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A METHODOLOGY OF IDENTIFICATION OF THE AIRCRAFT TRANSLATIONAL DYNAMIC STABILITY DERIVATIVES IN WATER TUNNEL EXPERIMENTS

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Abstract

The aircraft dynamic stability derivatives (DSD) describe the variation of aerodynamics forces and moments with respect to disturbances of kinematic parameters (translational or rotational). The knowledge of DSD is important due to determination of aircraft dynamic stability characteristics. Thus, the identification of DSD is an issue of analytical or numerical analysis and experimental researches. Experimental methods use air or water tunnel tests. The investigated model is submitted to forced oscillations with relatively low amplitude, which simulates the disturbances around steady state flight parameters. The variation of forces and moments are measured by strain balance system, which allows identifying DSD. This work is focused on development the methodology of experimental identification the aircraft translational DSD in water tunnel tests. Study of available publications shows that model manipulator system usually provides rotational movements around three axes. Therefore, the measurements can be performed with respect to rotational velocity disturbances. However, by addition the translational manipulator with one degree of freedom the measurements can be expanded into translational velocity disturbances (normal and sideslip). It is necessary to point that axial velocity disturbance is omitted due to lack of axial force component in strain balance construction. The proposed modification does not affect the construction of rotational manipulator or balance. The article contains translational manipulator scheme, modification of data acquisition system and mathematical process of identification the aircraft translational dynamic stability derivatives.

Keywords: *aircraft dynamic stability, dynamic stability derivatives, water tunnel*

1. Introduction

The dynamic characteristics of an aircraft can be divided into dynamic stability and dynamic control characteristics. The dynamic stability describes the aircraft natural response on external disturbances (atmosphere gusts). The control characteristics describe the aircraft response with control surfaces deflection. Both type of characteristics are obtained by solution of aircraft motion equations. Method of solution motion equations system relies on linearization of equations using the small perturbations theory. It is assumed that in the neighbourhood of steady state flight the disturbed parameters (velocities, accelerations or control deflections) result in linear variation of aerodynamics forces and moments acting on aircraft. The aircraft dynamic derivatives describe the gradient of aerodynamic forces and moments with respect to perturbed parameters. This work is focused on the natural aircraft dynamic stability characteristics. Therefore, the dynamic stability derivatives due to velocities and accelerations are considered.

Experimental identification of DSD can be realized in air or water tunnel tests. In general, the identification requires the aircraft model forced oscillation around steady state flight. The forces and moments are measured by strain balance system with the actual model position and point of time. The collected data are used to identification of DSD value with respect to perturbed kinematic parameter. Study of available publications shows that water tunnel experiments have the advantages in dynamic tests. Water medium enables to perform dynamics tests with significantly smaller frequency of forced oscillation of tested model than in the air [3, 6]. Thus, the model manipulator is less stressed and it is easier to collect measured data. Tested model is relatively small and lightweight, which reduces the negative influence of inertial, forces on measured aerodynamic data. Model manipulators used in water tunnels have three degrees of freedom with rotational movements around three axes. This multitask device enables to perform as well as static tests at high angles of pitch, yaw or roll and a variety of dynamic tests with respect to rotational velocities and accelerations. It is possible to identify the aircraft rotational dynamic stability derivatives [3, 8]. However, the manipulator has no possibility to perform translational movements. Considering the advantages of water tunnel dynamic tests the objective of this work is to propose the method for measuring the translational aircraft dynamic derivatives. By adding the manipulator with translational type of movement, it will be possible to measure the forces and moments with respect to translational velocities and accelerations. The basic assumption is not to modify existing measurement devices (rotational manipulator and strain balance). The translational manipulator will be mounted as additional component between the rotational manipulator and strain balance. The proposed device has one degree of freedom and performs translational movement crosswise to flow direction in water tunnel test area. In this way, it will be possible to measure DSD with respect to vertical and side velocity perturbations. The strain balance construction [4, 5] unable to measure longitudinal force. With this reason, the identification of DSD with respect to longitudinal velocity will not be measured. Is should be note that translational dynamics tests were performed in air tunnel [1]. The work on expansion of possibilities of water tunnel dynamic tests is a natural consequence.

