APPLICATION OF THE DISTURBANCE VALUE MEASURED DURING THE REAL FLIGHT TO THE FLIGHT CONTROL SYSTEM SYNTHESIS

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Abstract

The article presents the method and results of disturbance modeling for the purpose of simulation and calculations in the process of synthesizing the properties of an on-board aircraft control system. Data recording during the real flight were used to isolate disturbances that are the errors of the measurement system (measurement noise) and disturbances resulting from external influences, e.g. engine vibration, atmospheric turbulence, etc. The developed algorithms allow simulating the operation of the on-board control system in conditions similar to those occurring in the actual flight. In this way, it is possible to improve (tuning) the properties of on-board control systems for better flight quality.

The paper presents the method of data collection for modeling disturbances, algorithm of disturbances generation for simulation purposes and an example of the use of the described method for tuning autopilot for didactic flying laboratory aircraft.

1 Introduction

Synthesis of the fight control system is usually based on a mathematical model of control object, without taking into account the properties of the measuring systems and the nature of the real disturbances resulting from the impact of the environment (e.g. turbulence). In practice, the operation of aircraft control quality depends on the actual disturbances, in particular in the case of flying objects with small dimensions, for example micro or mini unmanned aircraft. The nature and magnitude of disturb measurements (measurement noise) depend on the properties of the sensors and the disturbances generated by a flying object. The measuring sensor noise is typically characterized by high frequency and low amplitude in the steady state conditions. Much more important are disturbances generated by the aircraft (vibration of the engine and on-board equipment, unsteady aerodynamic flow, variable electromagnetic fields, etc.). The effects of such disturbances will depend on the individual sensitivity of the sensor, but also from the place and fastening method of the sensors, flight phases and flight parameters, etc. During the flight, there is no way to distinguish between errors of measurement (static and dynamic) and disturbances process derived from external factors environment. Turbulence, unsteady flow around the plane or deformation of the structure of the airframe cause interference flight parameters measured by the sensors and activating control system. Control quality (error of selected state variables, for example) will depend on the measurement system sensitivity of the sensors on disturbances.

Typically, control systems designed for ideal flight conditions (without taking into account the influence of disturbances) require modification (tuning) in real flight conditions, which leads to complexity and usually expensive flight tests [1, 2]. This process can be accelerated and improved already at the design stage of the control system using models of real disturbances in the presence of real aircraft flight to construct and test control algorithms.

2 Modeling of the real disturbances

In the classical case of design calculations, the theoretical model of turbulence according to Dryden approximation (for example [3,4]) is used. The essence of the proposed method is the separation of the effects of external and measurement disturbances from flight signals registered on the real flight. These data will be useful primarily for the analysis of the flight control system properties of the aircraft of the same class as the aircraft used in the measurement flight and in similar flight conditions. However, having a sufficiently rich database of measurement flights, you can prepare a library of useful simulation procedures representative for a given group of project tasks. The data can be stored during typical students' flight exercises [5].
In particular, you can use the data recorded during the flight of the aircraft for which the control system will be designed.
The data stored in the on-board recorder's memory contains information with real quantities measured, on which disturbances generated in measurement systems are imposed, as well as disturbances originating from external exertions relative to the measurement system are effected. It is therefore necessary to use an algorithm that will allow you to separate the disturbances from the recorded signal. Unfortunately, information about "ideal" values of measured variables is not available. Constant or slow-changing (in relation to the dynamic properties of the controlled object) measurement errors (disturbances) do not have a visible effect on the dynamic quality of control. In this study, a fast-changing component of measurement disturbances is modeled, which has a significant impact on the quality of transient control processes. To extract this component, an approximation of measurement data with continuous functions is proposed, whose parameters will be selected according to the analyzed measurement variables. Depending on the flight condition and the characteristic properties of the measured signal (dynamic object transfer bandwidth), the polynomial of the appropriate stage will be used to approximate the "ideal" values of the measured signals, stretched over the selected time interval.

