Investigation of the Error Sources on the Balance and the Standard Dynamic Model in the Wind Tunnel

M.R. Hassani Ahangar
Qadr Research Center
Imam Hossein Univercity(IHU) &
Iran Univ of Science and Tech (IUST)
mrhassani@iust.ac.ir

M.R. Kangavari, R. Berangi
Department of computer engineering
Iran Univercity of Science and Technology(IUST)
Kangavari@iust.ac.ir,
Rberangi@iust.ac.ir

Abstract

Studying the movement of flying objects, either planes or missiles, in the atmosphere is a complicated issue that can hardly be mathematically formulated. Therefore, in many cases, this movement is simulated in the wind tunnels to measure the designer's required force and torque parameters. One of the most suitable measurement tools in the wind tunnel is a balance, on which strain gauge bridges are installed to suitably measure the applied strains in dynamic and static situations. This article describes a five sensor dynamic balance and its stimulation system and investigates the error sources on them when a standard dynamic model is installed on it. It calculates the system frequency response based on the practical tests to select the appropriate sampling frequency for the data acquisition system. In addition, it presents the design of a suitable filter to remove the noise from the original signal. It also presents a signal quality metric based on the minimization of the in-band noise to optimize the filter. This metric is also used to calibrate the system frequency and detect the signal phase and amplitude variations. The practical measurements in 1.5 Mach number on vertical force of the standard dynamic model show significant noise, phase and amplitude variations which indicate side rotations of the model and the instability of the air current on the model during the test.

Keywords:Wind Tunnel, Balance, Standard Dynamic Model, Data Acquisition, Signal processing, Filter, FIR

1.Introduction:

Ever-increasing need to create high maneuverability for missiles and fighters, as used today, brought about a dramatic change in the flight limits of such flying systems. Flight in high assault and lateral angles, speedy rate of turning (rotation) and thrust (acceleration) are considered the most important characteristics of modern flying systems. These maneuvers subject airplanes and missiles to instable current field so that their aerodynamic behavior becomes totally nonlinear [1,2]. The importance of studying dynamic stability has emphasized the requirement for appropriate methods to determine the stability derivatives [4,3]. While different existing numerical and analytical approaches have allowed, to some extent, examine the operations of flying systems in instable courses, they are not able to estimate the aerodynamic coefficients in general and thus they cannot precisely model the instable currents on any flying system. As the numerical and analytical methods are limited to certain restrictions, wind tunnel experiments can analyze the operation and investigate the stability more truly and accurately [5,6]. It also provides the designer's required force and torque parameters which are crucial in optimizing the structure of flying objects. The best and more general tool for measuring these parameters is a balance system [7,8]. This system of establishing equilibrium isolate the forces and moments of the model from each other and this let to measure them as precisely as possible. Then these measured parameters are digitally transmitted to a computing system in which a suitable software program extracts (derives) aerodynamic coefficients. In this process, exact and careful measurement and accurate processing is required to assure the designer about the results. There are many factors that can bring about errors in obtaining these results. This paper discusses them within possible limit and presents essential solutions to overcome them. Therefore it is very important to know the sampling frequency and the total number of samples required for extracting the information. To determine these quantities it is necessary to calculate the natural frequency of the model fitted on vibrating system.

2.Vibrating System and Dynamic Balance

2.1. A Dynamic Balancing System

Figure 1 shows a typical dynamic balancing system which is a device that can isolate and measure normal force Fy, lateral force (Fz) and three torque components (in 3 dimensions) Mx, My and Mz within the defined limits in a wind Tunnel.

Fig 1: A model of five component dynamic model.

The calibration results of this balance also show that the produced voltages of all sensors with the applied load are fully linear. Balance measuring system operates by using rules governing the strain gages operation. A strain gage is an electric resistance of steel or semi-conducting materials in which the length variation causes the resistance change. The relation between a varied resistance and strain can be calculated by examining the factors influencing the resistance. The strain gages are attached on the surfaces under stress and strain with a good paste. They are glued in an appropriate direction and connected in the form of a Weston Bridge [8,9].

