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Neural network modeling of unsteady aerodynamic characteristics at high angles of attack

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ABSTRACT

A neural network approach for modeling of unsteady aerodynamic characteristics in a wide angle-of-attack range is considered in the paper. Special tests have been carried out in TsAGI wind tunnel to investigate dynamic properties of unsteady aerodynamic characteristics of a generic transonic cruiser, which is a canard configuration. The aerodynamic derivatives have been studied with forced small-amplitude oscillations. In addition, forced large-amplitude oscillation tests have been carried out for the detailed investigation of dynamic effects on the unsteady aerodynamics in the extended flight envelope. To describe the nonlinear dependences of aerodynamic coefficients, observed in the dynamic experiments, two neural network models, which use the feed-forward and recurrent architectures, are developed and compared. A special regularization for the neural networks training taking into account that data are obtained in different experiments with different noise level is proposed to improve a model performance. The unsteady aerodynamics modeling results obtained with neural networks are compared with a state-space model results.

1. Introduction

Significant extension of the angles-of-attack range used in the modern flight leads to necessity of more adequate modeling of aircraft unsteady aerodynamic characteristics. Modern commercial airplanes use angles of attack close to stall during take-off and landing. Possible pilot mistakes, equipment faults and wind gusts can cause loss of control, stall and spin. In addition, according to EASA (European Aviation Safety Agency) a loss of control in flight has recently become the main cause of the commercial airplane fatal accidents [3]. That is why it is necessary to model aerodynamics in the extended flight envelope to study more thoroughly an aircraft dynamics and to provide realistic pilot training using ground-based simulators in the upset conditions [2,10].

The important role for a commercial airplane unsteady aerodynamics at high angles of attack is played by the dynamics of the wing flow separation and reattachment. A complicated dynamic interference of the separated flow upon the full aircraft configuration is a significant cause of nonlinearity of unsteady aerodynamic characteristics.

Development of computers and numerical techniques has recently led to significant progress in the CFD simulations of unsteady aerodynamic loads [6,20]. Nevertheless, at the present state of art the equations of fluid mechanics and aircraft dynamics cannot be solved simultaneously in certain flight mechanics problems, for example, in semi-realistic simulation of the aircraft flight using ground-based flight simulators. Simplified mathematical models of the unsteady aerodynamics describing the nonlinear phenomena in the extended range of kinematic parameters are required for solving the flight dynamics problems. In practice, such models are developed using experimental data obtained from a set of wind-tunnel dynamic tests with various test rigs that correspond to various ranges of kinematic parameters of motion.

In flight dynamics problems the aerodynamic forces and moments are usually represented in terms of aerodynamic derivatives [5,7]. For example, for small disturbance motion about a small trim incidence α_0, the pitch moment coefficient is supposed to be represented as the linear terms of Taylor series expansion in the motion parameters

$$C_m = C_m(\alpha_0) + C_{m_\alpha}(\alpha - \alpha_0) + C_{m_q} q\bar{c}/2V + C_{m_{\dot\alpha}} \dot\alpha\bar{c}/2V \qquad (1)$$

This method can be successfully applied in the range, where the aerodynamic derivatives exist and are unique, and can be represented as linear dependences on the kinematic parameters, i.e., for the flows without separation. Application of this method in the

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Nomenclature

A_α	amplitude of oscillation
a_i	target value
b_a	wing span
b_k	neuron bias
C_m	pitch moment coefficient
$\bar{c}$	mean aerodynamic chord
E_D	sum of squared neural network errors
E_W	sum of squared neural network weights
e_j	neural network error
err_i	error measure
F	objective function
f	oscillation frequency
f_k	neuron activation function
$\mathbf{H}$	Hessian matrix
$\mathbf{J}$	Jacoby matrix
k	reduced oscillation frequency
M	function of neural network operations
S_j	input signals fed into neuron
t	time
V	airspeed
w_{ik}	weights of the neural network connections
y_i	neural network operation results

α	angle of attack
α_0	mean angle of attack at the oscillations
ϕ_k	signal mapped by the neuron
φ_c	canard deflection angle
ϑ_0	initial angle of the dynamic rig
η, ρ_i	objective function parameters
τ_1, τ_2	characteristic times

Subscripts

dyn	dynamic
sep	separated
sim	simulation
st	static
test	testing
T	transpose

Aerodynamic derivatives

$C_{m\alpha} = \frac{\partial C_m}{\partial \alpha}$

$C_{mq} = \frac{\partial C_m}{\partial (q\bar{c}/2V)}$

$C_{m\dot{\alpha}} = \frac{\partial C_m}{\partial (\dot{\alpha}\bar{c}/2V)}$

range of nonlinear variation of the aerodynamic characteristics can lead to significant errors [5].

