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Passive Electromagnetic Damping for Aerospace Electromechanical Actuation using PMSM

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***Abstract*— This paper presents MATLAB based design and implementation of Passive electromagnetic damping for the spoiler surface in an aircraft. The main objective is to set the parameters of damper so that the disturbances to the spoiler position can be minimized to an acceptable level hence, improving the response of the spoiler to a disturbance and also the energy flow back to the motor, its controllers and power electronic circuitry. In this paper, out of different damping techniques, passive electromagnetic damping is used to develop this model. By the end, results are compiled to show the improvement in response of the spoiler position after addition of designed passive damper.**

***Index Terms*—PMSM, DQ transformation, Current Controller, Spoiler, Hinge moment**

I. INTRODUCTION

During the flight, an aircraft may experience certain disturbances which can add up to destabilize the aircraft as the stability of an aircraft during the flight is function of position and angle of different aerodynamic surfaces. External bird strike, general air turbulence and vibration of aircraft due to engines may be considered as examples of external disturbances. This paper is mainly related to spoiler surface which actually comes into action when the aircraft flies at low altitude. Spoiler surface helps the aircraft to descend in altitude and also help to stop or reduce speed.

Until the past decade, the aircrafts mostly used the high pressure pneumatic systems which had few flaws including wear and tear, high maintenance cost, leakage of fluids, high cost of repairing and increase in aircraft weight. These days, more electric aircraft or fly-by-wire terminologies are introduced. Aircrafts have electrical or electromechanical systems for controlling different motions. For spoiler, the hydraulic or pneumatic system is now replaced with the motor to be used as position controlling element. As mentioned before, the spoiler surface comes into action at low altitude, there are a lot of chances for external disturbances like bird strike and many others to unbalance aircraft. In this paper, electromagnetic damper is designed and tuned for the given motor and spoiler parameters and simulated in MATLAB simulink. Simulink, a program for simulating dynamic systems, is a toolbox extension of MATLAB [7]. Simulation of complex dynamic systems, graphical environment with visual real time programming and broad selection of tool boxes are the major advantages of Simulink [6]. Also, Simulink simulates analogue systems and discrete digital systems [8].

As Permanent Magnet Synchronous Motor (PMSM) is associated with most of the high performance applications [1], it is best suited for use in this study. Due to highly efficient performance characteristics, high torque-to-current ratio and low inertia, PMSM is ideal for advanced motion control system [1]. These motors are very popular in vast variety of industrial applications these days. [2, 3, 4]. The current and speed controller for the given PMSM are designed using the basic knowledge of control system and power electronics.

Practical implementation of above mentioned spoiler systems, its controller and electromagnetic damping system in an aircraft is shown below in Fig.. 1.

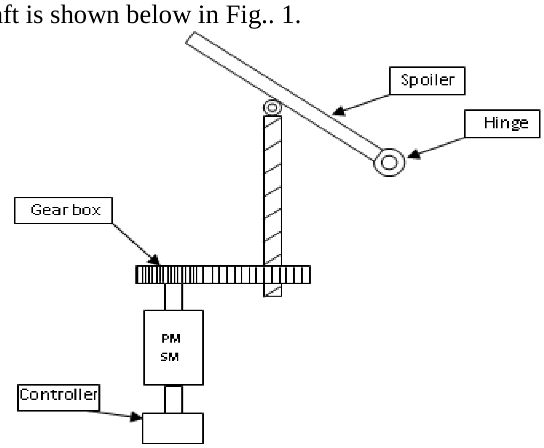

Fig. 1: Actual Picture of the Final Implementation of this Paper

For the MATLAB simulink implementation of this model, the block diagram is developed and shown in Fig.. 2. In the next stage of this paper, each block is implemented in Simulink and results are studied to modify the design parameters according to the desired response.

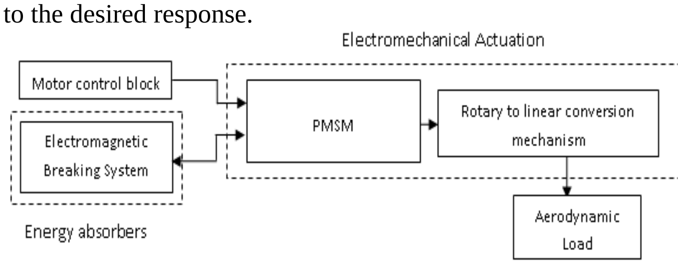

Fig. 2: Electromagnetic Damper – Proposed Block Diagram

In the final stage, individually studied block are joined together to finalize the output according the requirements.