Figure. 2, on the right, shows how the strain gages can be installed on the piece and the left picture shows the position of top strain gauges on the piece. Two strain gauges R1 and R4 are fixed on a surface under stress and the other two, R2 and R3, on a surface, pressurized by a handle that applies the twisting torque. By feeding this bridge by means of a stable power supply, the bridge is set in equilibrium first and then it is displaced once the level of strain gage resistances have changed by applying stress or strain. This appears as a varied voltage in the bridge output which can be used to measure strain and stress on the surface [8,9].

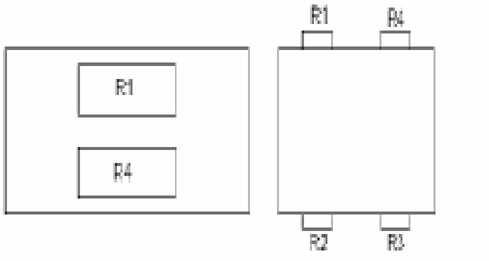


Fig 2: strain gages fitted on the surface

2.2.A Vibrating System and Standard Dynamics Model (SDM)

In this system, motor circulating movement is transmuted into a commuting one through a medium of crankshaft and then transmitted to SDM by means of linkages (linking arms). Figure. 3 show the view of this system with dynamic balance and the fitted model. In the wind tunnel it is supposed to measure the instantaneous angular variations of the model in pitching, as well as the level of model displacement in plunging versus time. Figure 4 shows how a SDM model moves in these two modes [2,3].

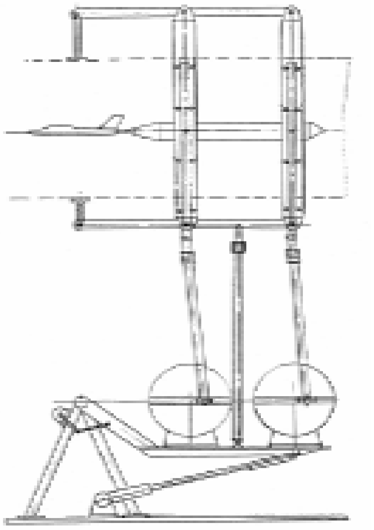
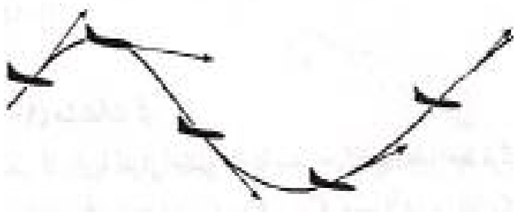
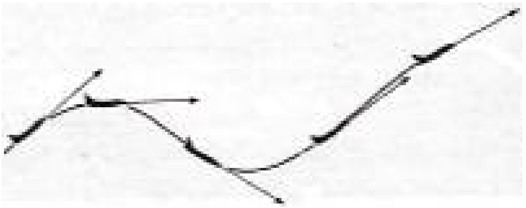


Fig 3: Schematic of the dynamic system, model, and balance.



a.Plunging



b.pitching

Fig.4: Representation of SDM modelMovement in two plunging and pitching modes

SDM model is a well accepted model that allows us to exercise dynamic experiments under unstable conditions. This model has already been tested worldwide and has many published test results [2,3]. The SDM is indeed a simplified airplane F-16 model (Fig.5).

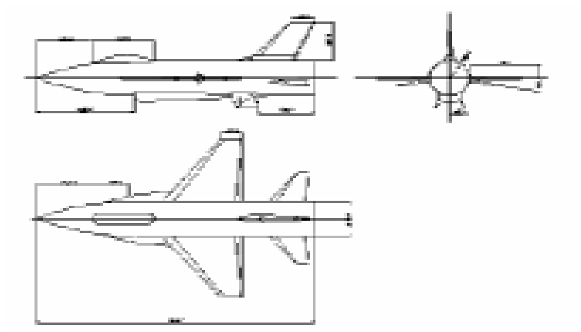


Fig 5: An SDM model

2. Error Sources on the SDM in Wind Tunnel

There are many error sources on a SDM model that can be divided into following two categories:

1. Atmospheric effects and disturbances and air flow- away ducts
2. Errors available in measuring systems

2.1. The Effects of Atmospheric Disturbances and Air Passing Ducts

The wind tunnel in Aerodynamic Research Center is the same size of an open- circuit wind tunnel, which is affected by atmospheric disturbances. The atmospheric disturbances and variations influence the results in two ways: steady and unsteady

3.1.1. Steady Effects

The steady disturbances comprise factors that affect the atmospheric conditions. These parameters consist markedly of environment pressure, temperature, density and entering combined air.