Tab. 1. List of aircraft dynamic stability derivatives.

Symmetrical DSD				Asymmetrical DSD		
X_u	X_w	X_q	$X_{\dot{w}}$	$\boldsymbol{Y_v}$	$\underline{Y_p}$	$\underline{Y_r}$
Z_u	$\boldsymbol{Z_w}$	$\underline{Z_q}$	$\boldsymbol{Z_{\dot{w}}}$	$\boldsymbol{l_v}$	$\underline{l_p}$	$\underline{l_r}$
m_u	$\boldsymbol{m_w}$	$\underline{m_q}$	$\boldsymbol{m_{\dot{w}}}$	$\boldsymbol{n_v}$	$\underline{n_p}$	$\underline{n_r}$

Table 1 contains the list of DSD used in analysis of aircraft dynamic stability [2]. The underlined derivatives are measured using rotational manipulator. Derivatives specified in bold and frame is the target of this work. They can be investigated using translational model manipulator.

2. Translational manipulator

In order to the measure of aircraft, translational DSD the basic feature of translational manipulator is to perform the simple translational harmonic motion of researched aircraft model. The slider crank mechanism was chosen to fulfil the type of motion requirement.

Figure 1 shows water tunnel test section, where the proposed components of translational manipulator are placed. The parts of translational manipulator are mounted to the C-strut (10) which is a part of rotational manipulator (11). The rotational manipulator (10), (11) need to be levelled and do not participate during translational dynamic tests. The main support (6) is mounted to the C-strut. This part has two slide blocks where the reciprocating guide (5) performs simple harmonic motion. Motor support (4) is also connected to C-strut, which provide the geometrical coherence of manipulator mechanism. The electric motor (2) drives the manipulator with constant rotational speed. By means of crank (1) and connecting rod (3) the rotational motion of motor shaft is transformed into simple harmonic motion on the reciprocating guide. It is necessary to point that tested aircraft model (7) need to move crosswise to the water flow direction. The aerodynamic derivatives are identified for different angles of attack (or slip angles). Thus, the strain balance (9) needs to connect the aircraft model with reciprocating guide by angle of attack adjustment (8).