II. MODELING OF PMSM IN MATLAB SIMULINK

PMSM can be modeled in DQ reference frame by following differential equations [1, 2, 5, 9, 10]:

$$V_d = r_s i_d + p\psi_d - \omega_r \psi_q$$

(1)

$$V_q = r_s i_q + p\psi_q + \omega_r \psi_d$$

Where,

V_d & V_q = D and Q axis voltages of synchronously rotating reference frame

I_d & I_q = D and Q axis currents

r_s = stator resistance

ψ_d and ψ_q = flux linkages

ω_r = electrical rotor frequency in rad/sec

p = differential operator d/dt

Flux linkages can be represented as follows

$$\psi_d = L_d i_d + \psi_m$$

(2)

$$\psi_q = L_q i_q$$

Where ψ_d is the flux linkage due to permanent magnet of the rotor. Putting eq. 2 in eq.1, following stator voltage equations are obtained:

$$V_d = r_s i_d + L_d p i_d - \omega_r L_q i_q$$

(3)

$$V_q = r_s i_q + L_q p i_q + \omega_r L_d i_d + \omega_r \psi_m$$

Electromagnetic torque can be expressed as:

$$T_e = 3\frac{P}{2}\left[\psi_m i_q + \left(L_d - L_q\right) i_d i_q\right] \quad (4)$$

In form of rotor dynamics, this equation becomes:

$$T_e = J\frac{2}{P}\frac{d\omega_r}{dt} + B\frac{2}{P}\omega_r + T_L \quad (5)$$

Here, P is number of pole pair, J is inertia, B is co-efficient of viscous friction and T_L is load torque. Eq. 3 to Eq. 5 are the mathematical model of PMSM and are used to implement it in Simulink.

III. CONTROLLING OF PMSM IN MATLAB SIMULINK

For three-phase PMSM, both the speed and current controllers need to be designed. To maintain the output torque at specific speed of the motor, the current needs to be controlled. Also during the start of the motor, jerks may cause harm to the circuit. But it is a difficult problem to control the current, and hence the torque of PMSM, in all the three phases. Therefore, by using matrix conversion technique, the three-phase ABC system is usually converted to DQ reference system for the sake of simplicity of controllers design and ease of implementation. As in DQ system, D axis current is referenced to zero, so controlling Q axis current will control all three phase currents of PMSM and hence the torque.

For the speed control of PMSM, a cascaded speed controller is designed and implemented. As explained above, only Q axis current needs to be controlled, the speed controller give the single output – Q axis reference current – depending on the demand value of position of the spoiler and actual position of the spoiler. Equations used to implement this controller are as under [9]:

As the ultimate target is to stabilize the spoiler position, a position controller is also cascaded. As the speed controller has to give only Q axis current, the output of the position controller is only reference speed with respect to the demand position. Field oriented block diagram of PMSM is shown below:

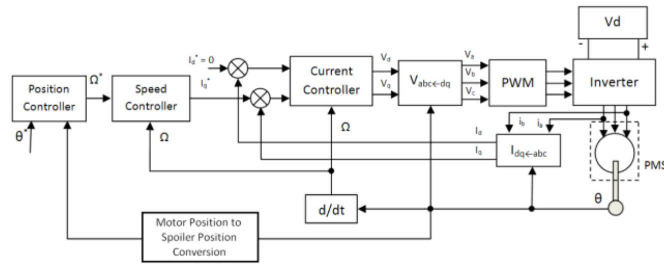

Fig. 3: Block Diagram for Field Oriented Control of PMSM

In this block diagram,

θ = Position of motor shaft

θ* = Reference position of motor shaft

Ω = motor shaft speed

Ω* = Reference speed for motor shaft

I_d* & I_q* = Reference D and Q axis currents

V_d* & V_q* = Reference D and Q axis voltages of synchronously rotating reference frame

V_a, V_b & V_c = A, B and C axis voltages

Without going into the detail of how the matrix conversion takes place to convert between ABC and DQ axis reference frame, the final results are shown here. For getting DQ axis quantities (currents or voltages) from ABC axis quantities (currents or voltages), following matrix will be used [5].