As it is evident, the initial conditions of air entry such as pressure and temperature were measured and some calculations were made based on it. In the event that an error develops in measuring these parameters, they will directly affect the results. Therefore, it is necessary to measure the temperature and pressure as accurately as possible and any of their variations during the test must be taken into account. The density, the percent of humidity in entering air is important parameters. Currently, the air dampness is not measured, but it is required for finding the accurate air density when a high precision is desired [5,6].

Furthermore, it has been most frequently observed in the wind tunnels that when the air cools while passing the nozzle, there might be a fluid humidity in the air. The resultant cloud creates some changes in the air density that must be carefully considered in the results.

3.1.2. Unsteady Effects

These factors influence the wind tunnel operation dynamically. The turbulences created in the wind tunnel are mainly rooted from atmospheric turbulences. The air entering the wind tunnel is sucked from the atmosphere, passes trough the tunnel and reaches the testing system. Therefore, any turbulence in the atmosphere directly affects the flow quality in two ways:

1- Direct transmission of turbulences from atmosphere.
2- Indirect effects by stimulation of air flow such that factors such as Honey-comb, screen and the air inlets variations bring about additional disturbances.

The way in which the atmospheric turbulences or disturbances on the testing system is a very complicated issue and must be discussed in greater details. It seems necessary to conduct some tests in this context. For example one can examine the effects that atmospheric turbulences on the results and flow quality in test level by measuring the full speed in the entrance gate (gap).

Use of a hot wire system seems to be appropriate such that one can investigate the turbulences by installing a probe in the entrance gap and another in the test level.

3.2.The Existing Errors in Measuring systems:

These errors consist of errors in measuring parameters such as force and torque. These errors are divided into two parts:

1- Error in balance
2- Error in obtaining data Acquisition system.

3.2.1. Error in Balance

Balance is used to measure force and torque levels. The true mechanism for it is that when a force and moments are applied to a model connected to the balance, some elastic deformations, which are dependent to the force or moments, are created in different parts of the balance. These deformations can be measured by strain gages. The following two groups of errors [8,9] may happen during the measurements.

1- Errors that develop as a result of balance structure.
2- Errors that are created as a result of strain gages.

3.2.1.1. Structural Errors

A balance must be designed in such a way that the deformations developed by a force or a torque are localized to allow the forces and moments are measured independently [8, 9]. However, in practice, interaction among the forces and moments creates non-linearity and some errors during the calibration process. Therefore, the balance structure and the strain gages positions must be so defined that the responses of the balance to the forces and moments become linear and without interactions between the applied forces and moments. The temperature variations always accounts for undesirable changes in the structure.

3.2.1.2.Errors Created in Strain Gages:

A strain gage is a resistance that its value changes as a result of change in its length by the strain. Errors that appear in strain gages can be divided as:

a. The sensor inherent error
b. Error in the glue that is used to fit the strain gage into the structure
c. The error in the power supply which is connected to the strain gage bridges.
d. The socket error and the transmission lines of strain gages heads.

These errors can be mitigated by using strain gages and other accurate and high reliability instruments [8, 9].

3.2.2.Error in the Data Acquisition System:

A suitable data Acquisition system can considerably influence the rise of speed and accuracy in making tests and eventually the efficiency of a wind tunnel [5, 9, and 8]. This system is made up of a PC (personal computer) with an A/D board, and a signal amplifying board and its auxiliaries. Figure 6 is a schema showing DCS (Data Acquisition system). DCS is a sensitive system depending on its function and application and thus, precision, dependability and safety are its inherent characteristics [7,9].

