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Determination of the T-38 Wind Tunnel Oscillatory Data of the Dynamic Calibration Missile Model

Zoran Anastasijević, PhD (Eng)[1)]
Marija Samardžić, MSc (Eng)[1)]
Dragan Marinkovski, BSc (Eng)[1)]
Snežana Vrtlar, BSc (Eng)[1)]
Milorad Rodić, BSc (Eng)[2)]

This paper presents determination of the required data for measurements of dynamic stability derivatives in the T-38 wind tunnel. The technique for measurements of stability derivatives applied in the T-38 wind tunnel is the forced oscillation technique. The data reduction procedures used in the VTI to obtain both direct and cross and cross-coupling derivatives are described. The determination of the primary motion amplitude and frequency is also described as well as the determination of the amplitude of the excitation moment signal and the phase shift between the reference signal and the excitation moment signal. The T-38 test results of roll-damping and pitch-damping measurements for Mach number *M*=0.6 and *M*=1.75 are compared with experimental data from the AEDC wind tunnel. Analysis of wind tunnel oscillatory data was done for the Modified Basic Finner Model.

Key words: **experimental aerodynamics, wind tunnel, stability derivatives, forced oscillation, internal balance.**

Introduction

DYNAMIC tests are used to validate the static tests results and to provide information about aircraft or missiles in flight where static data are no longer sufficient to describe their characteristics. The technique for measurements of stability derivatives applied in the T-38 wind tunnel is the forced oscillation technique. According to this technique, 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 “the primary motion”, can only be due to such motion [1].

All the experiments are based on the application of small amplitude oscillatory motion to a model in the primary degree of freedom and the measurement of aerodynamic reactions produced by such motion in that particular and in other (secondary) degrees of freedom. Those reactions, in turn, yield relevant direct and cross as well as cross-coupling derivatives due to the motion considered herein.

Two apparatus for measurements of stability derivatives were designed and produced in VTI. The problem of small amplitudes of output signals from forces and moments sensors is a common in measurements of dynamic stability derivatives. Some consideration of measured signals from five-component internal balance and transducers for primary motion and excitation moment are given in this paper.

A special software package for data reduction in the T-38 wind tunnel stability derivatives measurements is developed in VTI. To obtain the frequency and amplitude of the primary motion, the power spectral density in the frequency domain is calculated from the measured primary oscillation. The amplitude and phase shift of the secondary oscillation as well as amplitude and phase shift of the excitation moment are calculated in the frequency domain by applying the cross-power spectral density. All of the calculated amplitude and phase shift values are corrected using the data from the amplifier calibration measurement.

Apparatuses for the measurements of stability derivatives in T-38 wind tunnel

To provide the implementation of the forced oscillation technique principles, the apparatuses in the wind tunnel T-38 include the following elements [2-4]:

- Sting support.
- Elastic suspension mechanism characterized by its relatively high compliance in the primary degree-of-freedom and its high stiffness in the other degrees.
- Internal five-component balance.
- Hydraulic driving mechanism for imparting the oscillatory primary motion to the model.
- Sensors for detecting the primary motion as well as the excitation moment.
- Servomechanism, which ensures a constant-amplitude primary motion.

Full model apparatuses include a model mounted on the balance, which is, in turn, attached to one end of the elastic suspension. Its other end is anchored to the sting. The driving mechanism straddles the suspension in order to impart the primary motion of the model. The apparatuses are shown in Figures 1-2.

1) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA
2) Defensive Technolies Department, Ministry of Defense, 11000 Belgrade, SERBIA

Figure 1. Roll apparatus

Figure 2. Pitch/yaw apparatus

Data reduction

In order to obtain the static and dynamic derivatives, the following data are required:

- Amplitude and frequency of the primary motion.
- Amplitude and phase shift of the excitation moment relative to the primary motion.
- Amplitude and phase shift of the secondary oscillation relative to the primary motion.

