Active Vibration Control of Aircraft Wing Using Piezoelectric Transducers

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**Original Article*

Abstract— Decreasing of system's vibrations is an important issue for all mechanical structures like an aircraft wing where it is subjected to many types of disturbances. Many methods were proposed to decrease or even to eliminate such vibrations by using many techniques like changing the design of structure or even trying to change the material of studied structures, but until now the problem is with completely manufactured structures in which the designer can't change material, so utilizing controlling method may serve as a tool to apply active vibration control (AVC) on a vibrated structure where by which one can convert passive structure to smart structure.

In this work authors focus on applying the controlling method called velocity feedback method [VF] on aircraft wing by using piezoelectric transducers (PZT) to serve as actuators on the upper skin of the model. Total wing was simulated in ANSYS.16 software with 4 actuators, various gains were tested for the same disturbance to reach the optimal actuation voltages of actuators. Voltage range was within ±100V this range of voltage was selected to protect actuators from breaking. A comparison between free, control OFF and control ON with different gains was performed to show the action of VF controller. The results show that at a gain of 1.2 high degree of response enhancement was satisfied where at his gain settling time of controlled wing was decreased to 55% of its free vibrated settling time.

Index Terms— Aircraft wing, Piezoelectric transducers, Active vibration control, Velocity feedback method, ANSYS software,Control ON,control OFF .

1.INTRODUCTION

Vibration in any mechanical system is undesirable issue due its dangerous manifold on any part of the structure, so it is important to safe the vibrated structure from collapse to prevent disastrous results, especially if the structure is in direct contact with humans like aircrafts, trains, buildings,…. Etc. Active vibration control is defined as a technique to remove undesired vibration. It is controlled by applying a counter force that is reversed to original force, but equal in amplitude to the original vibration to achieve the desired response. As a result two counter forces cancel each other and structure become steady state. Active vibration control is a modern approach in respect of vibration control at various places. The classic control technique is becoming too large for modern machine where space is limited and regular maintenance is not possible and if possible, it is too expensive, at such conditions AVC techniques comes handy, it is very cheap requires no manual maintenance and the life expectancy is also much more than the passive control. AVC makes use of smart structure [1]. The structure mainly requires actuators, sensors and control mechanism that performs well when vibration occurs. The analysis of a structure can help in improving the response of the structure under poor working conditions involving aircraft wing vibrations. Therefore the main objective of active vibration control is to reduce the vibration of a system by automatic modification of the system's structural response. In many situations, it is important to reduce these structural vibrations, as they may affect the performance and stability of the structures. Here some of previous works are presented where Shashikala Prakasha, et al introduced in [2] a remediable controller for actively controlling of system vibration.

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Full scaled multilayer composite airplane wing was used in his works as a tested model. The controller was consisted of multiple components with multiple input/ output ports. Microfiber composite (MFC) actuator was used in this study due to its ability to be sticking to curved surfaces, position of MFC actuators and sensors were estimated by using genetic algorithm technique. Experimental results showed excellent performance of this controller. In [3], Ehsan Omidi, et al studied the effect of introducing Integral Consensus Control (ICC) for controlling of structural vibration. Beam built in from one end and free from the other was used to estimate the effectiveness of the introduced controlling method via finite element analysis for many types of excitations. Results show that ICC led to improving system stability for any intended mode. S. Yavuz, et al worked on controlling of vibration for the single link arm which was modeled as cantilever beam in [4]. The studied arm was made from composite material with [0/90] and [45/-45] lay-ups. Frist three modes of vibration were targeted to reduce the vibration of arm's end by using finite element analysis via ANSYS program besides experimental work. To reduce the arm's end oscillation the authors worked on introducing the profile of velocity by recording residual vibrations of arm and tacking root mean square (RMS) for the recorded values it was observed that decreasing of the 1st mode vibration playing a major role on residual vibration. The authors noticed that the residual vibrations of arms can be manipulated or reduced by selecting the best deceleration time in both trapezoidal and triangular velocity inputs. In [5] Kumar V. Singh studied the dynamical behavior for realistic systems modeled by theirs shape of vibration for each natural frequency. Oscillation in aeroelastic system, such as resonance, related to corresponding natural frequency targeted to be suppressed via pole placement as one famous method for active vibration control techniques However, the controller may effects or oscillate other not targeted modes as a result of spillover. So by using an individual time delay with a system of actively state feedback can effectively damp vibration for targeted mode without oscillation or increasing vibration for other natural frequencies. Also introducing the role of time delay on both controller gain and incorporation of actuation dynamics. Numerical model has been tested to evaluate controlling performance. Konda Chevva tested in [6] the performance of Minimum actuation, power (MAP) technique as an AVC method, where MAP is a new control method works on minimizing voltage feuded to structure by visualizing and controlling powers of control references. Implementation of MAP was done theoretically and experimentally on simply supported aluminum plate with piezoelectric transducers (PZT), where main actuators used to excite the tested structure while subaltern actuators were used to vibration suppression. In this method PZT easily used to evaluate input power via measuring the electrical voltage without using sensors to decrease the error. The MAP theory is also can be used for multi-frequency excitation.