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - 120) & -\sin(\theta - 120) \\ \cos(\theta - 240) & -\sin(\theta - 240) \end{bmatrix} \begin{bmatrix} Vd \\ Vq \end{bmatrix} \quad (6)$$

For getting ABC axis quantities (currents or voltages) from DQ axis quantities (currents or voltages), following matrix will be used [5].

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = 2/3 \begin{bmatrix} \cos(\theta) & \cos(\theta - 120) & \cos(\theta - 240) \\ -\sin(\theta) & -\sin(\theta - 120) & -\sin(\theta - 240) \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (7)$$

After tuning the controllers, the final parameters were fixed. To illustrate, the position response of the whole system to the demand position of 45^o shown in Fig. 3 is shown below.

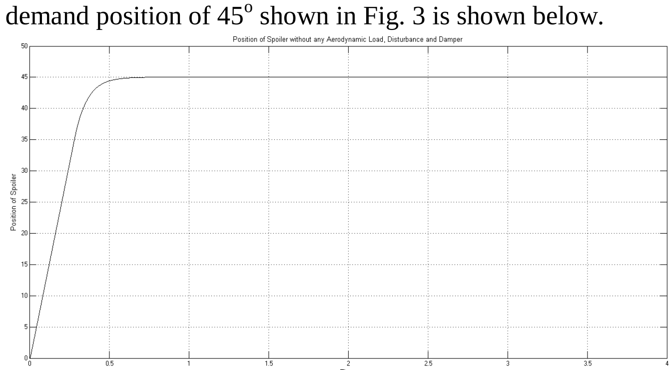

Fig. 4: Position Curves with No aerodynamic load, No disturbance and No damper

IV. MODELING OF AERODYNAMIC LOAD AND ACTUATOR

The motor used in this project has electromagnetic torque (Te) of 33 Nm while the aerodynamic load and inertia of Spoiler surface give the disturbance torque of 3000 Nm. So a gearbox is added to the system so that it becomes compatible with the load to overcome inertia. Another issue is related to the motion of aerodynamic load because it moves linearly while the motor rotates so rotary to linear conversion is also needed. In next few lines, the model for these two blocks will be modeled and results will be shown.

Torque due to the load of spoiler and the air pressure on the spoiler surface constitute the aerodynamic load. From experimental data, the relation between angular position of spoiler θ_m and hinge moment torque (T_{hm}) is shown below.

$$T_{hm} = m\theta_m + c \tag{8}$$

When manipulated according to the design requirements Eq. 8 becomes:

$$T_{hm} = 100\theta_m - 2000 \tag{9}$$

Gear ratio is now given by:

$$n = \frac{T_L}{T_e} = \frac{3000}{33} = 91 \tag{10}$$

The final aerodynamic load is now T_{hm} which is geared down by n = 91 gear ratio box.

For modeling the inertia introduced by the spoiler, following basic relation between inertia and torques of the motor was considered.

$$J_m\alpha_m = T_e - \frac{T_L}{n} - J_s\alpha_L \tag{11}$$

Where,

J_m = Inertia of Motor (PMSM)
J_s = Inertia of Spoiler
α_m = Acceleration of Motor (PMSM)
α_L = Acceleration due to spoiler load
T_L = Torque due to Spoiler load

On some computations and simplifications, above Eq. 11 becomes

$$\left(J_m + \frac{J_s}{n^2}\right)\alpha_m = T_e - \frac{T_L}{n} \tag{12}$$

For this paper, massive inertia of $J_m = 1.45\,e^{-3}$ Kg.m^2 and J_s = 200 Kg.m^2 are considered therefore, saturation limit for the motor currents is also defined to minimize the losses due to heating up of motor. After the addition of the aerodynamic load and actuator, the position response is shown below.

