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Measurement of the Direct Damping Derivative in Roll of the Two Callibration Missile Models

Measurement of the direct damping derivative in roll in the T-38 wind tunnel is described in this paper. The T-38 wind tunnel data for the Basic Finner Model and Modified Basic Finner model are shown. The forced oscillation technique was used for these measurements. The roll apparatus for the stability derivatives measurement is a full-model forced oscillation apparatus with primary angular oscillation around a longitudinal axis of the model. The excitation moment in roll was measured with the five-component strain gauge balance. This balance was designed and built for the wind tunnel dynamic measurements. The amplitudes and phase shifts of the excitation moment were calculated in frequency domain by applying cross-correlation technique. The T-38 wind tunnel results are compred with published experimental results of the Arnold Engineering Development Center-von Karman 4ft wind tunnel.

Keywords: *wind tunnel, stability derivative, forced oscillation technique, strain gauge balance, calibration model, cross-correlation technique.*

1. INTRODUCTION

The modern aerospace vehicle is exposed to unsteady flow fields that may have significant effects on its characteristics of motion. This occurs whenever an oscillatory motion is experienced by an aircraft or missile flying at an angle of attack that is high enough to cause flow separation or vortex shedding, or whenever two configurations flying in close proximity are exposed to some unsteady disturbance as it may happen immediately after a separation manoeuvre. The modern aircraft often flies in conditions causing significant flow asymmetry, such as associated with asymmetric vortex shedding, application of direct side-force controls or presence of a small angle of sideslip. The unsteady flow fields involved are usually highly nonlinear and complex and result in stability characteristics that are strong functions of angle of attack and that may represent a significant aerodynamic coupling between the longitudinal and lateral degrees of motion. Because of these influences on an aircraft or missile flying, dynamic stability information is the object of high interest.

Dynamic stability information can in principle be obtained from model experiments in many different types of facilities. The best way to obtain model-scale dynamic stability information at realistic Reynolds and Mach numbers is to perform captive-model experiments in high Reynolds number wind tunnel.

The T-38 wind tunnel of the Military Technical Institute is a blowdown-type pressurized wind tunnel with 1.5x1.5 m test section [1]. Mach number in the range 0.2-4.0 can be achieved in the test section. One of

the main advantages of the T-38 wind tunnel is its high Reynolds number capability: up to 110 million per meter.

The main aim of the wind tunnel experiments is experimental support of research and development during design phase of an aircraft and missile project. The forced oscillation technique (also called rigidly forced oscillation) is used for the measurement of stability derivatives in the T-38 wind tunnel [2-4]. In this technique a preselected motion is imparted to the model and forces and moments between the model and the forcing part of the apparatus are measured. The model motion can be angular or translational and is usually sinusoidal, in which case the derivatives are obtained from the in-phase and out-phase components of the measured aerodynamic reactions. Both force and moment derivatives can be measured using this technique.

Basic equations and corresponding data reduction for the determination of the direct damping derivative in roll are shown in this paper.

2. DETERMINATION OF THE DIRECT DAMPING DERIVATIVE IN ROLL IN THE T-38 WIND TUNNEL

In the measurement of stability derivatives in the T-38 wind tunnel, a model is forced to oscillate at constant amplitude within a single degree of freedom, which implies that any aerodynamic reaction coherent with such motion, donated as primary motion, can be only due to such motion. Experiments are based on giving a small amplitude oscillatory motion to a model in the primary degree of freedom and measuring aerodynamic reactions produced by such motion in that particular and other (secondary) degrees of freedom.

In the body axis system, oscillatory motion of the symmetrical model in the roll is given by (1) (see Figure 1):

$$I_x \ddot{\varphi} + f_\varphi \dot{\varphi} + K_\varphi \varphi = |L_T| e^{j\omega t} \quad (1)$$

where I_x is roll moment of inertia, φ is a model angular oscillatory motion in roll, f_φ is total damping in roll, K_φ is total stiffness in roll, $|L_T|$ is amplitude of the excitation moment in roll, ω is angular velocity and t is time.