All of the above data are obtained by signals from appropriately located strain gages on the apparatus. A five-component internal monoblock balance measures static aerodynamic loads as well as primary and secondary aerodynamic reactions. The primary motion is sensed by strain gages located at the cross-flexure suspension on the pitch/yaw apparatus or at the flexural support on the roll apparatus. The primary motion can be also measured by strain gages located on the cantilever spring. The excitation moment is sensed by strain gages located on the actuator arm and on the drive shaft on the pitch/yaw apparatus and the roll apparatus, respectively.

A typical wind-tunnel run includes the following stages:

- An amplifier calibration runs, when known signals from the signal generator are an input to the 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 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 with the wind tunnel running.

Dynamic stability derivatives are obtaining by subtracting data from the wind-off run and the wind-on run. During the above measurements, all the sensor signals are amplified, filtered and then digitized by a 16-bit AD converter. Parallel sampling analog data are obtained using a computer-controlled data acquisition system by TELEDYNE. Data acquisition computer is PC Compaq 5100. The data reduction system consists of a Compaq Alpha Server DS20E and an appropriate software package developed by the VTI.

Static aerodynamic loads are obtained from the stationary mean values and tare loads due to the model and balance weights. Tare loads are determined by the gravity matrix and the model attitude angles. The frequency, amplitude and phase shift for each component are determined with respect to the primary motion. All of the calculated amplitude and phase shift values are corrected using the data from the amplifier calibration measurement.

Determination of the direct derivative stability

The direct derivative stability is calculated using the following data for the wind-on and wind-off measurement: the amplitude and frequency of the primary motion, the amplitude of the excitation moment and the phase shift between the signals from the primary motion sensor and the excitation moment sensor.

The amplitude and frequency of the primary motion can be determined in the time and frequency domain.

In the time domain, the frequency is determined by the expression:

$$f = \frac{N_p}{N_{tac} \cdot \Delta t} \tag{1}$$

where:

f - frequency

N_p - total number of full periods in the signal

N_{tac} - number of samples for full number of periods

Δt - sampling interval.

In the frequency domain, the frequency of the signal can be determined by the maximum of the spectral signal.

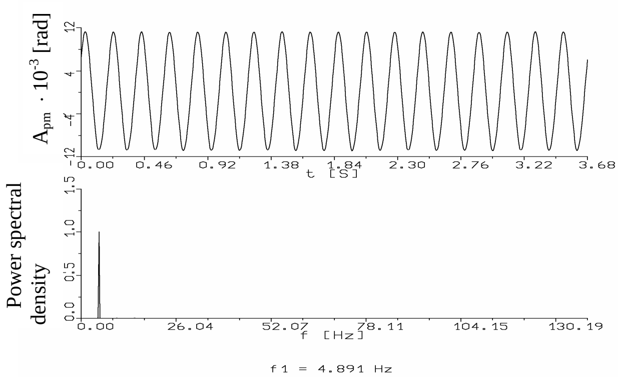


Figure 3. Primary motion signal in pitch measured by strain gages located at the cross-flexure suspension

The amplitude of the primary motion (A_{pm}) can be determined in the time domain by [5]:

- the maximum of harmonic function
- auto-correlation function.

For the harmonic signal, the amplitude is determined by the expression:

$$A = \frac{\sum_{i=1}^{N} |a_i|}{N} \tag{2}$$

where:

A - mean amplitude

a_i - maximum or minimum values of the signal
N - total number of the sum of maximum and minimum values.

The auto-correlation function is determined by:

$$R(\tau k)=\frac{1}{N+1}\sum_{n=0}^{N-k} y_n \cdot y_{n+k} \qquad (3)$$

where:
$R(\tau k)$ - auto-correlation function
N - number of the points of the series y
y - series of the discrete values for y.

