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Effects of the Sting Oscillation on the Measurements of Dynamic Stability Derivatives

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This paper presents a method for determination the effects of the sting oscillation on the measurements of dynamic derivatives due to oscillatory pitching. Measurements of stability derivatives in the T-38 trisonic blowdown wind tunnel of the Military Technical Institute in Belgrade are described. The paper presents the sample tests results of pitch-damping measurements of the Modified Basic Finner Model made using the new mathematics model of stability derivatives measurements at Mach numbers 0.6. The test results are compared with published experimental data from the AEDC wind tunnel (USA) and with calculated pitch-damping coefficient values obtained by the DMAC semi-empirical method developed by the Military Technical Instute.

Key words: **wind tunnel, experimental aerodynamics, aerodynamic derivatives, stability derivatives, forced oscillations, pitching.**

THE experience from wind tunnel stability derivatives measurements in the Military Technical Institute, especially in the T-38 wind tunnel, showed that large aerodynamic loads on the models cause the sting deflection and the sting oscillation. The influence of the motion of a model support system is always present to some extent in dynamic stability tests of captive models in wind tunnels. The effects of the sting translational motion on the measured stability derivatives are manifested in three different ways:

- the reactions from which the moment derivatives are obtained contain the translation effect,
- the location of the axis of oscillations is determined by the plunge amplitude,
- the model angular orientation changes with sting deflection [1].

The model angular orientation changes with the sting deflection are accounted for in the standard data reduction procedure. One part of the new mathematical model for stability derivatives measurements in the T-38 wind tunnel is presented with a special view on the effects of the sting plunging oscillation. The impact of the sting oscillation on the measurements due to oscillatory pitching is determined.

Measurement equipment and technique

The T-38 test facility is a blowdown-type pressurized wind tunnel with a 1.5x1.5 m square test section [2, 3]. Mach number in the range 0.2 to 4.0 can be achieved in the test section, with Reynolds number up to 110 million per meter. The run time is in the range 6s to 60s, depending on Mach number and stagnation pressure.

The method for measuring stability derivatives is the forced oscillation method. A model is forced to oscillate at a constant amplitude within a single degree of freedom, which implies that any aerodynamic reaction coherent with such a motion, known as “the primary motion”, can only be due to such a motion [4-6]. The experiments are based on the application of a low amplitude oscillatory motion to a model in the primary degree of freedom and on the measurement of aerodynamic reactions produced by such a motion in that particular and in other (secondary) degrees of freedom. These reactions, in turn, yield relevant direct and cross as well as cross-coupling derivatives due to the motion considered herein. A typical wind tunnel run includes:

- Wind-off run, when the model is oscillated but the tunnel is not running. This measurement enables determination of the inertial forces.
- Wind-on run, when the model is oscillated at the same frequency as during the wind-off run but the wind tunnel is running.

Dynamic stability derivatives are obtained by subtracting data from the wind-off and wind-on run. For determining direct stability derivatives, the following physical values must be measured: the amplitudes of the primary motion and the excitation moment, the frequency of the primary motion as well as the phase shift between the excitation moment and the primary motion.

The pitch/yaw apparatus for measuring stability derivatives was designed and produced in the Military Technical Institute, Fig.1. The suspension system consists of a pair of cross flexures ensuring the necessary compliance in pitch or yaw, depending on the model orientation of the balance. The primary motions are impaired by the hydraulic driving mechanism in which the

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piston moves and applies the driving force on the actuator arm linking it to the moving end of the cross flexures. A five-component balance is mounted inside the actuator arm between the cross flexures. The balance is of a monoblock type and the semiconductor strain gages were used in order to increase its sensitivity and consequently the signal to noise ratio as well. The actuator arm is gauged and calibrated to measure the moment applied to the moving system. In order to obtain the direct primary oscillations, the hydraulic actuator is driven by the hydraulic servo-valve, located at the sting base that is, in turn, driven by a signal from the control system. The provision is made to increase the suspension stiffness by adding a relevant auxiliary leaf spring.

In order to determine the sting oscillation, a three component transducer is realized at the sting root. This transducer is realized from foil strain gauges. The strain gauges are connected in a form of a four-active arm bridge.