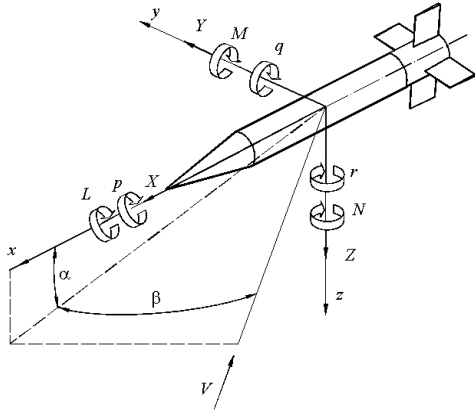**Figure 1. Body axis system**

Total damping in roll is obtained by equalising imaginary components of (1):

$$f_\varphi = \frac{|L_T|}{|\varphi|} \frac{\sin \eta}{\omega} \quad (2)$$

where $|\varphi|$ is amplitude of the model angular oscillatory motion in roll and η is the phase shift between model angular oscillatory motion and excitation moment.

Total stiffness in roll is obtained by equalising real components of (1):

$$K_\varphi = I_x \omega^2 + \frac{|L_T|}{|\varphi|} \cos \eta \quad (3)$$

Measurement of the aerodynamic damping using forced oscillation technique cannot be performed directly. The aerodynamic damping is obtained as a difference between the total damping obtained in the presence of aerodynamic load and mechanical damping which is obtained in absence of aerodynamic load. The complete wind tunnel run includes two stages: the tare run and wind-on run. In the tare run the model is oscillated but the wind tunnel is not running. The tare run enables measurement of the mechanical damping. In the wind-on run the model is oscillated at the same frequency and amplitude as during the tare run, but with the wind tunnel running. The wind-on run enables measurement of the total damping. Damping derivatives are obtained by subtracting tare run data from wind-on run data.

The equations for the determination of the static and dynamic stability derivatives in roll, in the body axis system, may be written as:

$$L_\beta \sin \alpha = -I_x \left(\omega^2 - \omega_o^2 \right) - \left(\frac{|L_T|}{|\varphi|} \cos \eta - \frac{|L_{To}|}{|\varphi_o|} \cos \eta_o \right) (4)$$

$$L_p + L_{\dot{\beta}} \sin \alpha = \left(\frac{|L_{To}|}{|\varphi_o|} \frac{\sin \eta_o}{\omega_o} - \frac{|L_T|}{|\varphi|} \frac{\sin \eta}{\omega} \right) \quad (5)$$

where $L_\beta \sin \alpha$ is rolling moment due to angle of sideslip and $L_p + L_{\dot{\beta}} \sin \alpha$ is direct damping derivative in roll. All values with index (o) are measured in the tare run.

Non-dimensional coefficients are obtained in the following forms:

$$C_{l\beta} \sin \alpha = \frac{L_\beta \sin \alpha}{q_\infty S d}, \ C_{lp} + C_{l\dot{\beta}} \sin \alpha = \frac{L_p + L_{\dot{\beta}} \sin \alpha}{\dfrac{q_\infty S d^2}{2V}}$$

where q_∞ is dynamic pressure, d is a model reference length, S is a model reference area, V is free stream velocity.

2.1 Roll apparatus

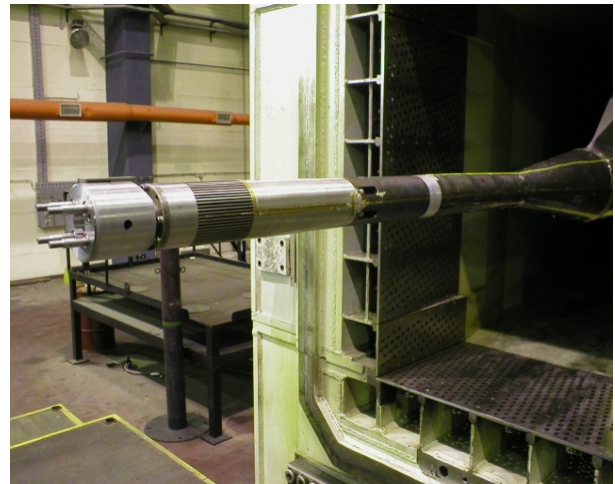The roll apparatus in the T-38 test section is shown in Figure 2.