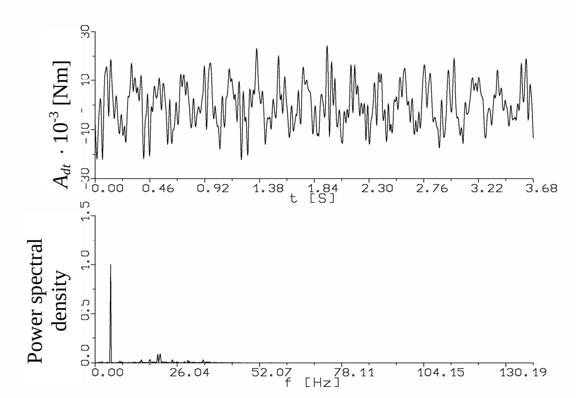
The amplitude of the auto-corelation function is:

$$A_{R(\tau k)}=\frac{A_y^2}{2} \qquad (4)$$

A_y - amplitude of the signal y, ($A_y=\sqrt{2\cdot A_{R(\tau k)}}$).

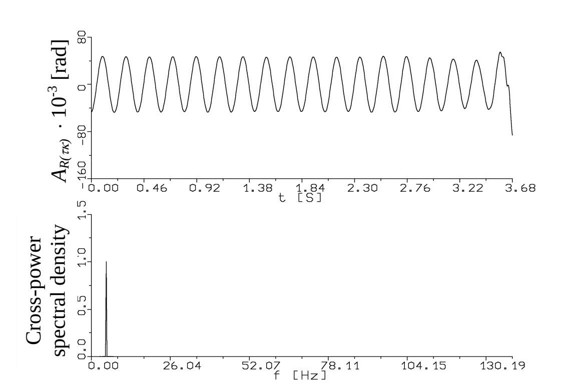
It is obvious from Fig.3 that the primary motion signal is noise-free and the amplitude is determined by the auto-correlation function. This is a reference signal for the data reduction.

The amplitude (A_{dt}) and the phase shift of the excitation moment are calculated in the frequency domain by applying the cross-power spectral density. The excitation moment signal, the cross-correlation function of the excitation moment signal and the cross-power spectral density for the primary oscillation in the pitch is shown in Fig.4.



f_1=4.891

a)



f_1=4.891

b)

Figure 4. Excitation moment signal and power spectral density a), cross-correlation function of the excitation moment signal (primary oscillations are in the pitch) and cross-power spectral density b)

The cross-correlation function of two signals is:

$$R(\tau k)=\frac{1}{N+1}\sum_{n=0}^{N-k} x_n \cdot y_{n+k} \qquad (5)$$

where:
$R(\tau k)$ - cross-correlation function
N - number of the points for the series x and y
x - series of the discrete points for signal 1 (excitation moment signal)
y - series of the discrete points for signal 2 (primary motion signal - reference signal).

The amplitude of the cross-correlation function is:

$$A_{R(\tau k)}=\frac{A_x\cdot A_y}{2} \qquad (6)$$

A_x - amplitude of the signal x
A_y - amplitude of the signal y.

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 shift is determined by the cross-spectrum density function. The cross-spectrum is a complex value, and can be expressed as:

$$G_{xy}(f)=C_{xy}(f)-jQ_{xy}(f) \qquad (7)$$

The phase shift between the two signals is defined as:

$$\eta_{xy}=arctg\left|\frac{Q_{xy}(f)}{C_{xy}(f)}\right| \qquad (8)$$

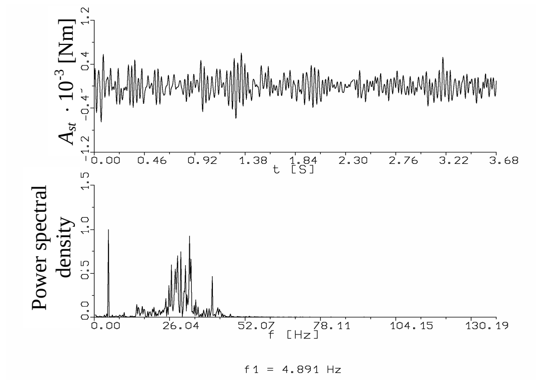
where:
C_{xy} - real part of the cross-spectrum density function
Q_{xy} - imaginary part of the cross-spectrum density function
f - frequency.

From Fig.4a) it is obvious that the signal for the excitation moment in the time domain is contaminated by noise with frequency of about 20 Hz. The amplitude and the phase shift of the excitation moment signal must be determined by cross-correlation function. The reference signal is a primary motion signal.