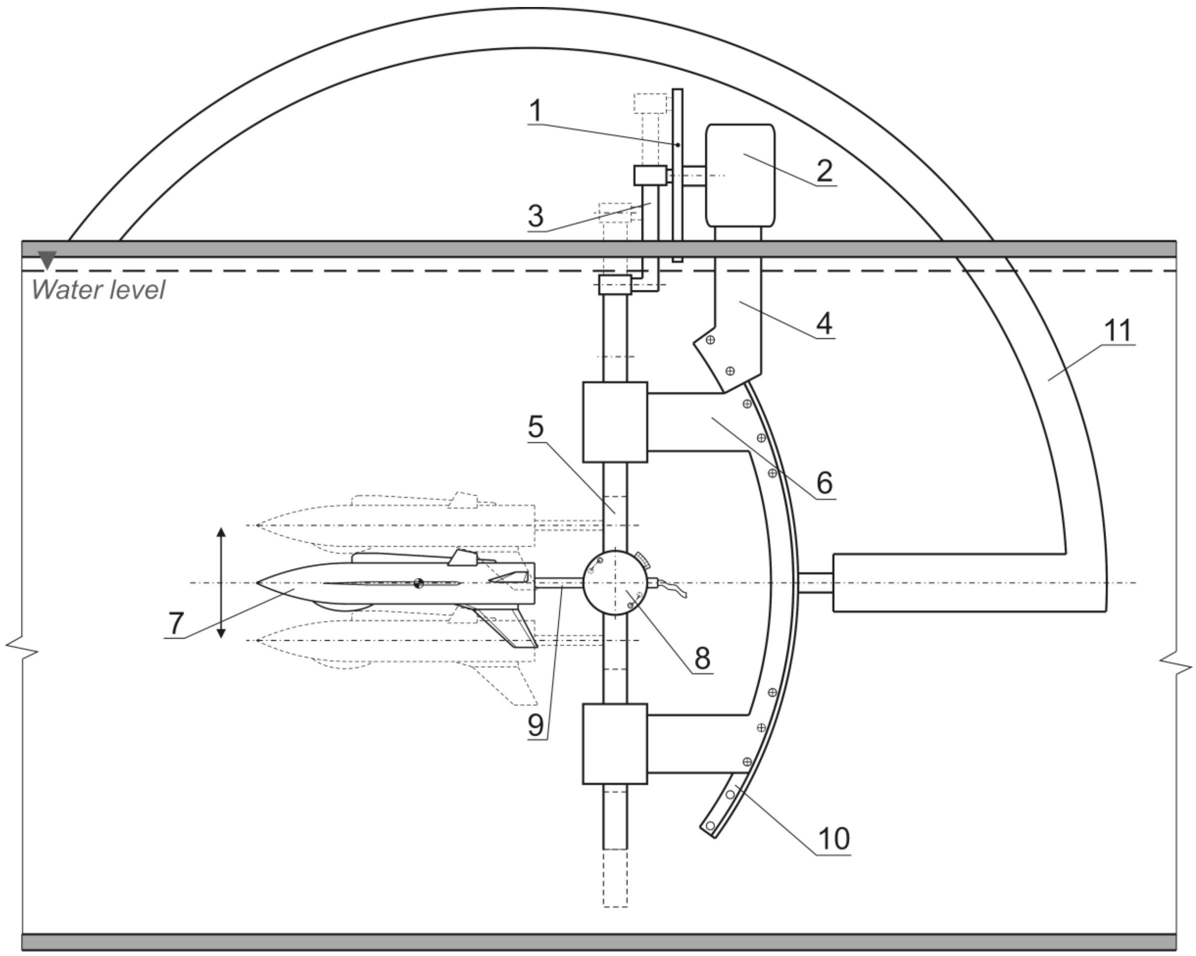

Fig. 1. Translational manipulator layout. Description: 1 – crank, 2 – motor, 3 – connecting rod, 4 – motor support, 5 – reciprocating guide, 6 – main support, 7 – aircraft model, 8 – angle of attack adjustment, 9 – strain balance, 10 – C strut, 11 – rotational manipulator

3. Identification of translational dynamic derivatives

Identification of translational dynamic derivatives relies on measuring the changes of forces and moments acting on aircraft model during steady harmonic motion. The collected data are combined with the linearized theory of dynamic flight parameters, which lead to identification of translational dynamic derivatives. The method of identification is described for vertical force coefficient component (C_Z) variation with respect to vertical velocity component (w).

3.1 Kinematic parameters

The attitude, velocity and acceleration for harmonic motion are:

$$A(t) = A_m \sin \omega t \,, \tag{1}$$

$$A = A_0 + A_m \sin \omega t \,, \tag{2}$$

$$w = \dot{A} = A_m \omega \cos \omega t \,, \tag{3}$$

$$\dot{w} = \ddot{A} = -A_m \omega^2 \sin \omega t \,. \tag{4}$$

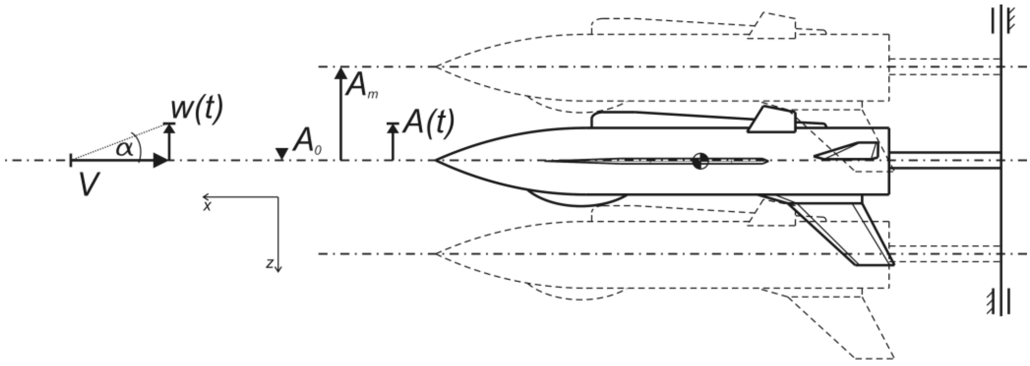

Fig. 2. Kinematic parameters of aircraft model

The changes in speed component (w) results in aircraft angle of attack variation:

$$\alpha = \arctan\left(\frac{w}{V}\right) = \arctan\left(\frac{A_m\,\omega\cos\omega t}{V}\right). \tag{5}$$

The angle of attack rate is:

$$\dot{\alpha} = \frac{-A_m V \omega^2 \sin\omega t}{V^2 + A_m^2\,\omega^2 \cos^2 \omega t}. \tag{6}$$

While the ω and V are constant, the kinematic parameters are known in DSD identification process.

3.2 Data processing

Linearized form of force coefficient variation during oscillations is expressed by with Taylor series in terms of steady state force and selected force derivatives:

$$C_Z(t) = C_{Z_0} + \left[\left.\frac{\partial C_Z}{\partial \alpha}\right|_{t=t_0} [\alpha(t)-\alpha_0]\right] + \left[\left.\frac{\partial C_Z}{\partial w}\right|_{t=t_0} w(t)\right] + \left[\left.\frac{\partial C_Z}{\partial \dot{\alpha}}\right|_{t=t_0} \dot{\alpha}(t)\right] + \left[\left.\frac{\partial C_Z}{\partial \dot{w}}\right|_{t=t_0} \dot{w}(t)\right] + \dots. \tag{7}$$

Equation (7) contains derivatives important in dynamic stability analysis. Higher order derivatives are neglected. The derivatives are non-dimensioned by aerodynamic time parameter $\overline{c}/2V$. The value of force aerodynamic coefficient variation is given by the:

$$C_Z = C_{Z_0} + C_{Z_\alpha}(\alpha - \alpha_0) + C_{Z_w}\frac{w\overline{c}}{2V} + C_{Z_{\dot{\alpha}}}\frac{\dot{\alpha}\,\overline{c}}{2V} + C_{Z_{\dot{w}}}\frac{\dot{w}\overline{c}}{2V}, \tag{8}$$

including the kinematic parameters (1)-(6):

$$C_Z = C_{Z_0} + C_{Z_\alpha}\left(\arctan\frac{\dot{A}}{V} - \alpha_0\right) + C_{Z_w}\frac{\dot{A}\overline{c}}{2V} + C_{Z_{\dot{w}}}\frac{\dot{A}\overline{c}}{2V} + C_{Z_{\dot{\alpha}}}\frac{\ddot{A}\overline{c}}{2[V^2 + (\dot{A})^2]}. \tag{9}$$

In tunnel tests, the measured data are vertical coefficient C_Z and attitude A in time sequence steps:

$$\mathbf{A} = \begin{bmatrix} A(t_0) & A(t_0+\Delta t) & A(t_0+2\Delta t) & \dots \end{bmatrix}^T, \tag{10}$$

$$\mathbf{C_Z} = \begin{bmatrix} C_Z(t_0) & C_Z(t_0+\Delta t) & C_Z(t_0+2\Delta t) & \dots \end{bmatrix}^T. \tag{11}$$