Figure 1. Pitch/yaw apparatus

The performance of the pitch/yaw apparatus is:

- amplitude: 0.25 ÷ 1.5°
- frequency: 1 ÷ 15 Hz
- sting diameter: 50 × 70 mm
- hydraulic pressure: 200 bar
- maximum axial force: 5.5 kN
- maximum side force: 7 kN
- maximum normal force: 10 kN
- maximum rolling moment: 300 Nm
- maximum pitching moment: 660 Nm
- maximum yawing moment: 350 Nm.

Determination of the effects of the sting oscillation

Assuming the sting oscillation, a model in the wind tunnel test section performs two motions:

- small oscillations in the pitch plane and
- translation in *z* direction.

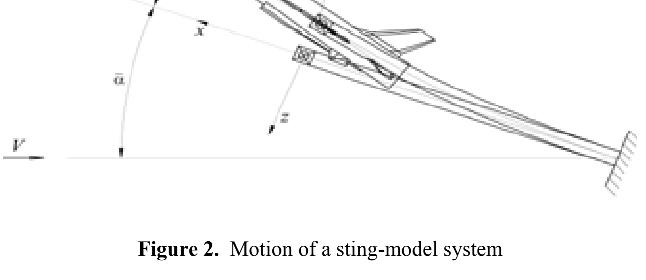


Figure 2. Motion of a sting-model system

The motion of a sting-model system is shown in Fig.2, where:

$\bar{\alpha}$ - mean angle of attack,
θ_m - pitch perturbation angle (amplitude of the model oscillation),
θ_s - pitch perturbation angle of the model oscillation caused by the hydraulic driving mechanism,
θ_f - pitch perturbation angle caused by the sting translation,
V - free stream velocity.

The model angle of attack is:

$$\alpha = \bar{\alpha} + \theta_m + arctg \frac{\dot{z}}{V \cos \bar{\alpha}} .$$

Assuming the linear aerodynamic and small oscillation amplitudes, the differential equations of motion for a model oscillating in the pitch plane, where $q = \dot{\theta}_m$, may be written as:

$$\begin{gathered} I_y \cdot \ddot{\theta}_m + m \cdot x_{CG} \cdot \ddot{z} + D_\theta \cdot \dot{\theta}_m + K_\theta \cdot \theta_m = \\ M_\alpha \cdot \theta_m + \left(M_q + M_{\dot{\alpha}}\right) \cdot \dot{\theta}_m + M_{\dot{\alpha}} \frac{\ddot{z}}{V \cdot \cos \bar{\alpha}} + M_\alpha \frac{\dot{z}}{V \cdot \cos \bar{\alpha}} + M_P \end{gathered} \tag{1}$$

$$\begin{gathered} m \cdot \ddot{z} + m \cdot x_{CG} \cdot \ddot{\theta}_m + D_z \cdot \dot{z} + K_z \cdot z = \\ -Z_\alpha \cdot \theta_m - \left(Z_q + Z_{\dot{\alpha}}\right) \cdot \dot{\theta}_m - Z_{\dot{\alpha}} \frac{\ddot{z}}{V \cdot \cos \bar{\alpha}} - Z_\alpha \frac{\dot{z}}{V \cdot \cos \bar{\alpha}} \end{gathered} \tag{2}$$

where:

I_y - pitch moment of inertia,
m - model and balance mass,
M_α - pitching moment due to the angle of attack,
x_{CG} - center of mass position,
D_θ, D_z - linear damping constants,
K_θ, K_z - linear spring constants,
$M_{\dot{\alpha}}$ - pitching moment due to vertical acceleration,
M_P - excitation moment,
$M_q + M_{\dot{\alpha}}$ - direct damping derivative in pitch,
Z_α - normal force due to the angle of attack,
$Z_{\dot{\alpha}}$ - normal force due to vertical acceleration,
$Z_q + Z_{\dot{\alpha}}$ - direct damping derivative of the normal force due to the pitch rate.