A delayed controller was designed by Rui Huang in [7] for active flutter suppression of a three- dimensional wing model. The design of the controller can be divided into two steps. At the first step, a short time delay was artificially introduced into the control loop and the dynamic equations of the aeroelastic system with delayed control were converted into a set of delay-free state-space equations by using a state transformation. At the second step, the control law was synthesized by using the theory of optimal control for the delay-free state-space equations. In [8] Riessom W., et al used strain feedback method for actively controlling of beam vibration with piezoelectric actuators under harmonic excitation. Experimental and numerical implementation of the structure was done to validate the results.The beam was modeled by using ANSYS program similar to the real beam that used in real time test by using NI cRIO 9022.Results show a high degree of convergence between both tests with the high performance of controller to suppress beam vibration.

2. Velocity Feedback Controller [VF]

Equation of motion for multi degree of freedom system is presented by:

$$m\ddot{\delta} + k\delta = f + \beta q \qquad (1)$$

Where m, k, f are mass , stiffness and force matrices respectively . q is the central force and β is the influence matrix which effect of controlling. Force of control produced by VF is presented by:

$$q = c\dot{\delta} \qquad (2)$$

C is the controller gain and $\ddot{\delta}$, $\dot{\delta}$and δ are set of acceleration,velocity and displacement measurements respectively, here structural damping was omitted to present the full effect of controlling purely on the studied structure. So by a combination of both equations (1) and (2) will lead to:

$$m\ddot{\delta} + +\beta c\dot{\delta} + k\delta = f \qquad (3)$$

By comparing equation (3) with the general equation of motion $[M]\ddot{\delta} + +[C]\dot{\delta} + [K]\delta = f$ form it clear to be noted that with controller the [C] matrix which presents viscous damping will be increased due to controlling force [9]. Block diagram of VF control is shown in figure (1).

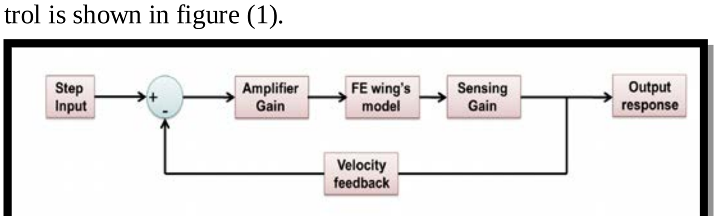

Figure (1) Block diagrams of VF

3. FE- MODEL

As mentioned previously an aircraft wings have been modeled in an ANSYSY 16.1 environment. A model was constructed by using ANSYS programming language, ZODIAC CH 650 aircraft wing was modeled closely to the real one. This wing is mainly containing two spars each one is located at 25% of chord length from both leading and trailing edges respectively. NACA 0015 is the airfoil section of the mentioned wing with 8 ribs along the wing's length, distance between each rib is 0.375m which is continuously exceeded until the 8th rib at which wing length reaches to 3m. The tapering ratio of modeled wing was 0.51 in X & the Y coordinates (coordinate system used for modeling process), chord length of the first airfoil section was 1.6 m. Each spar was about 3.3m total length, which was distributed as 3m wing's length inside the wing's body passing through the eight ribs with similar tapering ratio in Y direction only. The remaining 0.3m of spars length was used for fixation of the wing with airplane body. In ANSYS ZODIAC wing was modeled to scale of 1/3 real wing dimensions, where by using [KP] command 78 key points was modeled to form an airfoil shape as shown in figure (2). Through these keypoints splines were drawn via [spline] command to create the borders of the airfoil's border as shown in figure (3).