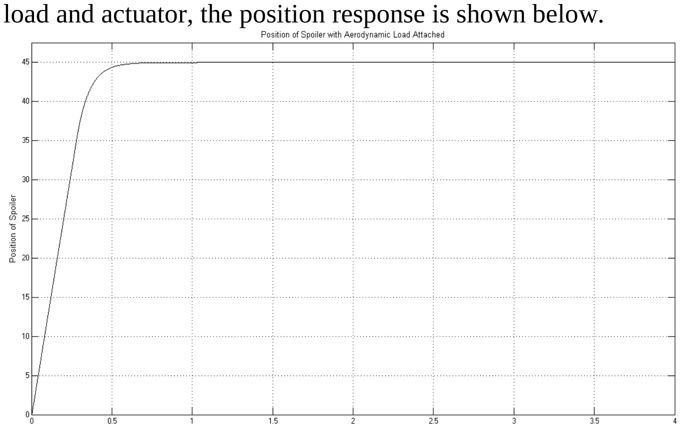

Fig. 5: Position Curves with aerodynamic load, No disturbance and No damper

V. MODELING OF EXTERNAL DISTURBANCES

In an aircraft, spoiler comes in action when it is at low altitude. Most common and easily understandable example of external disturbance is of bird strike. If the bird hits the spoiler, it may change its position which in turn destabilizes the aircraft. In addition to bird strike the continuous vibratory motion due to engines and any unavoidable and unpredictable factors may also occur. To model these factors, a spike and random blocks were used. As the damper is still not in introduced, the effect of bird strike on spoiler position is shown as under.

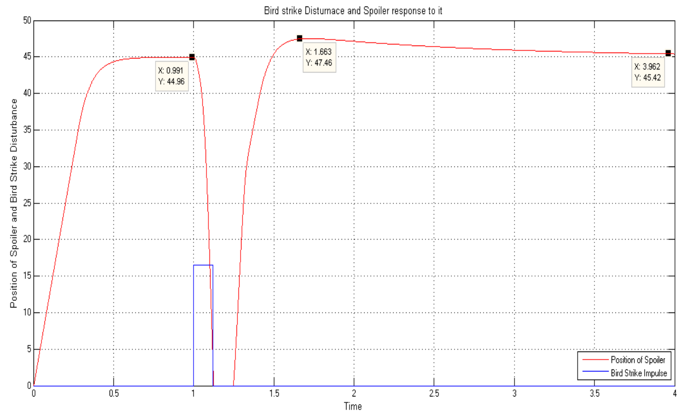

Fig. 6: Position response of spoiler to the bird strike, when no damper attached

This graph shows that the spoiler goes to 0^o on bird strike to it. It is also obvious that the controller is fast enough to retrieve the demand position of 45^o in about 2 second time.

VI. MODELING OF ELECTROMAGNETIC DAMPER

Damping is actually the process of absorbing the unwanted energy from any system. Here, in case of this paper, the unwanted energy caused the spoiler to fully close (go to 0^o position). This effect of spoiler can be minimized if some energy is given in opposite direction to the applied energy due to bird strike or vibration effects. Relationship between motor torque and speed is given as:

$$T_d = T_{max} * \frac{2\alpha\Omega}{\Omega^2 + \alpha^2} \tag{13}$$

Where,

T_d = Demand torque
T_{max} = Maximum torque
Ω = Angular speed
α = Peak angular speed

When the bird struck the spoiler, Eq. 13 was the equation of response for the motor. To design the damper, the Eq. 13 is added to the net disturbance to the motor. As the disturbance torque is subtracted from total motor torque, the overall effect of this demand torque will be negative. As soon as the bird strikes the spoiler, Td is also generated in order to counterbalance so the net result is the minimum disturbance in spoiler position. For the sake of simplicity, "T_{max}" is taken to 3.3 Nm (10% of Te) and "α" is taken to be 200 rad/s for the results shown here.

Now that, all the components of disturbances have been designed, the final shape of the actuator becomes as under in MATLAB Simulink.

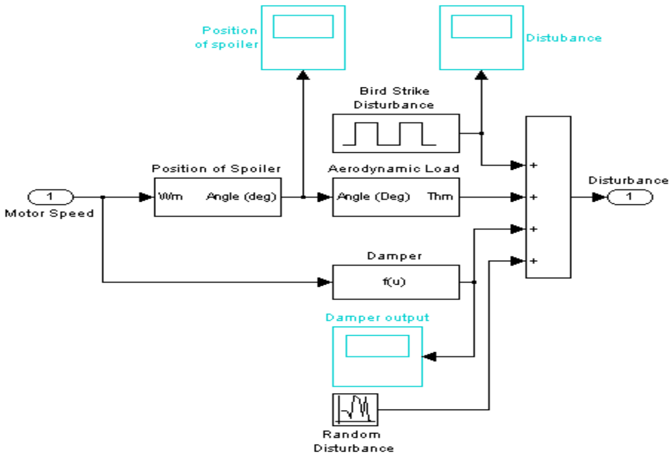

Fig. 7: Total disturbances on motor including Damper

Final position response of the spoiler when the damper is in action and bird hits is shown below.