Assuming that the sting is relatively rigid, i.e. $\theta_f \ll \theta_s = \theta_m = \theta$, and that $x_{CG} = 0$ (model is balanced), the derivatives are:

$$M_\alpha = \frac{I_y \left(\omega_o^2 - \omega^2\right) + \left(\frac{|M_P|}{|\theta|} \cos \phi\right)_0 - \frac{|M_P|}{|\theta|} \cos \phi}{1 - \frac{\omega^2}{V^2 \cos \bar{\alpha}} \left(\frac{\Delta z}{|\theta|}\right)^2} \tag{3}$$

$$M_q + M_{\dot{\alpha}} = \left(\frac{|M_P| \sin \phi}{|\theta| \omega}\right)_0 - \frac{|M_P| \sin \phi}{|\theta| \omega} + \frac{\Delta z}{|\theta|} \frac{M_\alpha}{V \cos \bar{\alpha}} \cos \phi_S \tag{4}$$

where:

$(\ )_o$ - values measured in wind-off run,
$|\theta|$ - amplitude of the model oscillation,
ω - angular velocity,
ϕ - phase angle between the excitation moment and the pitch oscillation,
ϕ_s - phase angle between the translational and the rotational motion,
Δz - amplitude of the sting plunging (Fig.2)

The terms $1-\frac{\omega^2}{V^2\cos\bar{\alpha}}\left(\frac{\Delta z}{|\theta|}\right)^2$ and $\frac{\Delta z}{|\theta|}\frac{M_\alpha}{V\cos\bar{\alpha}}\cos\phi_s$ in equations (3) and (4) present the correction of sting plunging oscillations.

Wind tunnel test of the calibration model MBFM

Only one part of the stability derivatives measurements of the Modified Basic Finner Model (MBFM), Figures 3 and 4, conducted in the T-38 wind tunnel is presented in this paper. The results of the tests at Mach number $M = 0.6$ are shown. These results are obtained using a new mathematical model.

The tests results obtained in the T-38 wind tunnel are compared with the published experimental data from the AEDC wind tunnel [7, 8] (Arnold Engineering Development Center-von Karman - USA). The wind tunnel data at $\alpha = 0°$ are also compared with the calculated coefficient values obtained by the DMAC semi-empirical method developed in the MTI [9].

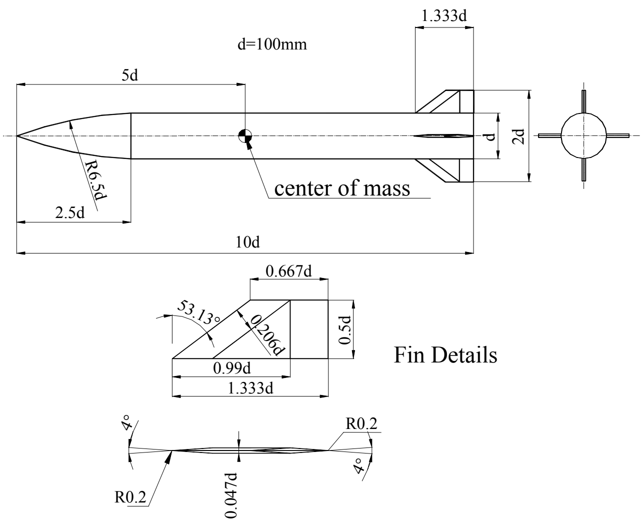


Figure 3. Basic dimension of the Modified Basic Finner Model

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

Table 1 shows the frequency (*f*) and the amplitude of the model oscillations $(|\theta|)$, the amplitude of the excitation moment $|M_P|$, the amplitude of the sting translational oscillations $|M_S|$, the phase angle between the excitation moment and the pitch oscillation ϕ and the phase angle between the sting translational and the pitch oscillation ϕ_S, measured at Mach number 0.6 on the MBFM model. These presented values were used in calculating the direct damping derivative in pitch.

Table 1.