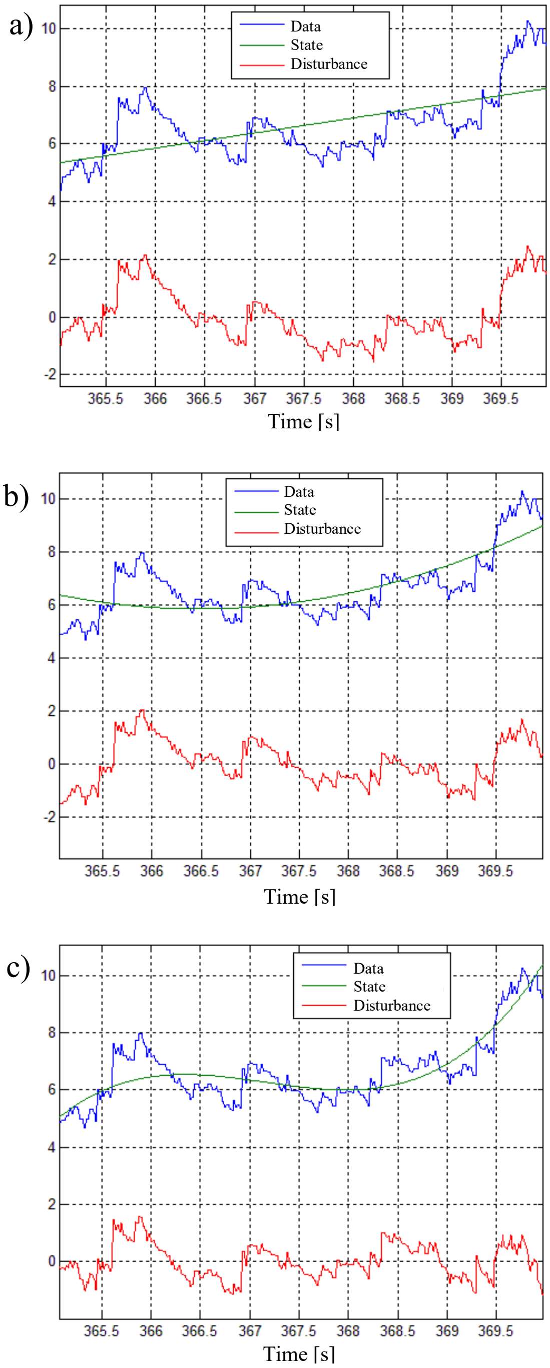


Fig. 1. Approximation of the pitch angle measurement data by polynomials of the first (a), second (b) and third degree (c), respectively

Fig. 1 presents the effects of separation of disturbances acting on the aircraft along with measurement disturbances for cases of various degrees of approximation polynomials. The measurement data was recorded during the flight of the Piper Seneca V aircraft in moderate turbulence conditions. According to the nature of changes in the observed signal, the degree of approximating polynomial and the approximation interval should be selected. A convenient method of proceeding is to use spline functions; appropriate calculation procedures are available in the MATLAB simulation package. The developed calculation programs allow you to select the approximation method of measurement data, as well as the choice of the recording time step, which may be different from the data registration step. This allows the use of a set of model interferences in simulation programs with different calculation steps, in particular in the case of simulation of the real-time control process, with a given frequency of calculation repetitions. This set may contain data tables on disturbances for various flight manoeuvres (take-off, climb, cruise, approach etc.), aircraft configuration or turbulent conditions.

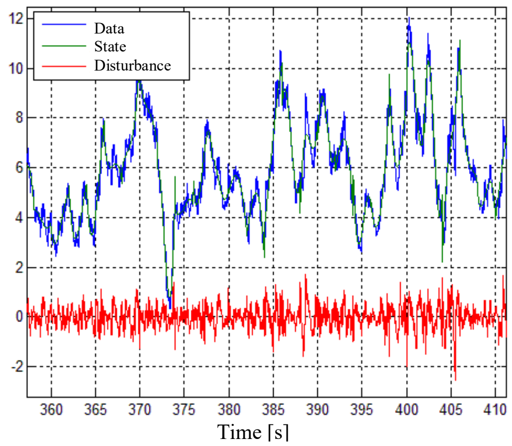


Fig.2. Disturbances in the pitch angle measuring channel [deg]

Figures 2-5 show examples of disturbed measured state variables of the Piper Seneca V aircraft and calculated disturbances. Three-degree polynomials with approximation intervals selected according to the nature of the observed variable and the dynamic properties of the aircraft were used. For example, for the angle of attack, the approximation interval was set to 1/2 of the short-term oscillation period, and 1/2 of the phugoid oscillation period for the indicated airspeed IAS, if there were no energetic manoeuvres for the change of the flight path angle. The database prepared in this way contains models of interference occurring in real measuring systems and takes into account typical effects of external disturbances.