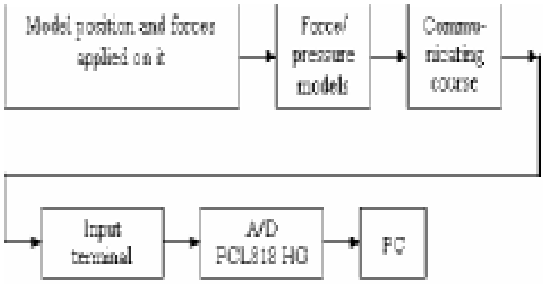


Fig.6: A generalized schema of a DAS

The analog to digital conversion is susceptible to the following errors:

1- The errors created because of inaccurate estimation and measurement of parameters in test receptacle such as Mach number, pressure, turbulence, calibration coefficients, distribution and etc.

2- The errors arise in electronic systems and computer such as varied input voltages, noise, saturated A/D board channels and etc.

3- The errors in interpreting the A/D board output caused by using inaccurate constants such as dynamic pressure, calibration coefficient, Mach number and etc.

The long transmission lines of the data acquisition system itself can expose the system to some additional errors, namely, signal attenuation, noise, and interference. The most prevalent mean to alleviate these effects is the use of a good shield around cables and having a good earth terminal [8, 9].

4.Calculating the Natural Frequency of the Vibrating System With Dynamic Balance

In dynamic testing, it is very important to determine the natural frequency of the model, balance and their linking system to avoid any resonance during the test. A straight forward method to measure this natural frequency is to apply a shock to the balance and observe the modulated output of the balance in frequency domain. The pulses which appear in the frequency domain indicate the natural frequencies of the system. Only the vertical force is used to measure the natural frequency, sampling frequency and the number of the required samples because the derivatives of the model vertical force (Cn) and the twisting torque (Cm) coefficients are very important in the study of the stability. Figure 7-a shows the output of Cn channel after a shock which dies three seconds later. Figure 7-b shows the discrete Fourier transform of Cn. The first and foremost pulse appears around 27 hertz while other smaller pulses can be observed at harmonics of this frequency. The presence of various harmonics makes it obligatory to select a relatively higher sampling frequency to avoid aliasing.

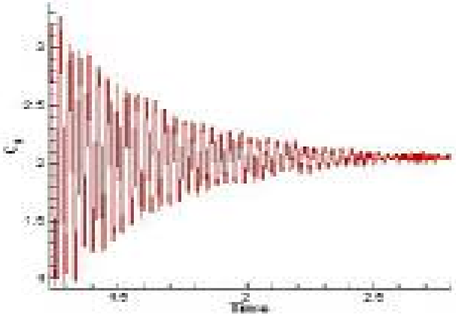


fig.7-a

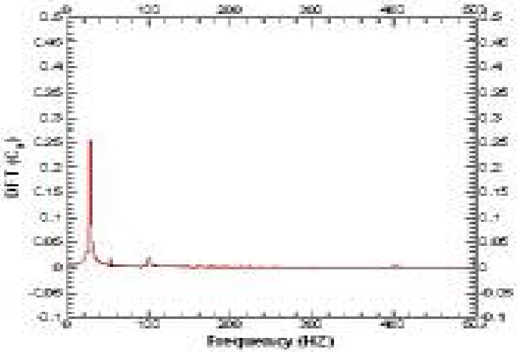


Fig.7-b

Fig.7: Normal force signal in time and frequency space.

A shock test on the SDM model was carried out in different sampling frequencies. Figure.8 shows the response of the model (output voltages of Cn versus time) to a step shock. The figure 8-a, gives the sampled response with a sampling frequency equal to the system natural frequency. Comparing this with the responses with higher sampling frequencies in figures 8-b, 8-c and 8-d clearly indicate that the low sampling frequency can obscure the system performance.

