Review of the Roll-Damping, Measurements in the T-38 Wind Tunnel

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Abstract- In this paper review of roll-damping measurements in the T-38 blow-down wind tunnel is presented. Fundamental elements of the mathematical model for stability derivatives measurements are shown. Measurements are based on rigidly forced oscillations method. Apparatus for stability derivatives measurements in roll oscillations tests and data reduction procedures used in VTI are described. Roll apparatus is designed and produced with regard to high requirements in stability derivatives measurements.

***Index Terms*-** wind tunnel, stability derivatives, experimental aerodynamics, forced oscillation

I. Introduction

VTI has great experience in wind tunnel stability derivatives measurement. Starting from 1960 up to now several generations of apparatuses were designed and manufactured. Nowadays, the technique for measurements of stability derivatives applied in the T-38 wind tunnel is forced oscillation technique [1, 2]. Model is forced to oscillate at constant amplitude within a single degree of freedom, which implies that any aerodynamic reaction coherent with such motion can only be due to such motion. Wind tunnel run includes the following three stages:

- An amplifier calibration runs, when known signals from the signal generator are an input to data acquisition system. The subject measurement yields the gains and phase shift for each channel with respect to the displacement channel;
- Wind-off run when model is oscillating but the wind tunnel is not running. This measurement, using the data from amplifier calibration run, enables determination of the inertial forces;
- Wind-on run, when the model is oscillating at the same frequency as during the wind-off run but with the wind tunnel running.

Used symbols

$L_p + L_{\dot\beta}\sin\alpha$ - Dynamic direct damping derivative in roll

$L_\beta \sin\alpha$ - Rolling moment derivative due to sideslip

*Clp** - Non-dimensional dynamic direct derivative in roll

f_φ - Mechanical damping

$I_{x,y,z}$ - Inertia moments about $O_{x,y,z}$ axes

I_{xz} - Centrifugal inertia moment

K_φ - Mechanical stiffness

L, M, N - Total moments about $O_{x,y,z}$ axes

X,Y,Z - Aerodynamic force components

u,v,w - Velocity components in *x*, *y* and *z* direction

$L_{aero.}$ - External aerodynamic moment about O_x axis

$L_{meh.}$ - External mechanical moment about O_x axis

L_T - Excitation moment about O_x axis

$L_\alpha, L_{\dot\alpha}, L_\beta, L_{\dot\beta}$ - Partial derivative $\frac{\partial L}{\partial \alpha}, \frac{\partial L}{\partial \dot\alpha}, \frac{\partial L}{\partial \beta}, \frac{\partial L}{\partial \dot\beta}$

L_p, L_q, L_r - Partial derivative $\frac{\partial L}{\partial p}, \frac{\partial L}{\partial q}, \frac{\partial L}{\partial r}$

p, q, r	- Roll, pitch and yaw rates
$\dot{p}, \dot{q}, \dot{r}$	- Time derivatives of roll, pitch and yaw rates
α	- Angle of attack
$\dot{\alpha}$	- Time derivative of angle of attack
β	- Sideslip angle
$\dot{\beta}$	- Time derivative of sideslip angle
φ, θ, ψ	- Angles of rolling, pitching and yawing motion
η	- Phase shift
ω	- Angular velocity
t	- Time
$\lvert ... \rvert$	- Amplitude

II. Determination of Roll-Damping Derivatives Using Method of Rigidly Forced Oscillation Technique

The equations of motion for the angular degrees of freedom relative to a set of moving axes that are fixed in the model, Figure 1, can be written as [2-3]:

$$L = \dot{p} I_x - \dot{r} I_{xz} \quad (1)$$

$$M = \dot{q} I_y \quad (2)$$

$$N = \dot{r} I_z - \dot{p} I_{xz} \quad (3)$$

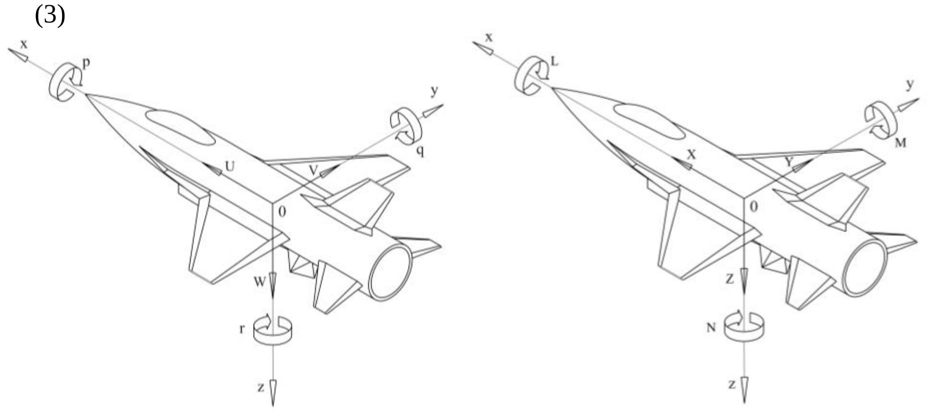

Figure 1: Body axis system

Left sides of above equations represent the sum of all the variations in the external moments acting on the model in the particular degree-of-freedom due to a very small departure from a steady-state motion. Such external rolling moment include:

$$L = L_{aero.} + L_{mech.} + L_T \quad (4)$$

For model at the equilibrium angle of attack performing small-amplitude low-frequency angular oscillation, aerodynamic reaction can be expressed by linear superposition of contributions caused by: α, β, derivative of α and β with respect to time, p, q and r. Relations between those parameters are:

$$\alpha = \theta, \quad \beta = \varphi \cdot \sin\alpha - \psi \cdot \cos\alpha, \quad p = \dot{\varphi}, \quad q = \dot{\theta}, \quad r = \dot{\psi}, \quad \dot{\alpha} = q, \quad \dot{\beta} = p \cdot \sin\alpha - r \cdot \cos\alpha.$$

Change in aerodynamic reaction due to the model oscillation can be expressed as follows:

$$L_{aero.} = L_\alpha \cdot \alpha + L_\beta \cdot \beta + L_{\dot{\alpha}} \cdot \dot{\alpha} + L_{\dot{\beta}} \cdot \dot{\beta} + L_p \cdot p + L_q \cdot q + L_r \cdot r \quad (5)$$

A captive model performing oscillatory motion experiences mechanical reactions caused by its support:

$$L_{mech} = -\left(f_\varphi \cdot p + K_\varphi \cdot \varphi\right) \quad (6)$$

Considering equations (4-6) the equation (3) becomes:

$$I_x \cdot \dot{p} + \left(f_\varphi - \left(L_p + L_{\dot{\beta}} \cdot \sin\alpha\right)\right) \cdot p + \left(K_\varphi - L_\beta \cdot \sin\alpha\right) \cdot \varphi =$$
$$I_{xz} \cdot \dot{r} + \left(L_r - L_{\dot{\beta}} \cdot \cos\alpha\right) \cdot r - L_\beta \cdot \psi \cdot \cos\alpha + \left(L_q + L_{\dot{\alpha}}\right) \cdot q + L_\alpha \cdot \theta + L_T \quad (7)$$

Stability derivatives in roll are obtained from equation (7) by equalizing left side of equation with excitation moment L_T :

$$I_x \cdot \dot{p} + \left[f_\varphi - \left(L_p + L_{\dot{\beta}} \cdot \sin\alpha\right)\right] \cdot p + \left(K_\varphi - L_\beta\right) \cdot \varphi = L_T \quad (8)$$

Excitation moment L_T is:

$$L_T = \left|L_T\right| \cdot \cos\omega \cdot t \quad (9)$$

Rolling oscillatory model motion is:

$$\varphi = \left|\varphi\right| \cdot \cos\left(\omega \cdot t - \eta\right) \quad (10)$$

Time derivative of the φ equation is:

$$\dot{\varphi} = -\left|\varphi\right| \cdot \omega \cdot \sin\left(\omega \cdot t - \eta\right), \quad (11)$$

And time derivative of the $\dot{\varphi}$ equation is:

$$\ddot{\varphi} = -\left|\varphi\right| \cdot \omega^2 \cdot \cos\left(\omega \cdot t - \eta\right) \quad (12)$$