Figure (2) Outlines of NACA 0015 airfoil

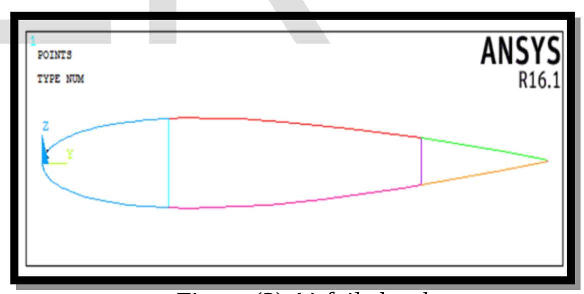

Figure (3) Airfoil sketch

Then by using [AL] command a completed area of airfoil section was created as shown in figure (4) a. Front and back spars were formulated firstly by a line connecting between two key points of airfoil points as shown in figure (3) for both first and back spars respectively . These two lines are converted directly to the area when [vext] command be used as will be explained. [vext] command was applied for offsetting of 3m in z direction and 0.2m in the x direction to generate wing's body as a volume with mentioned tapering ratios, after that 6 rectangular area was modeled starting from the 2nd rib until the 7th , the benefit of these rectangular areas was to generate remaining ribs where via [asbv] command the total wing's body was divided into 7 volumes, each one with an extension of 0.375m.

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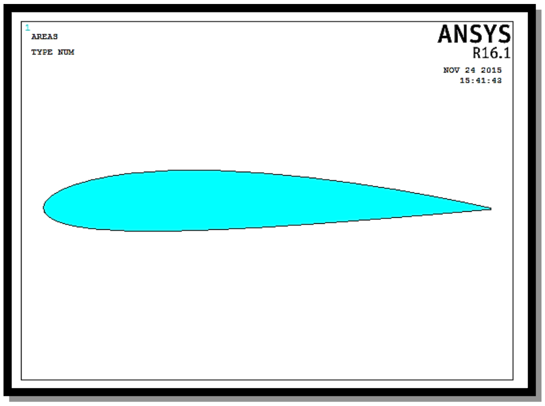

Figure (4) 2D Airfoil section

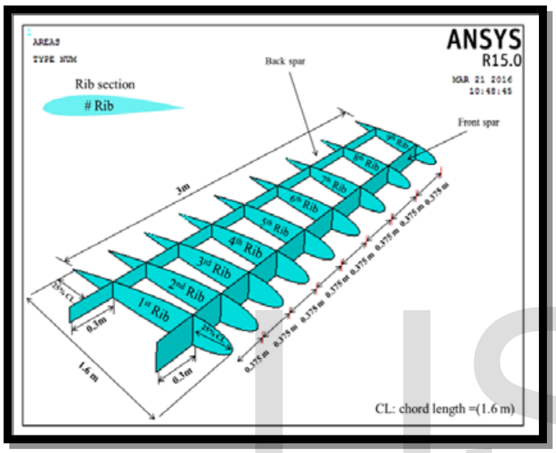

Figure (5) Wing's inner construction

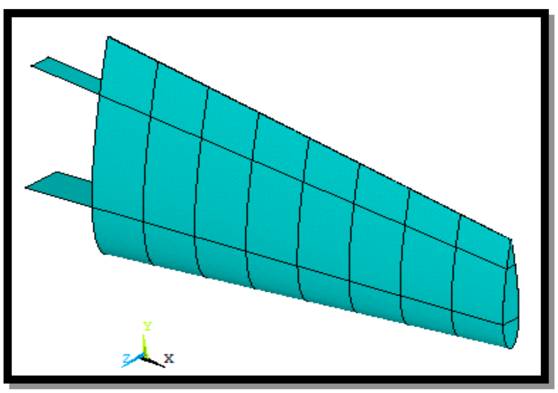

Figure (6) Total wing model

Table.1 : Ch30 wing dimensions

Total wing span (m)	1.2
Wing area (m^2)	0.432
Aspect ratio	2.3148
Taper ratio	0.51
Mear	
Root	
Tip c	
Wing section profile	NACA 0015

The real wing is hollow internally, so [vdele,,,,1] command was used to delete volumes only with keeping all covering areas as they were. Inner wing construction is shown in figure (5) with dimension of each part. In figures (6),(7)total wing is shown with skin as a final result of previously mentioned steps. Wing was modeled in an unique method presented by the authors in which a little number of commands were used to simplify modeling and in the same time modeling of studied wing precisely. Shell 181 was used to mesh total wing's structure as shown in figure (8). SOLID5 element is capable to modeling seven different types of specialties. When chosen this type of piezoelectric, Mechanical APDL will only consider the behaviors of the element for SOLID5 in u_x, u_y, u_z and volt degrees of freedom. It shall be noted that u_x, u_y and u_z indicate the displacements in the global coordinate system x, y and z directions, while volt mentioned the difference in potential energy of the electrical particles between two locations [10].