Figure 2. Roll apparatus in the T-38 test section

Basic elements of the roll apparatus are:
- sting support system that provides a mounting for hydraulic driving mechanism and houses drive shaft that carries the driving torque from the driving mechanism to a model through the internal five-component balance;
- elastic suspension system that allows an oscillatory primary motion in roll of the model-suspension subsystem and provides the stiffness necessary to ensure an adequate mechanical resonance frequency for such system;
- five-component balance for the measurements of the aerodynamic load and excitation moment in the roll;
- hydraulic driving mechanism to impart the oscillatory primary motion of the model;
- sensor to detect the primary motion;

- servomechanism which ensures a constant amplitude primary motion.

Performance parameters of the roll apparatus are:
- model oscillation amplitude: 0.25°-1.5°;
- model oscillation frequency: 1-15 Hz;
- sting diameter: 76 mm;
- maximum normal force: 18000 N.

The primary oscillatory motion sensor is mounted on the elastic suspension system. This sensor is formed from the foil strain gauges.

An important requirement for the wind tunnel balances used in the dynamic measurement is a good signal-to-noise ratio. Semiconductor strain gauges, with gauge factor about 70 times larger than those of foil strain gauges, offered the possibility of measuring useful signal from very stiff measuring elements. In order to use to advantage those characteristics, the five-component balance with semiconductor strain gauges was designed and built for stability derivatives measurement in the T-38 wind tunnel [5-7]. BLH SPB2-12-35 (350Ω) phenolic-glass-backed P-type silicon semiconductor strain gauges were used for all balance components, connected in the form of four-active-arms bridges.
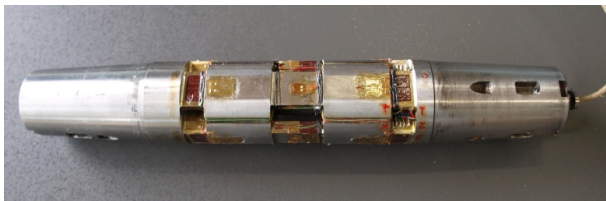

Figure 3. Five-component wind tunnel balance for measurement of stability derivatives

The five-component balance was manufactured out one piece of Armco PH 13-8 Mo steel, Figure 3. Three section of the balance body were shaped by milling and ED machining to obtain flexures for component transducers. Measuring bridges for the normal force and pitching moment, as well as the side force and yawing moment were formed on the forward and aft measuring sections shaped as three-bar cages. Measuring bridge for the rolling moment was obtained using the central measuring section shaped as a five-bar cage.

Table 1. Design loads and accuracy of the five-component balance

Component	Design loads	Maximum errors [% FS]
Side force	7000 N	-0.102
Normal force	10100 N	0.162
Rolling moment	300 Nm	-0.156
Pitching moment	660 Nm	0.076
Yawing moment	340 Nm	0.144

Table 1 lists the design full scale loads of the balance and summary of the achieved accuracy of the balance calibration.

3. THE T-38 WIND TUNNEL TEST RESULTS

Measurements of the direct damping derivative in roll of the Basic Finner Model (BFM) and Modified Basic Finner Model (MBFM) were done in the T-38 wind tunnel. These models are used for calibration of the wind tunnels, as well as for verification of the wind tunnels equipment [8].

The BFM model geometry is a cone-cylinder fuselage with square fins in the + configuration (see Figure 4). The cone section has 10° half-angle, and the centre of mass is 6.1 base diameters from the nose along the longitudinal axis of the body.

The MBFM model geometry is a 2.5 caliber tangent-ogive cylinder fuselage with trapezoidal fins in the + configuration, Figure 5. The centre mass is located 5 base diameters from the nose along the longitudinal axis of the body.
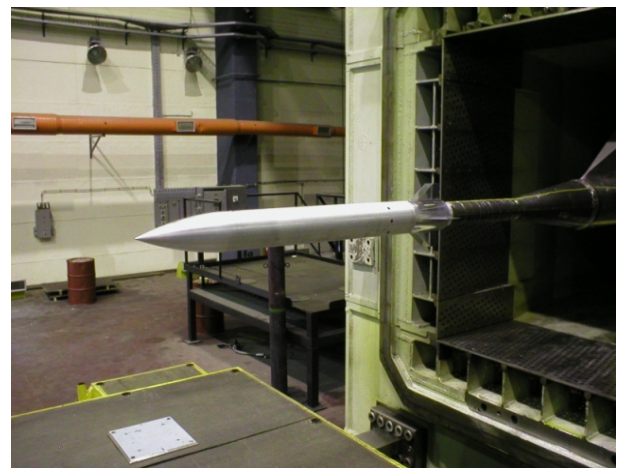

Figure 4. BFM model in the T-38 test section

Figure 5. MBFM model in the T-38 test section

During the T-38 wind tunnel measurements, all the sensors signals are amplified, filtered and then digitized by a 16-bit resolution A/D converter. The data acquisition system consists of Teledyne 64 channels "front end" controlled by a PC computer. Overall accuracy of the acquisition system is about 0.05% to 0.1% FS of the channel signal rang. The data reduction system consists of a COMPAQ Alpha Server DS20 and an appropriate software package.