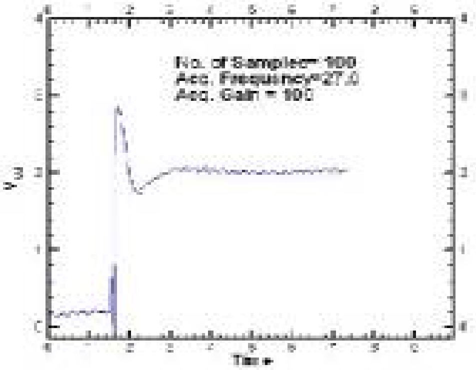


Fig.8-a

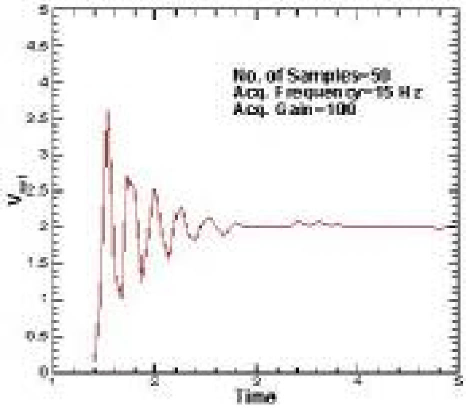


Fig.8-b

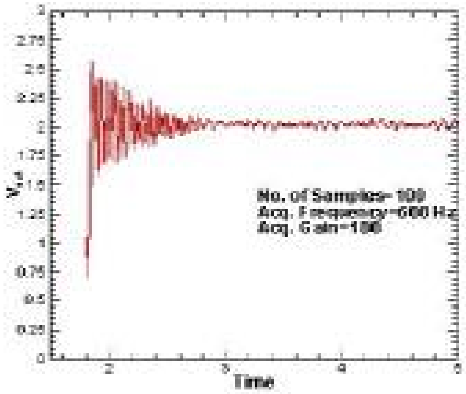


Fig.8-c

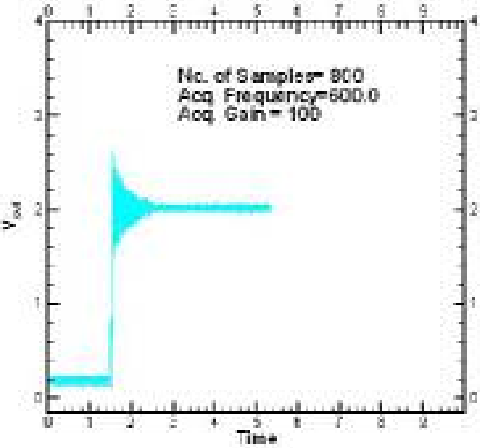


Fig.8-d

Fig. 8-: effects of sampling Frequency and number of samples For Cn variations pre- and post. Shock application on dynamic balance

After various tests on the five components of the balance, a sampling rate of 600Hz has been selected (fig.8). The number of samples to have a reasonable accuracy in the frequency estimation, is important because, the frequency measuring error depends on the measuring length of time. If M cycle of signal with a frequency of F takes T seconds, the frequency can be calculated from the following formula:

$$F=M/T \qquad (1)$$

The maximum absolute time error is about half of the sampling period (Ts/2). As a result one can give the maximum frequency error as follows

$$e=[\frac{M}{(T-T_S/2)}-\frac{M}{(T+T_S/2)}]/2=\frac{MT_S/2}{T^2-T_S^2/4} \qquad (2)$$

By dividing e by F one relative frequency error can be found as:

$$error=[\%]=\frac{T_S/2}{T-T_S^2/4T}\times 100\approx 50\frac{T_S}{T} \qquad (3)$$

As (3) shows the error is proportional to $\frac{T_S}{T}$. The number of samples taken in time T is equal to

$$N = Ts/T \qquad (4)$$

Therefore, for the sampling frequency of 600Hz there must around 800 samples to reach 1.5% of frequency measuring error. This number of samples was used to measure forces and aerodynamic moments of the model in the wind tunnel tests by using the dynamic balance. This number of samples was taken by a data Acquisition system and stored in files. Since the outputs of balance sensors are always mixed with different interferences, these sparsely extra signals must be removed from the results before processing and obtaining aerodynamic ratios. The source of interference must also be identified.

5.Review and Analysis of C_n Component in SDM Model

These review and analysis are made on the C_n component data derived from a SDM model test in 1.5 Mach number by considering the fact that this component has the maximum impact in two mentioned movement positions [2, 3]. Cn component has noise, phase momentary transformations and distortion. Figure 9-a shows the Cn output signal and figure 9-b its spectrum.