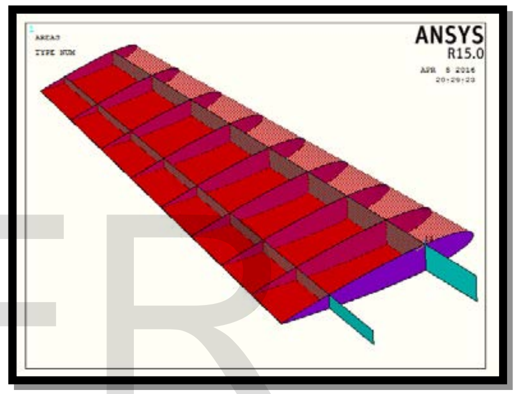

Figure (7) 3D model of wing

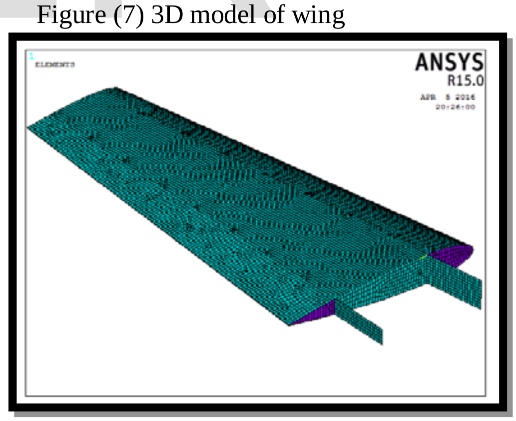

Figure (8) Meshed model of studied

SOLID5 has 8 nodes, 3-D magnetic, thermal, piezoelectric, electric and the structural field capability with limited coupling between the fields. Each node has u_x, u_y and u_z displacements along x, y, and z axis, with up to 6 DOF at each node. When used in piezoelectric and structural analyses, A prism shaped element is useful in modeling a system that has a geometric curvature (e.g., cylinder). In figure (9) wing's boundary condition is presented also position and dimensions of piezoelectric actuators on studied model is presented in figures (10),(11) respectively.

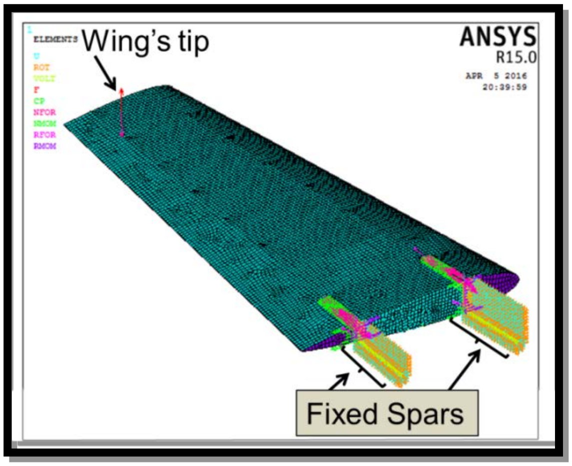

Figure (9) Boundary condition

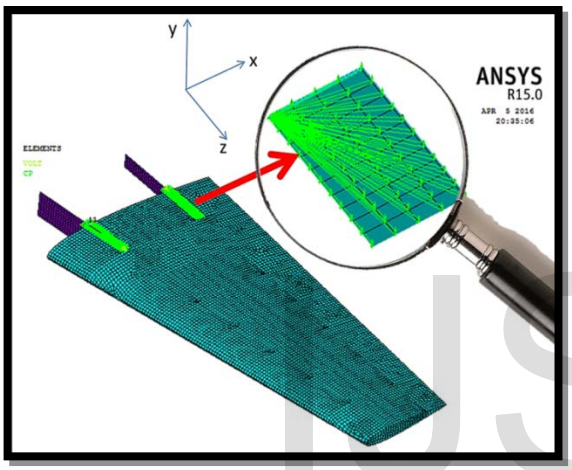

Figure (10) Position of PZT

3.Material Properties

Material properties of Aluminum and material properties of PPA-1001 piezoelectric transducer produced by (MIDE) are listed in table.1. Aluminum properties were calculated according to ISO 6892-1:2009E by the Iraqi Central Organization for Standardization and Quality Control (COSQC) which will be used in the next extension of the present work. Also, all physical and electrical properties of piezoelectric transducers are supported from (MIDE Co. For PPA-1001)[10].