Determination of the direct damping derivative requires measurement of following values:

- amplitude of the model angular oscillatory motion;
- amplitude of the excitation moment;
- frequency of the model oscillations;
- phase shift between model angular oscillatory motion and excitation moment.

In most cases, signals from the sensors of the primary and secondary oscillations are seriously contaminated by noise generated mainly by flow unsteadiness. As a noise level can be several times higher than that of a desired signal, it is generally impossible to extract them adequately using conventional narrowband pass filters. Knowledge that the signals are coherent with the primary motion permits the use of more sophisticated signal extraction techniques. These are auto-correlation and cross-correlation techniques. Cross-correlation technique is especially suited to applications where a clean reference signal coherent with the one that needs to be extracted from the noise is available.

In the stability derivatives measurements presented in this paper, amplitudes of the excitation moment in roll were measured with balance measuring bridge for the rolling moment. Amplitudes of the models angular oscillatory motion were measured with primary oscillatory motion sensor located on the elastic suspension system.

The models were forced to oscillate in roll mode at amplitude $\pm 1°$ and frequency 10 Hz. The amplitudes and phase shifts of the excitation moment were calculated in frequency domain by applying the cross-power spectral density. The signals from the balance bridge for rolling moment were cross-correlated with primary signal generated by the primary oscillatory motion sensor.

One test run was done for each models angle of attack. The duration of each test run was 12 s, of which 8 s was the sampling data time. Sampling rate was 1000 sample/s. Cross-correlation functions were determined from 82 periods of the models oscillations.

It is obvious from Figure 6 that primary motion signal is noise-free. The amplitude of this signal was determined by applying auto-correlation function.

The auto-correlation function is determined by the equation:

$$R_A(\tau k) = \frac{1}{N+1} \sum_{n=0}^{N-k} y_n \cdot y_{n+k} \qquad (6)$$

where $R_A(\tau k)$ is the auto-correlation function, N is the number of the sampled data in the wind tunnel run and y is the series of the discrete values for the primary motion signal.

The amplitude of the auto-correlation function, $A_{R_{A(\tau k)}}$, is:

$$A_{R_A(\tau k)} = \frac{A_{pm}^2}{2} \qquad (7)$$

where A_{pm} is the amplitude of the primary oscillatory motion signal.

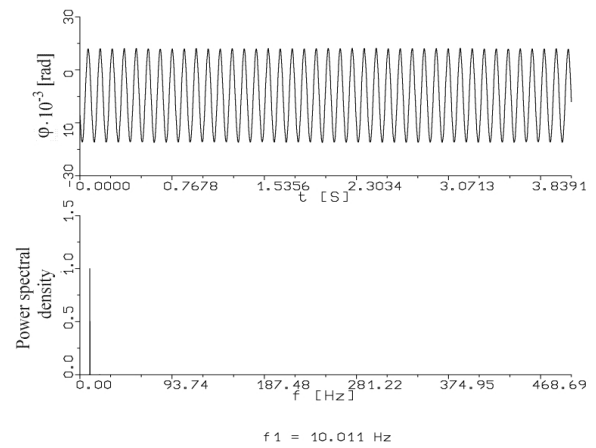**Figure 6. Primary oscillatory motion signal in roll, MBFM model (M=1.75, α = 0°)**