α [°]	F [Hz]	$\lvert\theta\rvert$ [°]	$\lvert M_P\rvert$ [Nm]	$\lvert M_S\rvert$ [Nm]	ϕ [°]	ϕ_S [°]
-2.053	10.011	0.504	9.132	50.096	-7.4496	1.5732
-1.069	10.011	0.500	9.010	48.045	-6.8117	1.2246
-0.112	10.011	0.498	8.915	47.877	-6.6475	1.8670
0.857	10.011	0.494	8.831	47.136	-7.9473	1.2188
1.826	10.011	0.504	9.304	47.921	-6.2534	0.5914
2.817	10.011	0.508	9.130	49.843	-7.5849	1.2202
3.783	10.011	0.510	8.962	51.341	-6.0145	0.6713
4.727	10.011	0.512	8.289	54.990	-8.9312	0.4753

Fig.5 shows a signal from the model oscillations transducer (ODF) and a signal from measuring the bridge for sting translational oscillations (FMS) during the oscillation in the pitch plane at $\alpha = 0^\circ$.

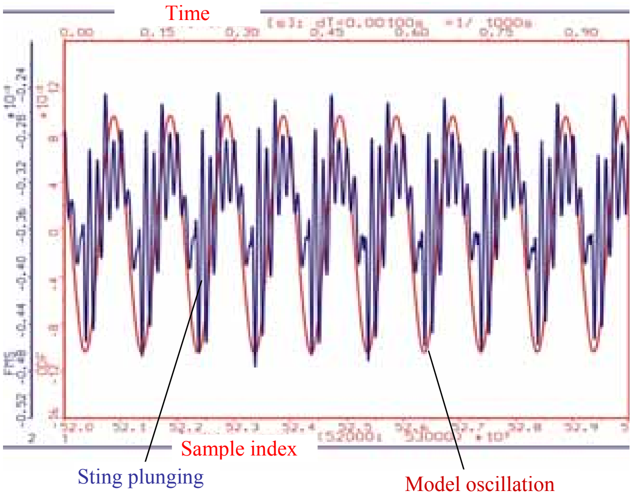
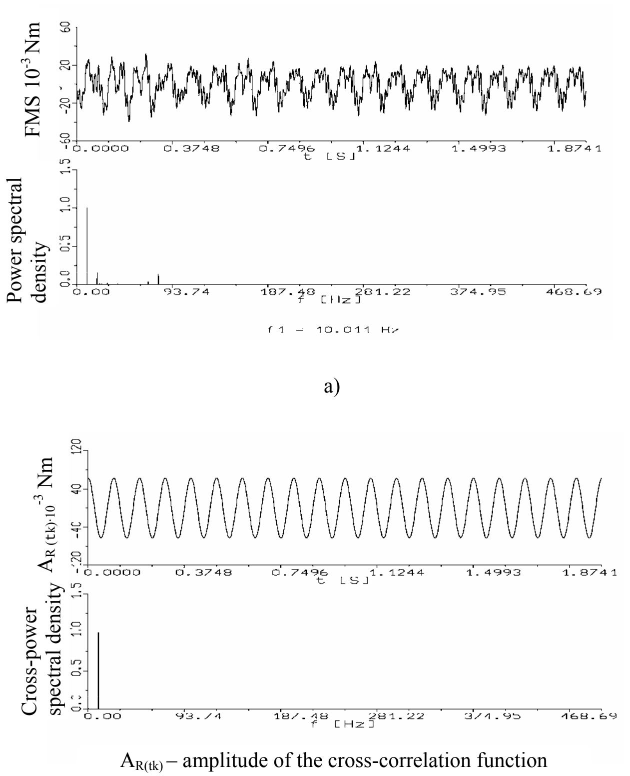


Figure 5. Signals from the model oscillation and sting plunging transducers

The amplitude of the sting plunging and the phase angle between the sting translational and pitch oscillations are calculated in the frequency domain by applying the cross-power spectral density, Fig.6.

The non-dimensional coefficient of the direct damping derivative in pitch is presented in Fig.7. ($CMQ^* = C_{mq} + C_{m\dot{\alpha}}$) [10]. The measured values in the T-38 wind tunnel are approximated by third-order polynomial. For the angle of attack $\alpha = 0^\circ$, the difference between the T-38 wind tunnel measured values and the average values of the pitch damping derivative measured in the AEDC wind tunnel is 0.45%. Also, the T-38 wind tunnel measured values deviation to the calculated coefficient values obtained by DMAC semi-empirical method is 5.2%. In both cases, the agreement between the pitch damping data is very good.



a)

$A_{R(tk)}$ – amplitude of the cross-correlation function

b)