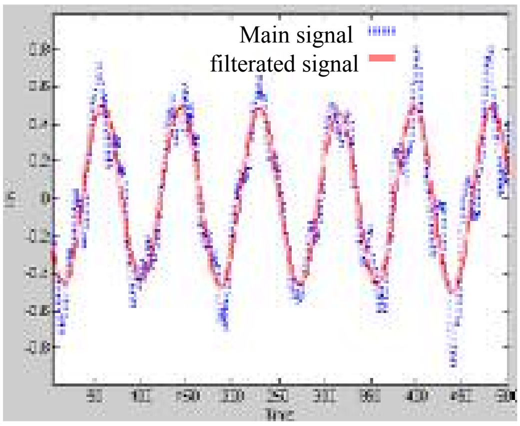


Fig.9-a

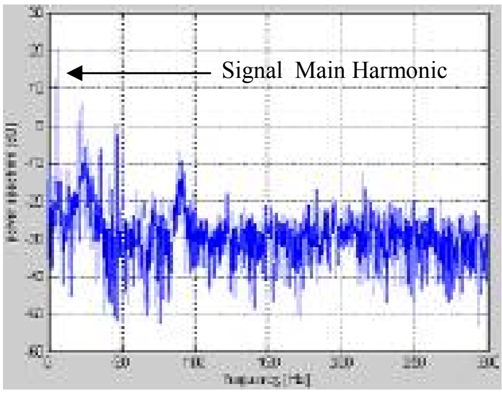


Fig.9-*b*

Fig.9: Cn component of SDM model pre and post filter in mach number 1.5and its spectrum

Digital filters can be used to remove noise and high harmonics caused by distortion. There are two kinds of digital filters: (1)- infinite impulse response (IIR) and (2)- finite impulse response (FIR). FIR filters have following advantages over IIR filters:

1. FIR filters can be designed linear phase which gives a constant group delay
2. FIR filters are stable under any conditions.

The output signal of the filter, $y(n)$ is obtained by convolving the input signal, $x(n)$ and the filter impulse response, $h(n)$:

$$y(n) = \sum_{m=-\infty}^{\infty} h(m) \times x(n-m) \quad (5)$$

For the FIR filters number of impulse response samples is limited and therefore, (5) can be written as

$$y(n) = \sum_{n=0}^{N-1} h(m) \times x(n-m) \quad (6)$$

The designing FIR filters can be easily carried out with existing software such as MATLAB. The design must target removing maximum noise and distortion from the signal and this can specify filter specifications such as bandwidth, pass band and etc based on a special criterion [16, 15, 17, and 14]. This criterion can be selected to be the level of noise power in the filtered signal (Figure 9-a shows the output of this filter). The noise power cannot be easily measured because the signal is not only distorted but also attenuated. Figure 10 shows a model of such a distorting system [14] in which output signal y is sum of a distorting signal, *n*, and the original signal, *x*, which is linearly amplified by the gain, *a* :

$$y = ax + n \quad (7)$$

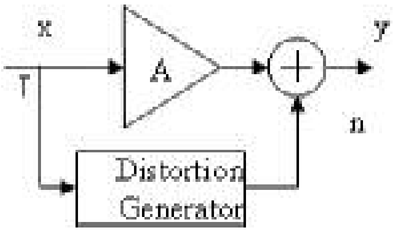


Fig.10: A model of a distortion generator.

The distortion signal power, N, can be obtained from the following equation:

$$N = \overline{nn} = \overline{(y-ax)(y^* - a^* x^*)} \quad (8)$$

where the asterisk * indicates the complex conjugate and the bar indicate the time average. The equation (8) can be expanded as follows:

$$N = |y|^2 + |a|^2 |x|^2 - axy - \overline{axy} \quad (9)$$

In order to find the value, *a,* that minimize *N*, we make the derivatives of *N* versus its real and imaginary parts equal to 0.

$$\frac{\partial N}{\partial real} | imag(a) = \frac{\partial N}{\partial \mathrm{Imag}(a)} | real(a) = 0 \quad (10)$$

By replacing equation (9) in the equation (10) we have:

$$real(\alpha) = \frac{\overline{x^* y} + \overline{xy^*}}{2|x|^2}, imag(\alpha) = \frac{\overline{x^* y} - \overline{xy^*}}{2j|x|^2} \quad (11)$$

By combining both equations in (11), *a,* is obtained as follows:

$$a = \frac{\overline{x^* y}}{|x|^2} \qquad (12)$$

Distortion power is obtained by replacing (12) into (9):

$$N = |y|^2 - |a|^2 \, |x|^2 \qquad (13)$$

As the power of the undistorted signal is equal to $S = |a|^2 |x|^2$ we can easily show that $x^* n = xn^* = 0$ which indicates that the distortion, *n*, does not have any correlation with the input signal.