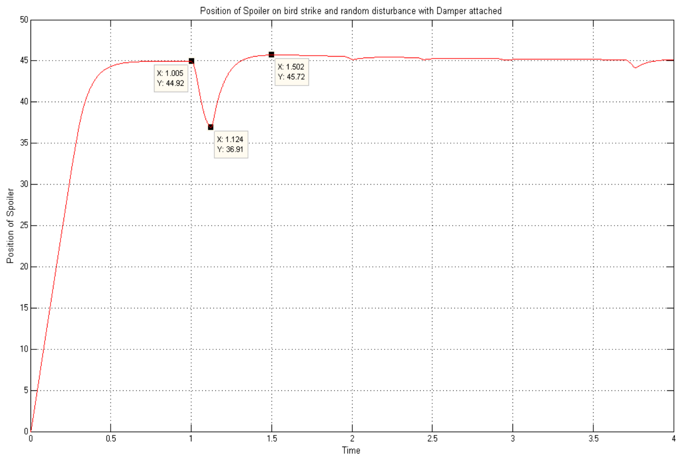

Fig. 8: Position response of spoiler to the bird strike, with damper attached

When comparing Fig. 6 and Fig. 8, it is obvious that the damper has improved the response of the spoiler position controller to greater extent. Now the spoiler is not fully closing when the bird hits it.

VII. COMPARATIVE RESULTS FOR DIFFERENT PARAMETERS OF DAMPER

Now that the damper is designed, its final tuning is compulsory to finalize it the discussion of damper. As shown by Eq. 13, two factors which are controlling the demand torque are T_{max} and α. Here is the graph for the damper with when T_{max} is kept constant at 3.3 Nm.

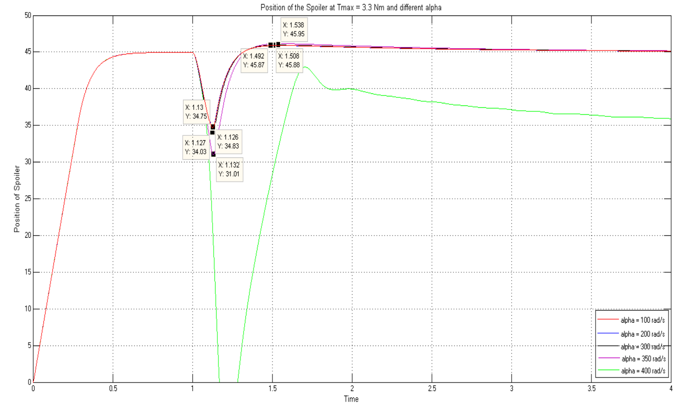

Fig. 9: Position of spoiler for different values of α while keeping T_{max} = 3.3 Nm

This graph shows that the increase in "α" at constant T_{max} destabilizes the spoiler on bird strike at 400 rad/s. The best result is found at peak angular speed of 100 rad/s. Therefore, the results for T_{max} are now shown while keeping the peak angular speed constant at 100 rad/s.

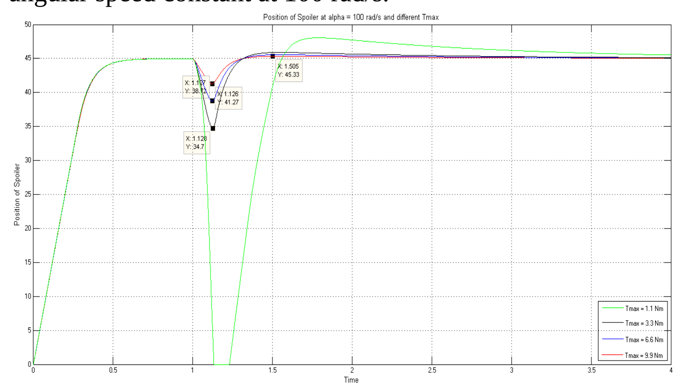

Fig. 10: Position of spoiler for different values of T_{max} while keeping α = 100 rad/s