The excitation moment signal and its power spectral density for the MBFM model, Mach number 1.75 and angle of attack 0° are shown in Figure 7. The cross-correlation function of the excitation moment signal and primary oscillatory motion signal is shown in Figure 8.
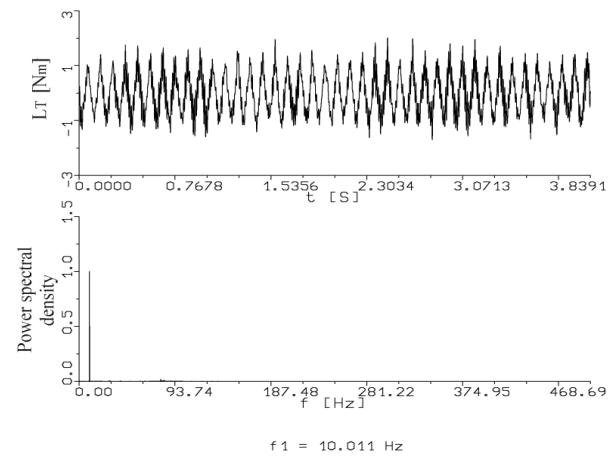

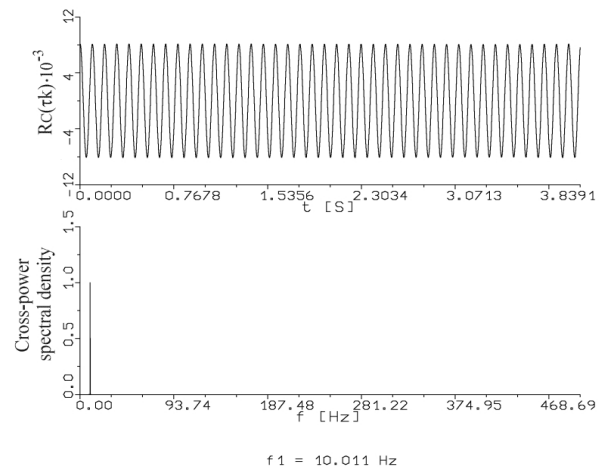**Figure 7. Excitation moment signal and its power spectral density, MBFM model (M=1.75, α = 0°)**

Figure 8. Cross-correlation function of the excitation moment signal and its cross-power spectral density, MBFM model (M=1.75, α = 0°)

The cross-correlation function is given by:

$$R_C(\tau k) = \frac{1}{N+1} \sum_{n=0}^{N-k} x_n \cdot y_{n+k} \qquad (8)$$

where $R_C(\tau k)$ is the cross-correlation function, x_n is the series of the discrete values for the excitation moment signal and y_{n+k} is series of the discrete values of the primary oscillatory motion signal.

The amplitude of the cross-correlation function, $A_{R_C(\tau k)}$, is:

$$A_{RC}(\tau k) = \frac{A_x \cdot A_y}{2} \qquad (9)$$

where A_x is the amplitude of the excitation moment signal and A_y is the amplitude of the primary oscillatory motion signal.

In order to determine the amplitude of the excitation moment signal by the cross-correlation function, it is first necessary to determine the amplitude of the reference signal by the auto-correlation function.

The phase shifts were determined by the cross-spectrum density function. The cross-spectrum $G_{xy}(f)$ is a complex value, and it may be written as:

$$G_{xy}(f) = C_{xy}(f) - jQ_{xy}(f) \qquad (10)$$

where $C_{xy}(f)$ is the real part of the cross-spectrum density function, $Q_{xy}(f)$ is the imaginary part of the cross-spectrum density and f is the frequency.

The phase shift between two signals is defined as:

$$\eta_{xy} = arctg \left| \frac{Q_{xy}(f)}{C_{xy}(f)} \right|. \qquad (11)$$

The roll-damping derivative measurements of the MBFM model were done at Mach numbers 0.6 and 1.75. The model angles of attack were in the interval from -5° to 5°. The measurements of the BFM model were done at Mach number 0.2. The BFM model angles of attack were in the interval from -4° to 16° (see Figures 9-11). The roll angle was 0° for both of the models.
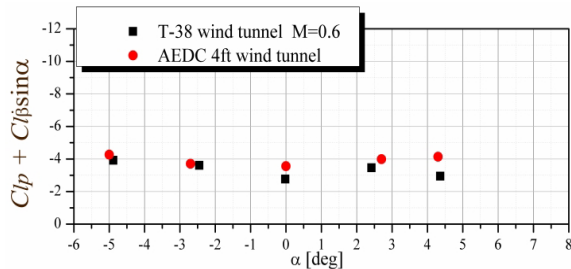
Figure 9. Direct damping derivative in roll for the MBFM model at Mach number 0.6