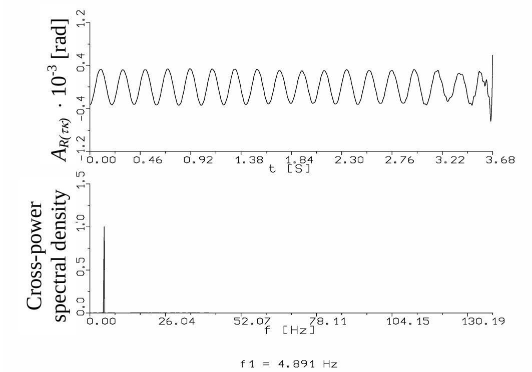
Determination of the cross and cross-coupling derivative stability

From the amplitude of the secondary loads measured by the internal balance for two different types of the primary motion and balance deflection matrix, the amplitude of the secondary oscillation is determined.

The causative moment in the secondary degree of freedom is obtained from the amplitude of the secondary oscillation, the phase shift between the primary motion and the secondary oscillations, the direct derivatives and the mechanical characteristic in the secondary degree of freedom. The difference between the wind-on and wind-off vectors eliminates mechanical coupling effects and thus yields the aerodynamic deflection vector in the secondary degree of freedom caused solely by aerodynamic moments due to primary oscillation. The aerodynamic deflection vector is then assumed to be a response of the system to an unknown moment in the secondary degree of freedom due to the primary motion, and cross and cross-coupling derivatives can therefore be calculated.



a)



b)

Figure 5. Secondary oscillations and power spectral density a), cross-correlation function of secondary oscillations in yaw and cross-power spectral density b)

For the determination of cross and cross-coupling derivatives it is necessary to determine the amplitude of secondary oscillation (A_{st}) and the phase shift to the primary oscillation.

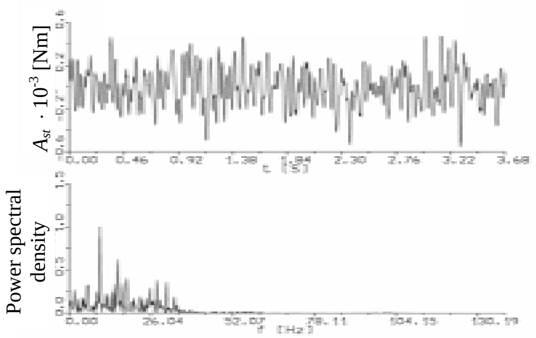


Figure 6. Secondary oscillation in roll and power spectral density

The amplitudes of secondary oscillations and the phase shift of the secondary oscillation to the primary oscillation are obtained in the same way as it was explained for the direct derivative. The reference signal for the cross-correlation function is the primary motion signal.

The secondary oscillations in the yaw and roll for the primary oscillations in the pitch and their power spectral density are shown in Figures 5 and 6.

Fig.5 shows the signal from the secondary oscillations in the yaw, hidden deeply in noise. The frequency of the primary oscillation is the first significant spectra component. Noise is located at approximately 30 Hz. The cross-correlation function is noise-free and its dominant spectra component is at 4.891 Hz, which is actually a frequency of the primary oscillation.

Fig.6 shows the signal from the secondary oscillations in roll, hidden deeply in noise. The frequency of the primary oscillation does not exist in the signal spectra. Noise is present up to 30 Hz. A causative aerodynamics moment in the secondary degree of freedom does not exist. Only secondary signals components coherent with the primary motion are of interest.

Wind tunnel tests of the calibration models

As an example of measuring stability derivatives in the T-38 wind tunnel, the results of the tests performed on the Modified Basic Finner Model (MBFM) are shown [6, 7].

The Modified Basic Finner Model geometry is a 2.5 caliber tangent-ogive cylinder fuselage with trapezoidal fins in the + configuration. The center of mass is located 5 diameters from the nose along the longitudinal axis of the body. The basic dimensions of the MBFM model are presented in Fig.7. The MBFM model mounted in the T-38 test section is shown in Fig.8.