The most general technique of modeling the unsteady aerodynamic characteristics uses the nonlinear indicial functions [21]. To develop the aerodynamics model based on the nonlinear indicial functions a large amount of unsteady aerodynamic data should be used. Nevertheless, it requires a set of serious simplifications when applied to real problems, so that final mathematical models are formulated in a simple form of first-order linear differential equations [14].

The state-space model [11] takes into account delays of flow separation and reattachment. The aerodynamic loads can be separated into linear non-delaying and nonlinear delaying components while using this approach [1,22]. Ordinary differential equations are used for modeling the intrinsic dynamics of the nonlinear components of aerodynamic characteristics. These equations contain time constants corresponding to the characteristic times of the flow separation and reattachment. These time constants are identified using the dynamic wind-tunnel test results. Such approach enables a dependence of aerodynamic derivatives on frequency and amplitude of oscillations, and aerodynamic hysteresis to be modeled quite precisely. Unfortunately, application of the state-space model in an arbitrary case is complicated because of a non-formalized and expert-based procedure of model structure development and selection of the nonlinear components of unsteady aerodynamic characteristics.

Neural networks (NN) have been shown recently to be a formal and effective tool for modeling of nonlinear unsteady aerodynamics regardless of the aircraft configurations [20,8,19,18,13,12]. Such an active application of NN is mainly connected with their universal approximation properties [15], which enable the neural networks to be used for an arbitrary aircraft without significant simplifying assumptions. NN was found to be capable of reproducing histories of unsteady aerodynamic loads on the suction side of pitching airfoils in real time [8]. Faller et al. used sets of experimental data to train a recurrent neural network (RNN) into predicting the pressure coefficient readings along three spanwise positions on the upper surface of the wing. They concluded that RNN was suitable for time-dependent problems. RNN was used to generate the response function for a nonlinear indicial model in [19]. NN was utilized for modeling the unsteady aerodynamic coefficients at high angles of attack for a number of aircraft configurations [18,13,12]. To develop a faster model for 3D dynamic stall aerodynamic loads a NN was put forward in [20] using both CFD and experimental data.

The study is aimed at development of the neural network model of unsteady aerodynamic characteristics in an extended angle-of-attack range. Results of the static and dynamic experiments, obtained for the pitch moment coefficient of the generic Transonic CRuiser (TCR), which is a canard configuration, is used. This aircraft configuration was studied in the SimSAC project of 6-th European Framework Program [17]. The main dynamic properties of the pitch moment coefficient obtained in the experiment for TCR are discussed in Section 2. A brief description of the NN configurations and training techniques, used in the present study, is given in Section 3. A special regularization technique based on Bayesian rule is proposed to increase performance of a NN developed with several types of experimental data. A brief description of state-space model developed for the TCR model is presented in Section 4. Section 5 deals with simulation and comparison of different model results. A recurrent NN architecture is compared with a feed-forward NN architecture, the proposed regularization technique is compared with the conventional one. The state-space modeling results are also given in the same section. Section 6 sums up the paper findings.

2. Experiments

The considered unsteady aerodynamics modeling approaches are developed and tested using the experimental data obtained with dynamic rigs of forced oscillations. The tests were carried out for a generic passenger aircraft designed for Transonic CRuise (TCR) flight during participation of TsAGI in the European Project SimSAC [17]. The aerodynamic configuration is characterized with high-sweep wing and canard surface. Interaction of the flow separated from the canard surface with the flow over the wing is the crucial physical effect at high angles of attack for this model. The main geometrical parameters of the tested TCR model are as follows: reference area $S = 0.3056\ \text{m}^2$, wing span $b_a = 1.12$ m, mean