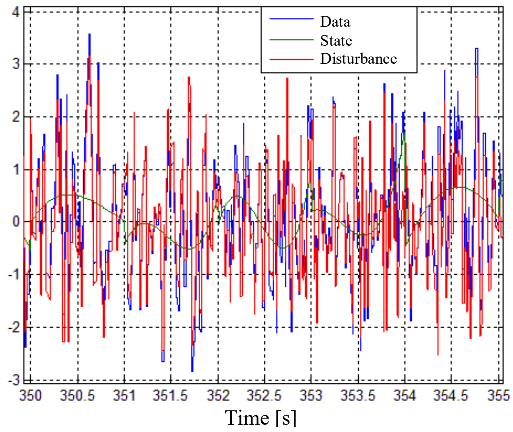


Fig. 3. Disturbances in the pitch rate measurement channel [deg / s]

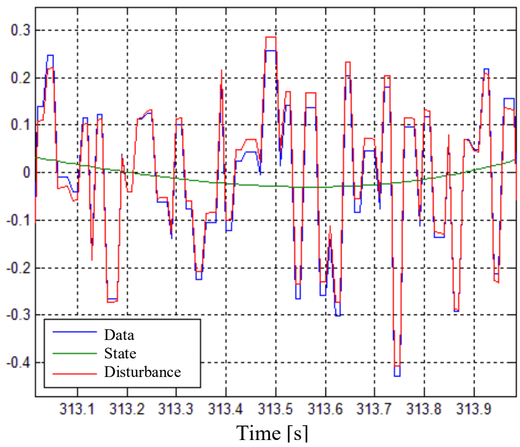


Fig. 4. Disturbances in the longitudinal acceleration measurement channel [m / s^2]

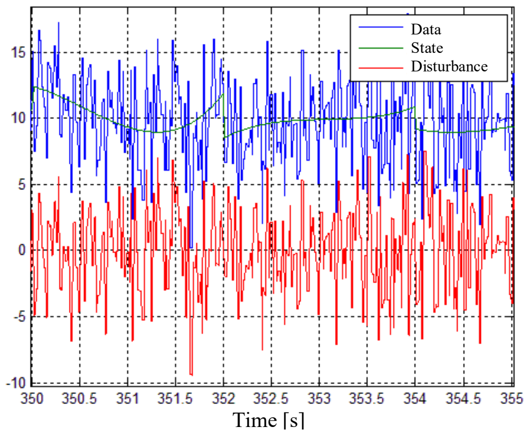


Fig. 5. Disturbances in the vertical acceleration measurement channel [m / s^2]

3 Tuning of the flight control system

Taking into account the impact of disturbances is particularly important in the case of plants with non-linear characteristics, which are described by set of nonlinear differential equations and/or taking into account the non-linearity of a structural nature, such as speed limiting of the actuators and limited deflection angle of aerodynamic surfaces. In general, in this case, the dynamic properties of the aircraft, measuring systems and actuators are modeled by a system of non-linear differential equations

$$\frac{dX}{dt} = f(X,U,t) \qquad (1)$$

where: $\boldsymbol{X}$ - state vector,
$\boldsymbol{U}$ - control vector,
$\boldsymbol{f}$ *(.)* - non-linear function describing the dynamic properties of the aircraft, measuring system and actuators.

In this case, an efficient method of properties calculation of a control system with a given structure is to minimize of the quality function

$$J_N(K) = \frac{1}{T}\int_0^T (EQE^T + URU^T)dt \qquad (2)$$

where: $\boldsymbol{E} = \boldsymbol{Y_D}-\boldsymbol{Y}$ - control error,
$\boldsymbol{Y_D}$ -desired output vector,
$\boldsymbol{Y}$ – output vector,
$\boldsymbol{Q}, \boldsymbol{R}$ - weight matrices,
$\boldsymbol{K}$ - a matrix of parameters defining the properties of the control system.

Design calculations are made using the MATLAB-Simulink package. In the first step, for the assumed aircraft maneuver, values of parameters describing the control system are calculated, which minimize the value of the quality function (2), for the case of "ideal" measurements and the absence of external interference. The modification of the calculation process consists in taking into account an additional function of assessing the impact of high frequency disturbances (measurement system errors and atmospheric turbulence)

$$J_F(K) = \frac{1}{T}\int_0^T X_F H X_F^T dt \qquad (3)$$

where: $\boldsymbol{X_F}$ - variable high frequency component of the state vector,
$\boldsymbol{H}$ - weight matrix.

Improved (corrected) values of control system parameters are obtained by minimizing of the modyfied quality function

$$J(K) = J_N(K) + J_F(K)$$

$$J(K) = \frac{1}{T}\int_0^T (EQE^T + URU^T + X_F H X_F^T)dt \qquad (4)$$

The scheme of simulations and calculations is illustrated in Fig. 6.