Taking equations (9-12) in equation (8) and separating values next to $\sin\omega \cdot t$ and $\cos\omega \cdot t$, two equations are obtained:

$$-I_x \cdot \left|\varphi\right| \cdot \omega^2 \cdot \cos\eta + \left[f_\varphi - \left(L_p + L_{\dot{\beta}} \cdot \sin\alpha\right)\right] \cdot \left|\varphi\right| \cdot \omega \cdot \sin\eta + \left(K_\varphi - L_\beta \cdot \sin\alpha\right) \cdot \left|\theta\right| \cdot \cos\eta = \left|L_T\right| \quad (13)$$

$$-I_x \cdot \left|\theta\right| \cdot \omega^2 \cdot \sin\eta - \left[f_\varphi - \left(L_p + L_{\dot{\beta}} \cdot \sin\alpha\right)\right] \cdot \left|\varphi\right| \cdot \omega \cdot \cos\eta + \left(K_\varphi - L_\beta \cdot \sin\alpha\right) \cdot \left|\theta\right| \cdot \sin\eta = 0 \quad (14)$$

Solving the above equations simultaneously direct dimensional static and dynamic stability derivatives in roll are obtained:

$$K_\varphi - L_\beta \cdot \sin\alpha = I_x \cdot \omega^2 + \left|\frac{L_T}{\varphi}\right| \cdot \cos\eta \quad (15)$$

$$f_\varphi - \left(L_p + L_{\dot{\beta}} \cdot \sin\alpha\right) = \left|\frac{L_T}{\varphi}\right| \cdot \frac{\sin\eta}{\omega} \quad (16)$$

where: $K_\varphi = I_x \cdot \omega_o{}^2 + \left|\frac{L_{To}}{\varphi_o}\right| \cdot \cos\eta_o$, $f_\varphi = \left|\frac{L_{To}}{\varphi_o}\right| \cdot \frac{\sin\eta_o}{\omega_o}$.

Finally, expressions for determination stability derivatives in roll are:

$$L_\beta \cdot \sin\alpha = -I_x \cdot \left(\omega^2 - \omega_o^2\right) - \left[\left|\frac{L_T}{\varphi}\right| \cdot \cos\eta - \left|\frac{L_{To}}{\varphi_o}\right| \cdot \cos\eta_o\right] \quad (17)$$

$$L_p + L_{\dot{\beta}} \cdot \sin\alpha = \left|\frac{L_{To}}{\varphi_o}\right| \cdot \frac{\sin\eta_o}{\omega_o} - \left|\frac{L_T}{\varphi}\right| \cdot \frac{\sin\eta}{\omega} \quad (18)$$

Values with index 'o' in equations (17-18) are measured in wind-off run.

1.1. Roll apparatus

The roll apparatus is shown in the Figures 2-3. The suspension system consists of two rings joined by axially oriented beams equal spaced around the periphery of the rings. There are two suspension systems for low and high loads. Such configuration provides the necessary compliance in the roll attitude while having a substantial stiffness in the other degrees-of-freedom. A five-component balance is mounted on the front end of the drive shaft and on the front end of the suspension system, protruding forward through the cavity surrounded by the suspension beams, while the aft part of the suspension system is firmly fixed to the end of the sting. A five-component internal balance is mono-block type and semiconductor strain gages are used in order to increase its sensitivity and, consequently, signal to noise ratio as well. The oscillatory rolling motion is imparted by hydraulic driving mechanism located at the rear end of the sting via drive shaft whose front end is attached to the balance.

Table 1: Performance list of the roll apparatus

Roll Apparatus	**Amplitude (°)**	**Frequency (Hz)**	**Sting Diameter (mm)**	**Hydraulic Pressure (bar)**
	0.25-1.5	1.0-15	76	200
Maximum normal force:	10000 N			
Maximum angle of attack:	up to 21^{o}			
Maximum angle of side slip:	0^{o}			
Mach number:	up to 2.0			
Blowing pressure:	up to 2.3 bar			
Driving mechanism:	Elastic suspension with internal hydraulic drive			