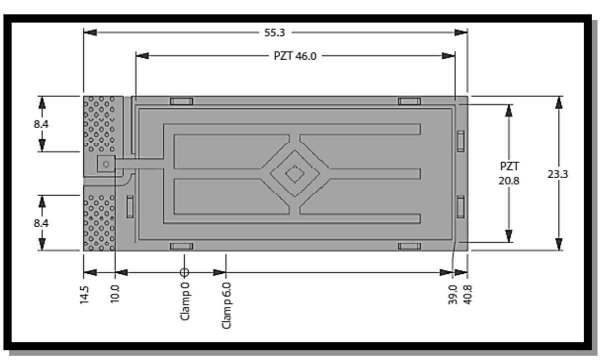

Figure (11) PPA-1001 transducer with its dimensions

Table .2 : Material properties

PPA-1001 Piezoelectric actuator	**Aluminum**
ρ =7350 kg/m^3	**ρ =2720 kg/m^3**
Piezoelectric strain matrix (C/m^2)	$\nu_{xy} = 0.33$
E31 = 6.5	**E=69 GPa**
E33 = 23.3	
E15 = 17	
Elastic stiffness matrix (N/m^2)	
C11 = 12.6	
C12 = 7.95	
C13 = 8.41	
C33 = 11.7	
C44 = 2.33	
Dielectric matrix (F/m)	
e11 = 1.503	
e22 = 1.503	
e33 = 1.3	

4. Free vibration analysis

Firstly, initial displacement of 0.001m was applied along the wing tip as shown in figure(3) in which the wing was built in at spars ,static analysis was performed in order to create transient initial condition to be applied by [ic] ANSYS command, where from the first step the displacement of all structure's nodes were collocated in matrix with a single column and nth row, nth is the total node counts. The extracted displacement will lead to make the structure oscillating freely.

It is important to be noted that the number of nodes included in [ic]command must be equal to the total number of nodes that forming meshed structure. A comparison between free, control OFF and control ON is then performed to decide which material was the best and which controller was the effector. Also modal analysis was performed by which 10 modes of vibration were calculated via block Lanczos for both materials. In order to show the effect of adding piezoelectric patches modal analysis was performed two times one with PZT and the other without PZT. The position of PZT was selected to be distributed on the position at which maximum stain inducing in order to get a total benefit of the PZT effect by positioning it in a similar place. Both top and bottom surfaces of PZT were assumed with zero voltage during modal analysis to prevent any opposite effect may produces by them. Table.2 presents natural frequencies with and without piezoelectric patches.

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Table .3 : Comparison of natural frequencies

Aluminum Wing	
Frequencies without PZT [Hz]	Frequencies with PZT [Hz]
59.654	60.587
185.456	186.99
194.382	195.14
203.721	204.95
207.574	208.62
217.612	218.12
226.409	227.58
227.333	228.68
228.087	229.63
241.909	243.84

5.Results and Discussion

In this section all structural responses are presented to be discussed, where Figure (12.a) shows the free response of Aluminum wing structure without embedding any PZT patch in this figure, it clear that the system response was decreased by its structural damping without any external damping , it is noticed from this figure that the settling time is more than 3sec which is longer by more than 1sec in comparison with the figure(12.b) in with pink line response presents control OFF case, it is noticed slight decrement in overall system response for both materials, this was returned to PZT masses and their positions where those two factors lead to increase the system stability by adding more stiffness and mass to structure even with small amount but their effect was slightly noticeable.

Both figures (12.a)&(12.b) Show exponential decrement in response by inherent structural damping, but with different effectiveness. Control ON wing's responses are presented in figures(13.a), (14.a), (15.a) and (16.a) in which responses were presented for systems with gain of 0.5,0.7,1,1.2 respectively, by comparison between free response and controlled response, the controller rule has emerged in high degree. The authors of this work aimed to balance between both controller performance and economic factors with output effect, although the voltage ranges were leveled by ±100v the controller show good performance. Actuation leveled voltages are shown in figures(13.b), (14.b) and (15.b) for VF controller of the aluminum wing model. In previously mentioned figures it is clear that increasing the controller gain acts on increasing both damping actuation voltage and decreases setting time more rapidly. More decreasing in settling time expected to be getting to upgrading voltage actuation level to more than ±100v. Figure (17) is presented to preview the clear enhancement in aluminum wing, settling time by 2sec. Although this enhancement if not very high, but it serves to decrease initial vibration of with from side and from another side it can be more effective with increasing voltage level. Total responses are presented in figure (18.a) to show the degree of effect for each gain on the overall responses with similar comparison but with voltage as presented in figure (18.b).