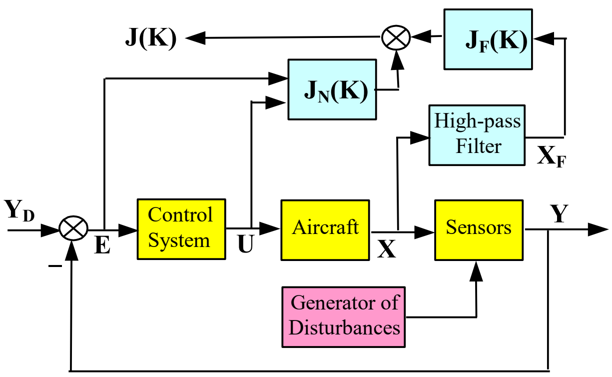
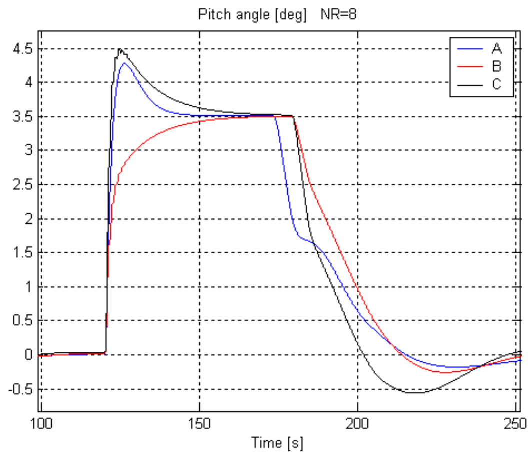


Fig. 6. The scheme of simulation process for calculation of the quality function value

Fig. 7 shows the waveforms of some state variables for the absence of disturbances and the occurrence of disturbances. The calculations concern the synthesis of the properties of the control system of the flying didactic laboratory based on the Piper Seneca V airplane. The influence of disturbances is particularly visible when using analytical redundancy of measurements, i.e. calculation of non-measurable values of state variables based on available measurements. In this case, the control precision deteriorates and the presence of disturbances can significantly affect the quality of control and even the stability of the system [6, 7]. In the design phase of the control system and laboratory tests "Hardware-in-the-loop-simulation" analyzing of the system's functioning in the presence of disturbances allows you to modify (tune) the control system in such a way as to obtain an acceptable resistance of the control system to disturbances.
Fig. 7 shows how to control the pitch angle during the flight altitude control simulation of

the Piper Seneca V aircraft. The case was analyzed when a pitch angle measurement is available and a case where the value of the pitch angle is estimated on the basis of vertical velocity, flight speed and the estimated value of the angle of attack. The simulation model takes into account the non-linear properties of the actuator and limitation of the elevator deflects. The tuning of the control system caused a reduction in the amplitude of the high frequency component of the state variables by 5-8%, which means improved flight comfort.

a)



b)

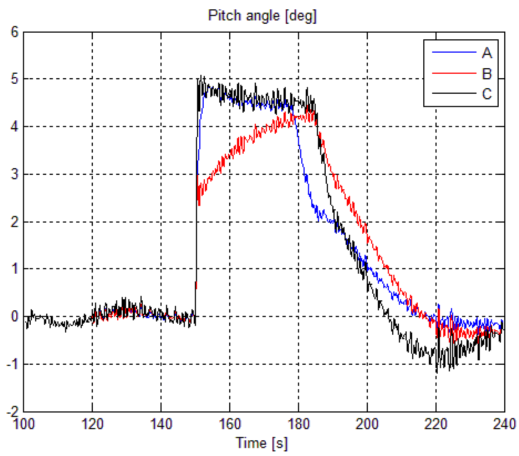


Fig. 7. Simulation stabilization control the angle of the flight altitude without (a) and including disturbances (b): A - control based on the measured value of the pitch angle, B – real pitch angle C - estimated value of the pitch angle

The proposed method has been used on a "Hardware-in-the-loop-simulation" test stand to verify the accuracy and quality evaluation of control under conditions simulating the actual properties of the on-board measurement system and the impact of external disturbances. Ideal (theoretical) values of the state variables being the solution of differential equations describing the dynamic properties of the object are summed with disturbances measured and recorded during the real flight.

4 Summary

This allows modifying the parameters of the flight control algorithms in such a way as to obtain statistically lower values of control errors and thus obtain better quality control. The flight control system synthesis take into consideration real properties of the turbulence disturbances and real measurement instruments errors. In particular, this way of modelling and flight control system testing is useful in the case of aircraft nonlinear dynamic properties. Described method have been used for testing and tuning the control system focused on small size unmanned aircraft with non-typical aerodynamic solutions and in the cases of partly damage of construction, measurement equipment or control system.

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