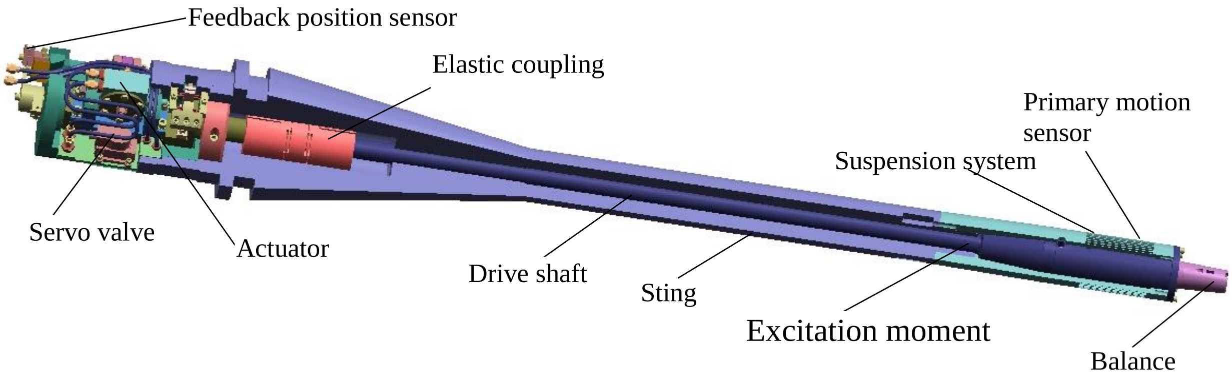

Figure 2: CAD model of roll apparatus

Figure 3: Roll apparatus

III. Data Reduction

For determination of direct stability derivatives in roll following physical values must be measured:

- Amplitudes of primary motion (φ) and excitation moment (L_T);
- Frequency of primary motion (ω);

- Phase shift between excitation moment and primary motion (η).

All of the above data are obtained by signals from suitable located strain gages on the apparatus. A five-component internal monoblock balance measures the forces and moments that act on the model during the tests. The primary motion is sensed by strain gages located at the suspension system. Excitation moment is estimated by strain gages located on the drive shaft or from balance bridge for rolling moment.

During the measurements, all the sensor signals are amplified, filtered and then digitized by a 16-bit AD converter. The sampling record of data covers approximately 82 cycles with 8192 measuring points of the primary oscillation. The data from the test runs are processed in the following steps:

- Data acquisition system interfacing and signals normalization;
- Determination of flow parameters;
- Determination of model attitude;
- Determination of static aerodynamic coefficients of forces and moments;
- Determination of frequency, amplitude and phase shift of each channel with respect to the primary motion channel;
- Determination of the direct damping derivatives;
- Calculation of non-dimensional aerodynamic direct derivatives;
- Output of tabulated results and plots.

Different software modules perform each stage of the above process.

Tests results of the roll-damping measurements on Modified Basic Finner Model are presented in the Figure 5. [4, 5]. Results obtained in the T-38 wind tunnel are compared with published experimental data from the AEDC wind tunnel [6] (Arnold Engineering Development Center-von Karman - USA) and at α = 0° with calculated roll-damping coefficient values obtained by DMAC semi-empirical method developed in the VTI [7].

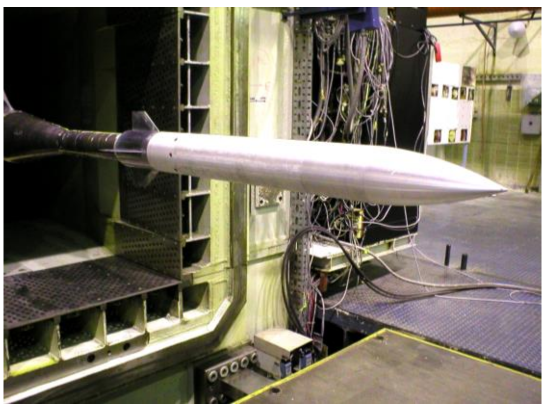

Figure 4: Modified Basic Finner Model in the T-38 test section

$$Clp^* = \frac{2V\left(L_p + L_{\dot{\beta}} \sin\alpha\right)}{q \cdot S \cdot d^2}$$

S - model reference area
d - model diameter
V - velocity
q - dynamic pressure

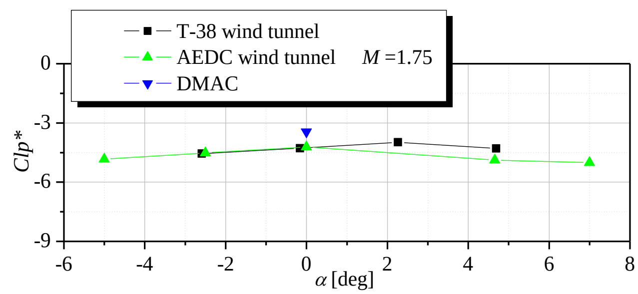

Figure 5: Roll-damping derivative for Modified Basic Finner Model at the M=1.75

IV. Conclusion

Complexity of wind tunnel stability derivatives measurements is well known. The determination of roll-damping derivatives using method of rigidly forced oscillation technique applied in T-38 wind tunnel is presented. Developed equipment, roll-apparatus and data reduction procedures have reached a stage to be a very good tool in design of missiles and aircrafts.

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