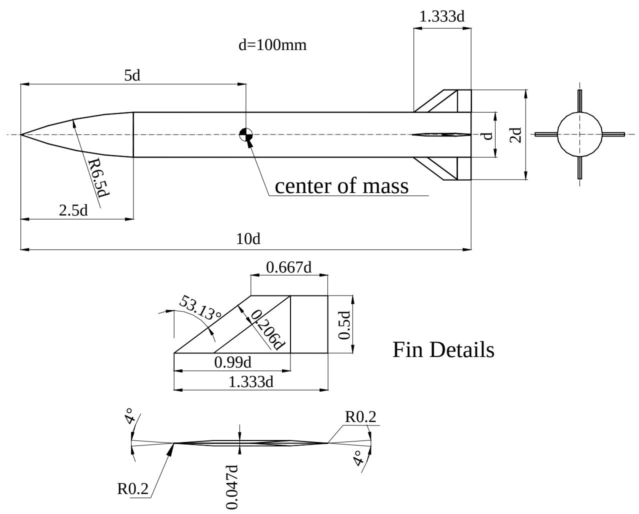


Figure 7. Basic dimension of the Modified Basic Finner Model

Figure 8. Modified Basic Finner Model in the T-38 test section

The test results of roll-damping ($CLP^* = C_{lp} + C_{\dot{\beta}} \sin\alpha$) and pitch-damping ($CMQ^* = C_{mq} + C_{m\dot{\alpha}}$) measurements for Mach numbers M=0.6 and M=1.75 are shown in Figures 9-12.

The tests results obtained in the T-38 wind tunnel are compared with the published experimental data from the AEDC wind tunnel [8-9] (Arnold Engineering Development Center-von Karman - USA). The wind tunnel data at α = 0° are also compared with the calculated roll-damping coefficient values obtained by the DMAC semi-empirical method developed in the VTI [10].

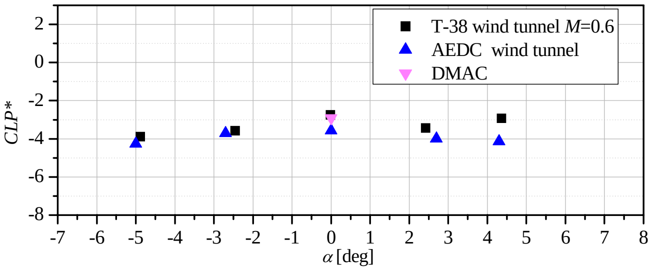


Figure 9. Roll- damping derivative for the MBFM model at M=0.6

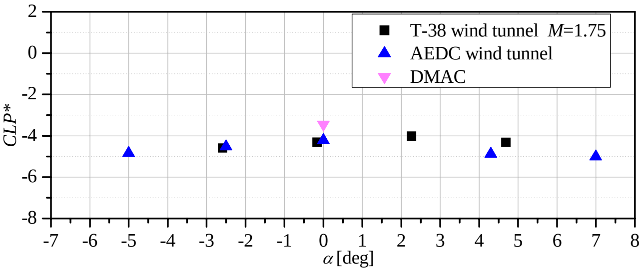


Figure 10. Roll- damping derivative for the MBFM model at M=1.75

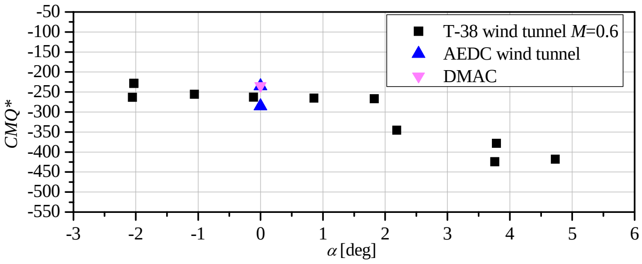


Figure 11. Pitch- damping derivative for the MBFM model at M=1.75

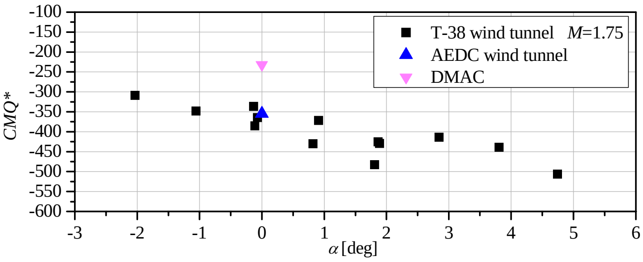


Figure 12. Pitch- damping derivative for the MBFM model at M=1.75

The agreement between the test data from the T-38 wind tunnel and the published experimental data is very good.