The T-38 wind tunnel data are compared with experimental data of the Arnold Engineering Development Center-von Karman 4ft wind tunnel (AEDC, USA) [9,10].
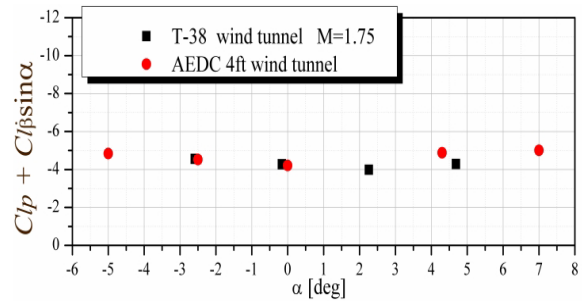
Figure 10. Direct damping derivative in roll for the MBFM model at Mach number 1.75
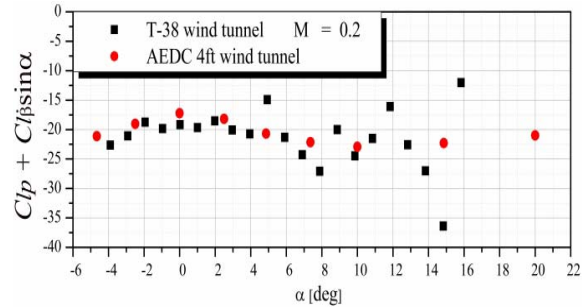
Figure 11. Direct damping derivative in roll for the BFM model at Mach number 0.2

4. CONCLUSION

The wind tunnel measurement of dynamic stability derivatives is a very complex process. This is particularly so in the blowdown pressurized wind tunnel. The wind tunnel balance (as well as all sensors on the roll apparatus) had to be designed for huge loads at the start and at the end of the T-38 wind tunnel runs. Also, balance has to enable quantification of the very small values in the stability derivative measurements. The use of semiconductor strain gauges can bring certain advantages in such specific type of the wind tunnel tests.

The rolling moment measuring bridge on the semiconductor five-component strain gauge balance, enables the determination of the oscillatory components of the signals. Also, the application of the auto-correlation and cross-correlation techniques for the determination of the necessary data from the tare run and wind-on run gives very good results. In the T-38 wind tunnel tests presented, the amplitudes of the excitation moment from the balance rolling moment measuring bridge are only 0.7 % of the rolling moment full scale (see Figure 7). However, the frequency of the primary oscillations is the first significant spectral component of the model oscillations. The cross-correlation function is noise-free and its dominant spectral component is observed at 10.011 Hz, which is actually the frequency of the primary oscillations. The T-38 wind tunnel data agree very well with the AEDC wind tunnel experimental data.

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NOMENCLATURE

FS	full scale
L	aerodynamic rolling moment
M	aerodynamic pitching moment, Mach number
N	aerodynamic yawing moment
p	rolling angular velocity
q	pitching angular velocity
r	yawing angular velocity
X	aerodynamic axial force
Y	aerodynamic side force
Z	aerodynamic normal force

Greek symbols

α	angle of attack
β	angle of sideslip

МЕРЕЊЕ ПРИГУШНОГ ДЕРИВАТИВА СТАБИЛНОСТИ У ВАЉАЊУ НА ДВА КАЛИБРАЦИОНА МОДЕЛА РЕКЕТЕ

М. Самарџић, Ј. Исаковић, М. Милош, З. Анастасијевић, Д. Наупарац

У овом раду описано је мерење пригушног дериватива стабилности у ваљању у аеротунелу Т-38. Приказани су резултати добијени на два калибрациона модела: Basic Finner Model и Modified Basic Finner Model. Уређај за мерење дериватива стабилности је уређај са принудним осцилацијама модела и то са примарним осцилаторним кретањем у равни ваљања. Побудни момент у ваљању мерен је петокомпонентном аеровагом са мерним тракама. Ова аеровага је пројектована и израђена за динамичка аеротунелска мерења. Амплитуде и фазни ставови побудног момента одређени су у фреквентном домену применом крос-корелационе методе. Резултати добијени у аеротунелу Т-38 упоређени су са објављеним експерименталним резултатима добијеним у Arnold Engineering Development Center-von Karman 4ft аеротунелу.