for the SWPL-1 system integration on the Mi-17 helicopter board (reported by the user) is that the value of any parameter presented by the system must correspond to the value presented by the imaging devices currently built on the helicopter. Such a formulation of the requirement entails the necessity of precise correlation of indications of the parameters presented by the helmet-mounted flight parameter display system with parameters demonstrated on the helicopter's instrument panel. In order to perform it, the system integration while complying with the condition of providing the conformity of indications of the SWPL-1 flight parameter display system with on-board systems in static and dynamic conditions can be solved by two methods:

The reliability of information subjected to imaging in the helmet-mounted SWPL-1 is also associated with minimising the static and dynamic errors. The static errors were compensated by calibration of the measurement chains under static conditions.

The dynamic errors occur during the dynamic change in the helicopter flight parameters. The problem of adjusting the indications of the helmet-mounted flight parameter display system to the indications of on-board instruments under dynamic conditions is particularly important in measuring channels of the vertical speed and actual height. These errors were minimised by using the simulation models of measurement chains. The optimised parameters of the simulated measurement chains were implemented later in the algorithms of information processing of the actual helmet-mounted flight parameter display system.

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