Conclusion

This paper gives a view in the problem of extracting a useful signal from high-level noise for using procedure and apparatuses for stability derivative measurement. In most cases, signals from sensors of 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. Both are especially suited to applications where a clean reference signal coherent with the one that needs to be extracted from the noise is available.

Roll and pitch-damping measurements of the Modified Basic Finner Model agree well both with published experimental data and with semi-empirical data. It has been concluded that the application of auto-correlation and cross-correlation techniques for determining necessary data from the wind-on and wind-off measurements gives very good results.

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Određivanje parametara oscilatornog kretanja dinamičkog kalibracionog modela rakete u aerotunelu T-38

U ovom radu prikazano je određivanje potrebnih podataka u merenjima aerodinamičkih derivativa stabilnosti u aerotunelu T-38. Za merenje aerodinamičkih derivative stabilnosti u aerotunelu T-38 primenjuje se metoda krutih prinudnih oscilacija. U radu je opisan postupak obrade podataka za dobijanje direktnih, unakrsnih i unakrsno spregnutih derivativa stabilnosti. Opisan je i način određivanja amplitude i učestanosti primarnog kretanja, amplitude signala pobudnog momenta i faznog stava između referentnog signala i signala pobudnog momenta. Izmerene vrednosti prigušenja u valjanju i propinjanju u aerotunelu T-38, upoređene su sa vrednostima izmerenim u aerotunelu AEDC. Prikazana je analiza podataka oscilatornog kretanja „Modified Basic Finner“ modela.

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

Определение параметров осцилляторного движения динамической тарированной модели ракеты в аэродинамической трубе Т-38

В настоящей работе представлено определение нужных данных в измерениях аэродинамических производных устойчивости в аэродинамической трубе Т-38. Для измерений аэродинамических производных устойчивости в аэродинамической трубе Т-38 используется метод жёстких вынуждённых колебаний. В работе тоже описан и спопоб определения амплитуды и частоты первичного движения, амплитуды сигнала возбуждающего момента и фазовой позиции между определительным сигналом и сигналом возбуждающего момента. Измеренные значения демпфирования при прокатывании и кабрировании в аэродинамической трубе Т-38 сопоставлены с значениями измеренными в аэродинамической трубе АЕДЦ. Представлен анализ данных осцилляторное движение „Modified Basic Finner“ модела.

Ключевые слова: **экспериментальная аэродинамика, аэродинамическая труба, аэродинамические производные, производные устойчивости, осцилляторное движение, вынуждённые колебания.**

Détermination des paramètres du mouvement oscillatoire pour le modèle dynamique de calibrage du missile dans la soufflerie aérodynamique

Ce papier présente la détermination des donnée nécessaires pour le mesurage des dérivées aérodynamiques de stabilité dans la soufflerie aérodynamique T-38. Pour mesurer les dérivées aérodynamiques de stabilités dans la soufflerie aérodynamiques T-38 on applique la méthode des oscillations forcées. Dans ce travail on a décrit le procédé du traitement des données pour obtenir les dérivées de stabilité qui sont directes, croisées et couplées en croix. On a exposé aussi la manière de déterminer l'amplitude et la fréquence du primaire mouvement, l'amplitude du signal du moment excitateur et la position de phase entre le signal de référence et le signal du mouvement excitateur. Les paramètres d'étouffement mesurés lors du roulement et du tangage dans la soufflerie aérodynamique T-38 ont été comparés avec les paramètres obtenus dans la soufflerie aérodynamique AEDC.

Mots clés: **aérodynamique expérimentale, soufflerie aérodynamique, dérivées aérodynamiques, dérivées de stabilité, mouvement oscillatoire, oscillations forcées.**