From this graph, it is clear that the T_{max} should be kept at 9.9 Nm for best results at 100 rad/s but it is not a practical value as far as the designed system is concerned. Increasing the T_{max} rating of damper to a higher level will increase the size of damper and hence it will not be a good damper for the weight sensitive applications like aircraft. Therefore, the finalized values of damper parameters are:

$$T_{max} = 6.6\,Nm; \quad \alpha = 100\,rad/s$$

VIII. CONCLUSION

Use of passive electromagnetic damper improved the response of spoiler position controller on application of unwanted external forces. The performance of passive damper is function of the maximum torque and the maximum permitted angular speed. If these two parameters are set properly, the resulting damper will have enough stability to control the aircraft more efficiently. Also the slight movement of the spoiler beyond the desired angle when it tries to stabilize it after unwanted disturbance can be minimized by designing the controllers to follow overdamped response characteristics but the overall performance will be slowed down.

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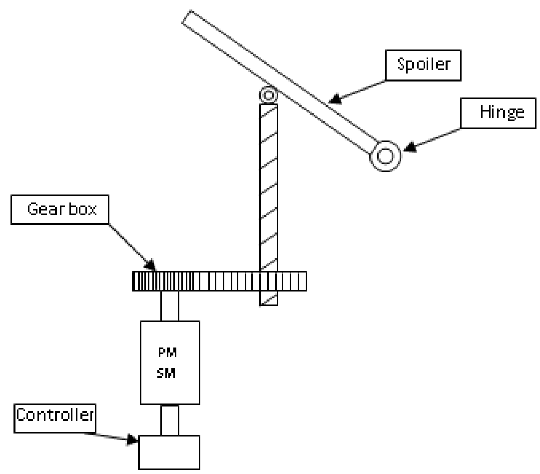

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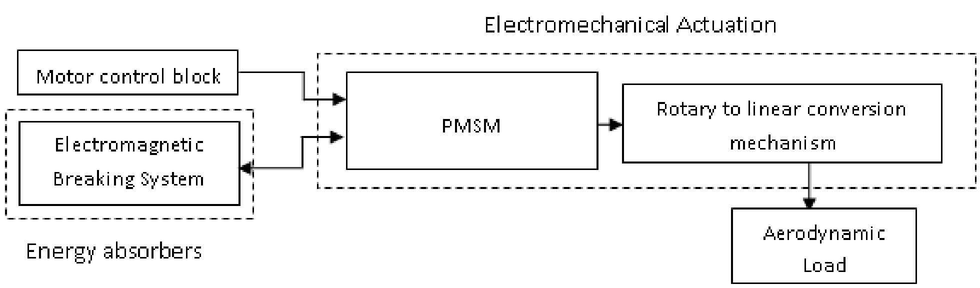
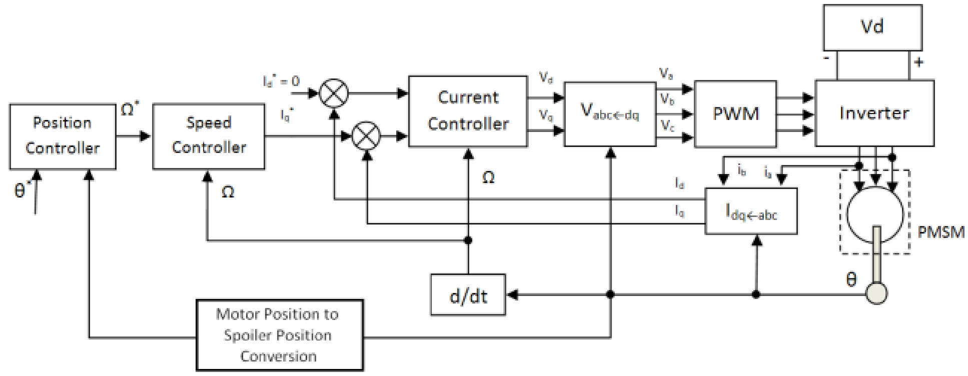