6. Conclusions

Generally results show that VF effected on increasing the system damping, but with different degree, although that the VF is better than P, PID controller, but there was some extra cost in applying such method experimentally in comparison with P or PID controller. Increasing of system damping ratio and natural frequencies in both studied model was achieved by means of simple AVC circuit by which no change in material properties was happening, but in another side enhancement of damping characteristics of the structure was noticed. Tested materials show enhancement in response even with control OFF circuit and this lead to say that both passive (or in another word semi-passive) and AVC strategies can be cooperated to give high performance with long circuit life as performed in this work. It is recommended for future works to test different materials with inherently high damping properties can lead to more improving on the overall performance of both structure and controller.

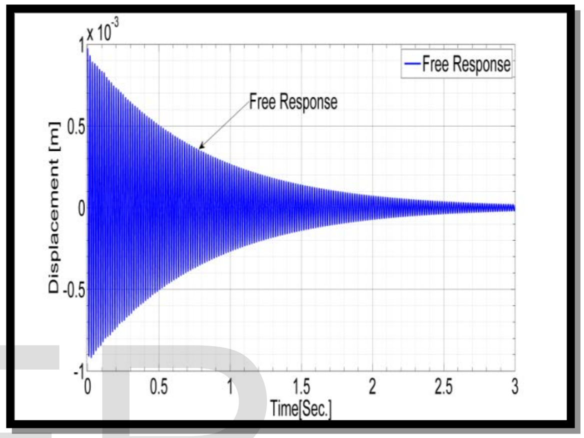


Figure (12) - (a)

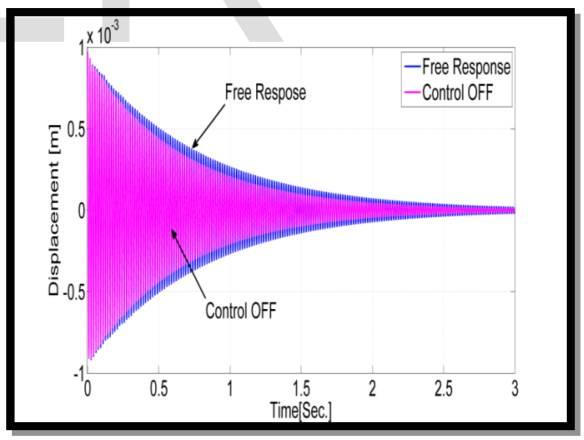


Figure (12) - (b)

Figure (12) Aluminum wing responses :
(a) Free response (b) Control OFF

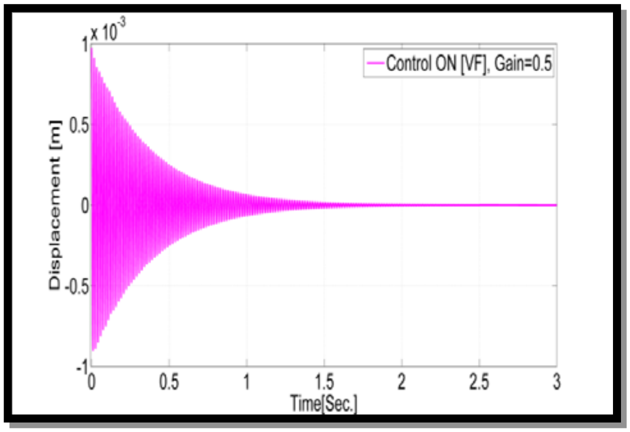


Figure (13) - (a)

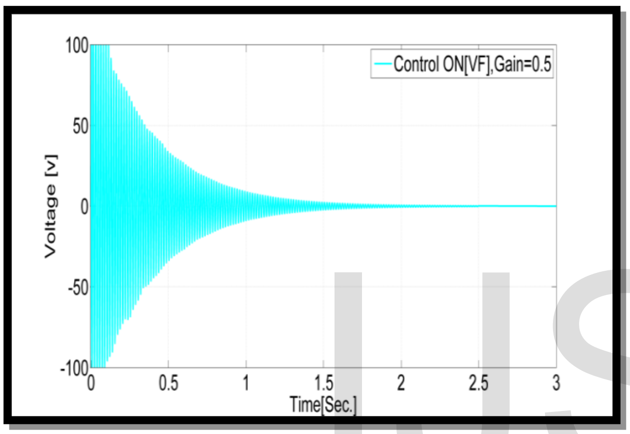


Figure (13) - (b)