For the constant parameters of model oscillations frequency, flow speed V and measuring time step Δt, the equation (9) forms the over-determined system of linear equations:

$$\mathbf{C_Z} = \begin{bmatrix} \mathbf{1} & \left(\arctan\left(\frac{\dot{\mathbf{A}}}{V}\right) - \alpha_0\right) & \frac{\dot{\mathbf{A}}\bar{c}}{2V} & \frac{\ddot{\mathbf{A}}\bar{c}}{2V} & \frac{\ddot{\mathbf{A}}\bar{c}}{2[V^2 + (\dot{A})^2]} \end{bmatrix} \cdot \begin{bmatrix} C_{Z_0} \\ C_{Z_\alpha} \\ C_{Z_w} \\ C_{Z_{\dot{w}}} \\ C_{Z_{\dot{\alpha}}} \end{bmatrix}. \tag{12}$$

The equation (12) is essential in identification of aerodynamic translational dynamic derivatives of an aircraft. The values of vertical force coefficient in steady state flow conditions C_{Z0} and static derivative $C_{Z\alpha}$ are known from static water tunnel tests. The aerodynamic dynamic derivatives C_{Z_w}, $C_{Z_{\dot{w}}}$, $C_{Z_{\dot{\alpha}}}$ exist separately. Thus, the problem of separation of combined dynamic derivatives is omitted. However, the solution of (12) remains problematic since the columns in matrix of kinematic parameters are linearly dependent. For the 2nd and 3rd column the linear dependency is solved by the fact that static derivative C_{Z_α} is known – the dynamic derivative C_{Z_w} can be identified. Identification of $C_{Z_{\dot{w}}}$ and $C_{Z_{\dot{\alpha}}}$ derivatives is interrupted by the linear dependency of 4th and 5th column in kinematic parameters matrix. At this stage, it can be seen that identification process of translational derivatives is connected with identification of rotational derivatives where the derivative $C_{Z_{\dot{\alpha}}}$ is identified [8]. In this way, the derivative $C_{Z_{\dot{w}}}$ can be identified.

4. Summary

The proposed method of identification the translational aircraft dynamic derivatives is a development of existing systems. The translational manipulator (chapter 2) need to be mounted to rotational manipulator. Moreover, the mathematical process of DSD identification (chapter 3.2) shows that the identification of translational DSD need to be preceded by identification of rotational DSD [8]. Thus, the chronology of aircraft aerodynamics characteristics investigation should starts with static water tunnel tests, where the characteristics in steady state flight conditions and static derivatives are obtained. The next stage is to perform the dynamic water tunnel tests, which lead to identify the rotational DSD. Finally the investigation of translational DSD can be performed.

The process of identification translational DSD was shown for non-dimensional symmetrical derivative of vertical force component with respect to vertical velocity and vertical acceleration component C_{Z_w}, $C_{Z_{\dot{w}}}$. In order to identify the remaining translational symmetrical pitching moment derivatives C_{m_w} and $C_{m_{\dot{w}}}$ the measured data (11) need to be replaced by $\mathbf{C_m}$. Investigation of asymmetrical derivatives requires mounting the aircraft model rotated at angle of 90° (the aircraft *y*-axis direction must coincide with model oscillation direction). Analogical to symmetrical derivatives, replacing the measured data in (11) the asymmetrical derivatives can be investigated.

Notations

X, *Y*, *Z* – components of aerodynamic force (longitudinal, side, vertical);
l, *m*, *n* – components of aerodynamic moments (roll, pitch, yaw);
u, *v*, *w* – components of linear velocity (longitudinal, slip, vertical);
p, *q*, *r* – components of rotational velocity (roll, pitch, yaw);

Z_w – example of dimensional derivative notation (vertical force derivative with respect to vertical velocity);
C_{Z_w} – example of non-dimensional derivative notation (vertical force coefficient derivative with respect to vertical velocity);
A – aircraft model attitude in simple harmonic oscillations;
A_m – magnitude of model oscillations;
α – aircraft model angle of attack;
$\overline{c}$ – mean aerodynamic chord;
V – flow speed in water tunnel.
Index "0" – steady state flight parameters.

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