This measurement method can only be used when a reference is available. Because the stimulating signal is sinusoidal, one can measure the level of noise using formulas (12) and (13) by producing a sinusoidal reference signal. As the phase of the received signal changes with time it is necessary to adjust the reference signal's phase accordingly. In order to do this, the phase of the reference signal is changed is several steps to find the phase with the minimal output noise. In this position the signal amplitude is calculated according to (12) and the phase is measured. Another problem that must be overcome is the error in adjusting the frequency of the stimulating signal which can influence the phase measurement. The error arises from the adjusting tools which adjust the frequency with a 10 % error that is considerably high. To alleviate it one can adjust the reference signal frequency by minimizing the error occurred between the main signal and that of the reference. Figure 11-a shows the measured phase variation with respect to the frames of samples (each block contains 24 samples). It represents the rate of lateral rotation of the model in the wind tunnel. Likewise figure 11-b shows the varied signal amplitude that represents the unequal flow of the model during the test. The polar plot of the amplitude and phase are illustrated in figure 12 which gives a better view of the model stability.

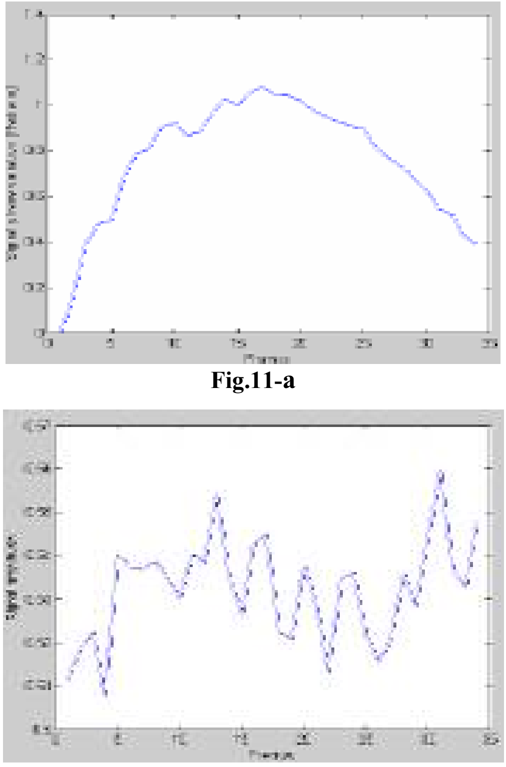


Fig.11-a

Fig.11-b

Fig.11: Variations of signal phase and amplitude of normal force.

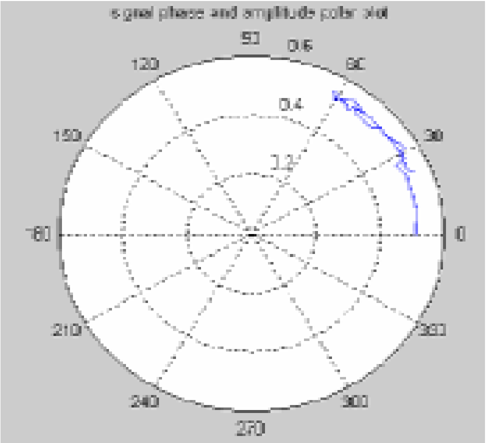


Fig.12: polar map of amplitude and its phase

6. Conclusion

Designing and optimizing the aerodynamic configurations of planes, missiles, vehicles and other driving bodies require studying the flow of air around them in a wind tunnel and precisely measuring the forces and moments applied on them. This activity is long term, complicated, expensive with side perils, which required the tests be so precise, safe with high reliability that the repeated tests should be avoided. Many test or experiments have been made in wind tunnel of Ghadr Aerodynamic Research Center on dynamic standard model in different Mach numbers and in plunging and pitching modes.