Figure (13) Aluminum wing responses
(a) Free response (b) Control OFF

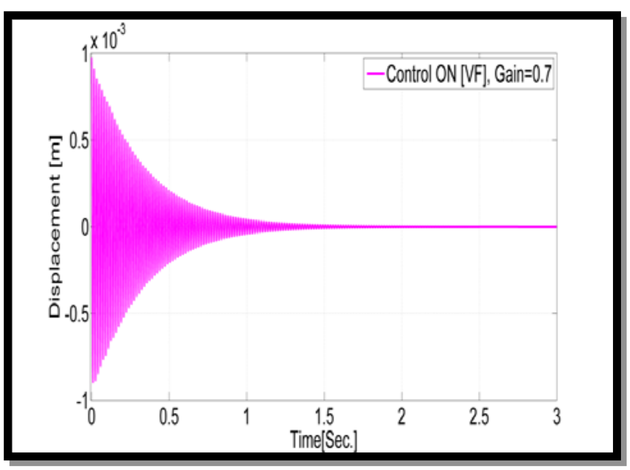


Figure (14) - (a)

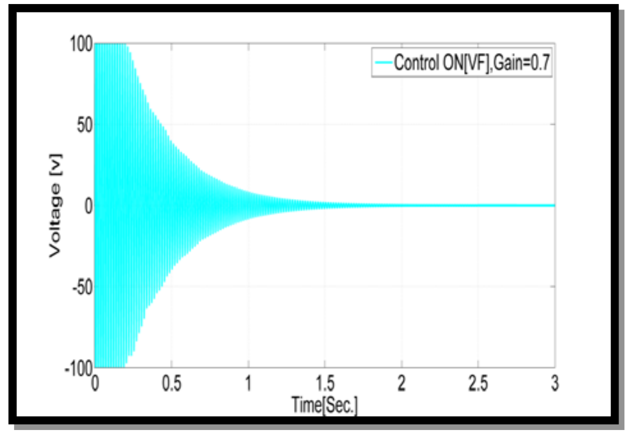


Figure (14) - (b)

Figure (14) Aluminum wing responses
(a) Free response (b) Control OFF

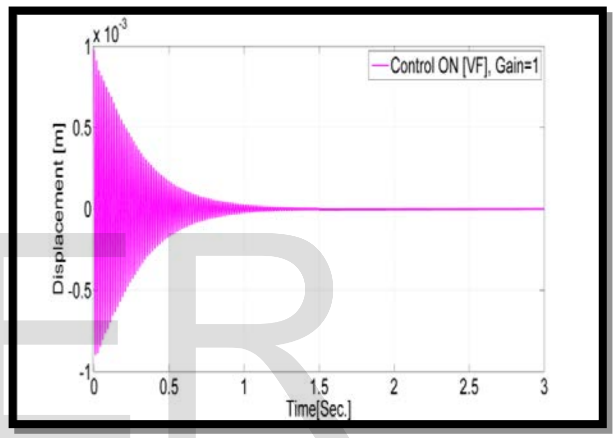


Figure (15) - (a)

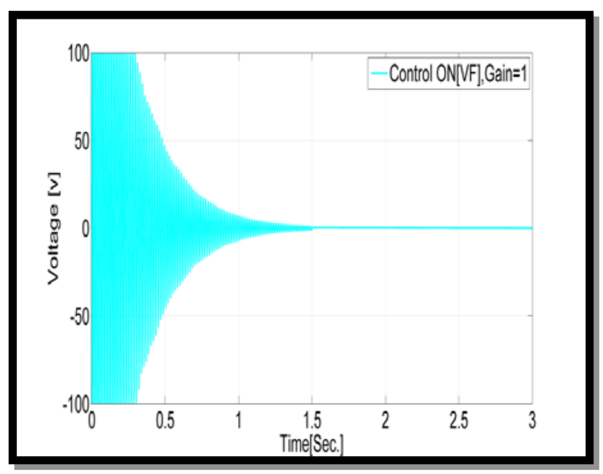
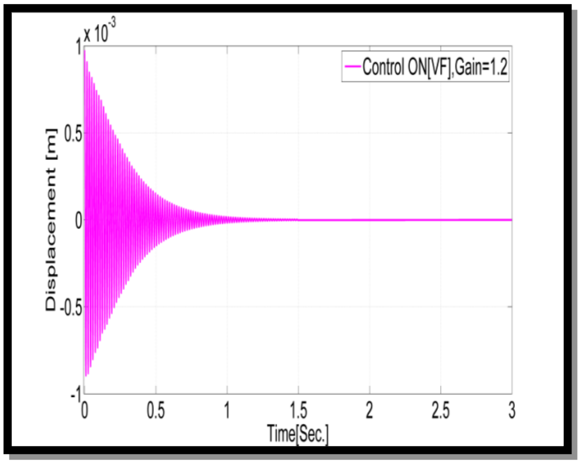