Figure 6. Sting translational oscillations signal and power spectral density a), cross-correlation function of the sting translational oscillation signal and cross- power spectral density b)

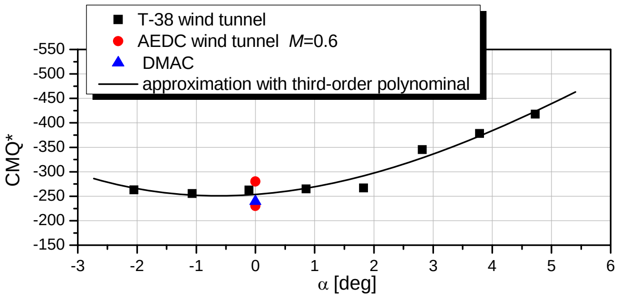


Figure 7. Pitch-damping derivative for the MBFM model at M=0.6

Conclusion

The equations for the effect of the sting translational oscillation on the pitch moment derivative are presented. The forced-oscillation tests of pitch-damping derivative with a new mathematical model were performed in the T-38 wind tunnel. The obtained test results were compared with available experimental data from the AEDC wind tunnel and with available semi-empirical data. The usage of the new mathematical model showed very good results. Taking this effect into account, the stability derivatives determination in the T-38 wind tunnel becomes more accurate.

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Uticaj oscilovanja nosača modela na merenje dinamičkih derivativa stabilnosti

U ovom radu prikazano je određivanje uticaja oscilovanja držača modela na merenje derivativa stabilnosti u propinjanju. Opisano je merenje derivativa stabilnosti u trisoničnom rafalnom aerotunelu T-38 Vojnotehničkog instituta u Beogradu. Prikazani su rezultati merenja prigušenja u propinjanju na Modified Basic Finner Model-u i na Mahovom broju 0.6. Ovi rezultati dobijeni su korišćenjem novog matematičkog modela. Rezultati merenja upoređeni su sa objavljenim rezultatima dobijenim u aerotunelu AEDC (USA) i sa vrednostima dobijenim poluempirijskom metodom DMAC koja je razvijena u Vijnotehničkom institutu.

Ključne reči: **aerodinamički tunel, eksperimentalna aerodinamika, aerodinamički derivativi, derivativi stabilnosti, prinudne oscilacije, propinjanje.**

Влияние колебания кронштейна модели на измерение динамических дериватив устойчивости

В настоящей работе показано определение влияния колебания кронштейна модели на измерение дериватив устойчивости в тангаже. Здесь описаны измерения дериватив устойчивости в триссонической аэродинамической трубе Т-38 Военнотехнического института в Белграде. Здесь показаны результаты измерения демпфирования в тангаже на модели Modified Basic Finner и при числу Маха 0,6. Эти результаты получены при помощи использования новой математической модели. Результаты измерений сопоставлены с опубликованными результатами получеными в аэродинамической трубе AEDC (США) и со значениями получеными полуэмпирическим методом DMAC, развитым во Военнотехническом институте в Белграде.

Kly~evwe slova: **аэродинамическая труба, экпериментальная аэродинамика, аэродинамические дериватив, дериватив устойчивости, вынужденные колебания, тангаж.**

Les effets de l’oscillation du dard de modèle sur le mesurage des dérivées dynamiques de stabilité

La détermination des effets de l’oscillation du dard de modèle sur le mesurage des dérivées de stabilité pendant le tangage fait l’objet de ce travail. On a décrit le mesurage des dérivées de stabilité dans la soufflerie rafale trisonique T-38 de l’Institut militaire technique à Belgrade. On a présenté les résultas des mesurages de l’étouffement pendant le tangage à l’aide du Modified Basic Finner modèle et à Mach 0.6. Ces résultats ont été obtenus par l’utilisation du nouveau modèle mathématique. Les résultats du mesurage ont été comparés avec les résultats obtenus dans la soufflerie aérodynamique AEDC(USA) et avec les valeurs obtenus via la méthode semi empirique DMAC développée à l’Institut militaire technique.

Mots clés: **soufflerie aérodynamique, aérodynamique expérimentale, dérivées aérodynamiques, dérivées de stabilité**