This paper presents a new approach to evaluate the signal quality based on the noise level minimization within the channel. With the help of the presented criterion, the noise alleviation filters were optimized; and the varied amplitude and phase of stimulating signal in wind tunnel were measured and the result for 1.5 Mach is presented. An important result that has been taken is that during the test, the current passing over the model must enjoy a suitable stability that can be reached by keeping the motors regimes stable. Moreover, it is necessary to decrease it side movement by using a suitable link between balance and a model so that the tested model would not have any momentary phase and amplitude changes. These results play important roles in decreasing the repeated tests of the model and reduces the time and cost of experiments.

7. Reference

[1]Milne, G.w.etal., “Maximum Likelihood Stability and Control Derivative Identification of a Cessana Citation II” , *AIAA paper* 2001-2013, 2001.

[2]Delaat , T.W.G.and Coene, R., “Unsteady Force on Slender Aircraft with Free Vortices in Inviscid Flow”, *AIAA Journal*, Vol. 40,no.4, 2002.

[3] Sunada, S., Kawachi, K.,Matsumoto, A.and Sakaguchi,A. “Unsteady Forces on a Two-Dimensional Wing in Plunging and Pitching Motions”, *AIAA Journal*, Vol. 39, No.7, 2001.

[4]Ericsson,L.E. and Begers, M.E, “Universality of the Moving Wall Effect,” *Journal of Aircraft*, Vol.37, No.3. June 2000.

[5]Volluz, R.J, “*Handbook of Supersonic Aerodynamics*, Section 20, Wind Tunnel Instrumentation and Operation”, *NAVORD Report 1488*, Volume 6, January 1991.

[6] Harper J.J., Pope A., “*Model force, moment, and pressure measurements, Low Speed Wind Tunnel Testing*, John Wiley & Sons, New York, Third Edition 1999.

[7] H.W.OTT, “*Noise reduction techniques in electronic system*”, *Signal Processing,*June 2000.

[8]Alex T. Edwards., “Comparison of Strain Gage and Fiber Optic Sensors on a Sting Balance In a Supersonic Wind Tunnel”, *Masters thesis*, Virginia University, December 2000.

[9]Robert W. Jevon, “Dynamic Strain Gage Balance For M.I.T Transonic Wind Tunnel”, *Master thesis* in the Department of Aeronautical Engineering, MIT, may 1951.

[10]Soo C. P. and Chien C. T, “Design of equiripple log FIR and IIR filters using multiple exchange algorithm”, *Signal Processing, Volume 59, Issue 3, Pages291-30, June 19973.*

[11] Shefeng Y., and Yuanliang M, “A unified framework for designing FIR filters with arbitrary magnitude and phase response”,*Digital Signal Processing,In Press, Corrected Proof, Available online 11 October 2004.*

[12]Elizabeth E, Per L, Håkan J and Lars W, “Tree-structured IIR/FIR uniform-band and octave-band filter banks with very low-complexity analysis or synthesis filters,” *Signal Processing, Volume 83, Issue 9, Pages 1997-2009, September 2003.*

[13]Toshiyasu T, Gary W. Small, Roger J. “Infinite impulse response filters for direct analysis of interferogram data from airborne passive Fourier transform infrared spectrometry,” *Vibrational Spectroscopy, In Press, Corrected Proof, Available online 11 September2004.*

[14] Berangi. R., “On the Clipping of the High Peak to Average Ratio Signals Based on Optimum Single Peak Clipping,” to be appeared in *IEEE communication letters*.

[15] Tolga Ç. “An efficient local search method guided by gradient information for discrete coefficient FIR filter design,” *Signal Processing, Volume 82, Issue 10, Pages 1337-1350, October 2002.*

[16]Yung A. K, and Sau G. C, “Design of finite-word-length FIR filters with least-squares error ,” *Signal Processing, Volume 80, Issue 8, Pages 1591-1596, August 2000.*

[17]Corneliu P, Bogdan D and Boris J, “Efficient state-space approach for FIR filter bank completion,” *Signal Processing, Volume 83, Issue 9, Pages 1973-1983, September 2003.*