Figure (15) - (b)

Figure (15) Aluminum wing responses
(a) Free response (b) Control OFF



Figure(16) - (a)

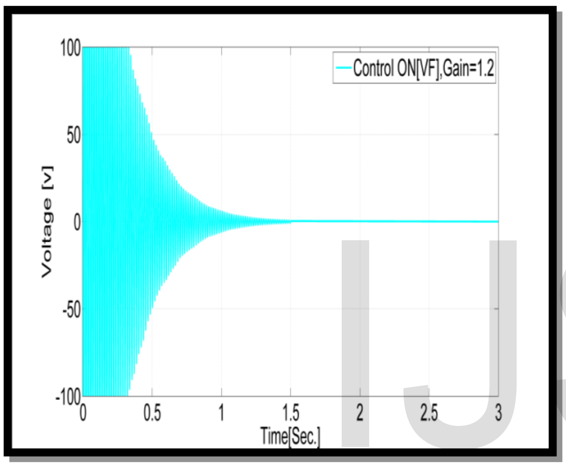
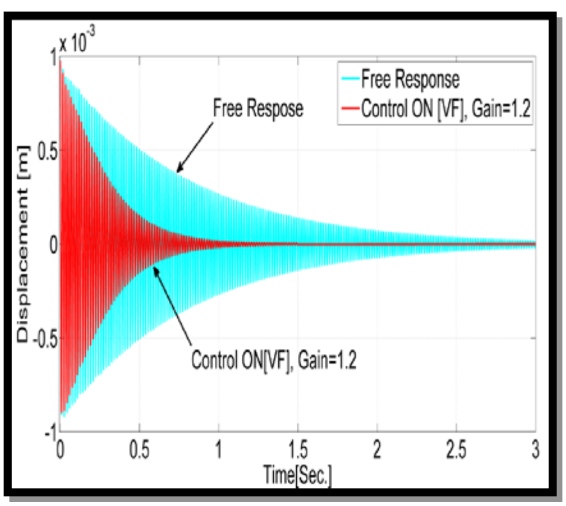
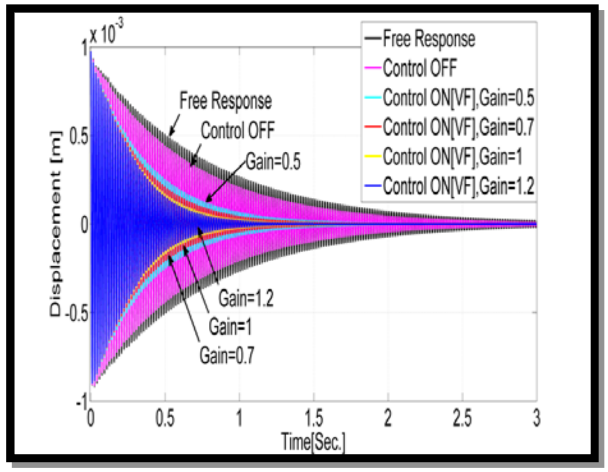


Figure (16) -(b)

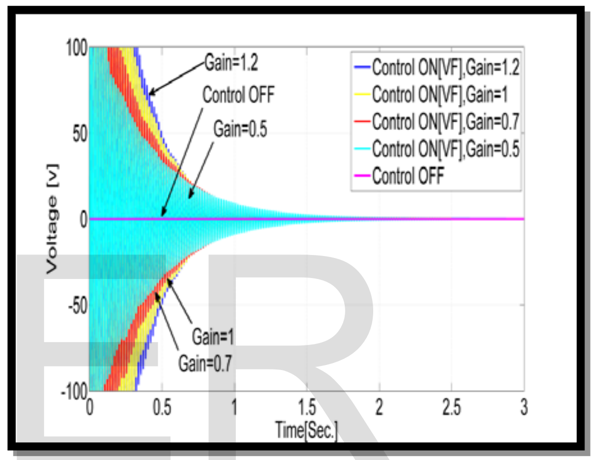
Figure (16) Aluminum wing responses
(a) Free response (b) Control OFF



Figure(17) Comparison between free and controlled response



Figure(18) - (a)



Figure(18) - (b)

Figure(18) Aluminum wing responses
(a) Free response (b) Control OFF

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