Fig. 2: Electromagnetic Damper – Proposed Block Diagram



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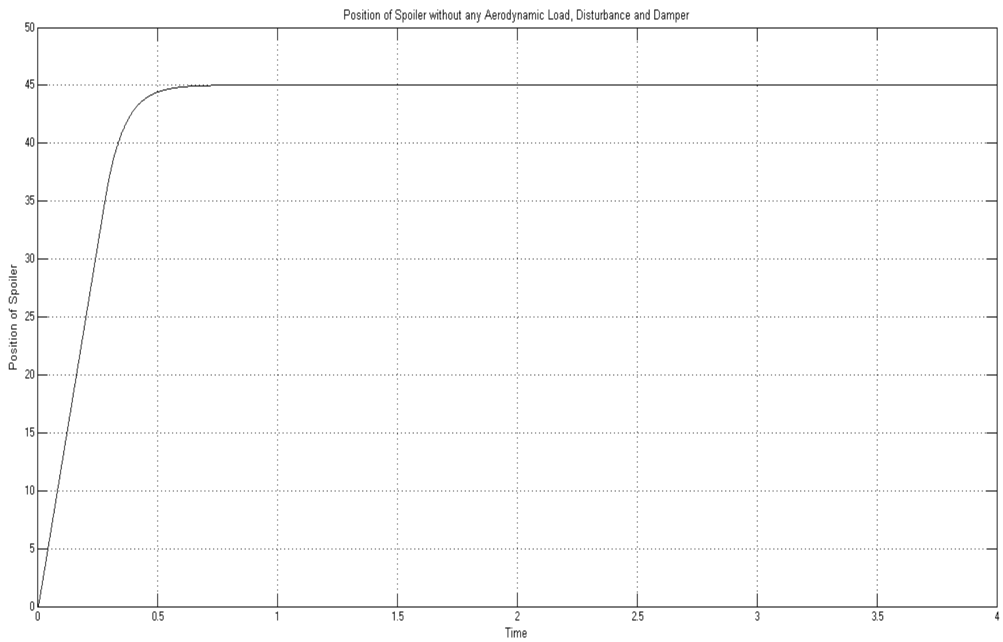
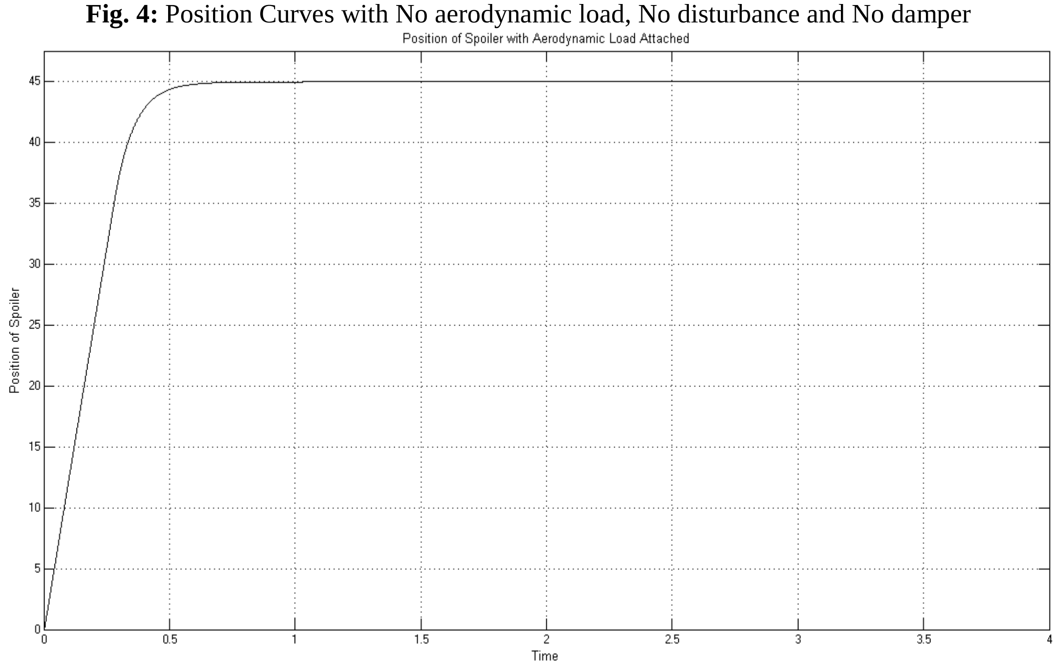


Fig. 4: Position Curves with No aerodynamic load, No disturbance and No damper



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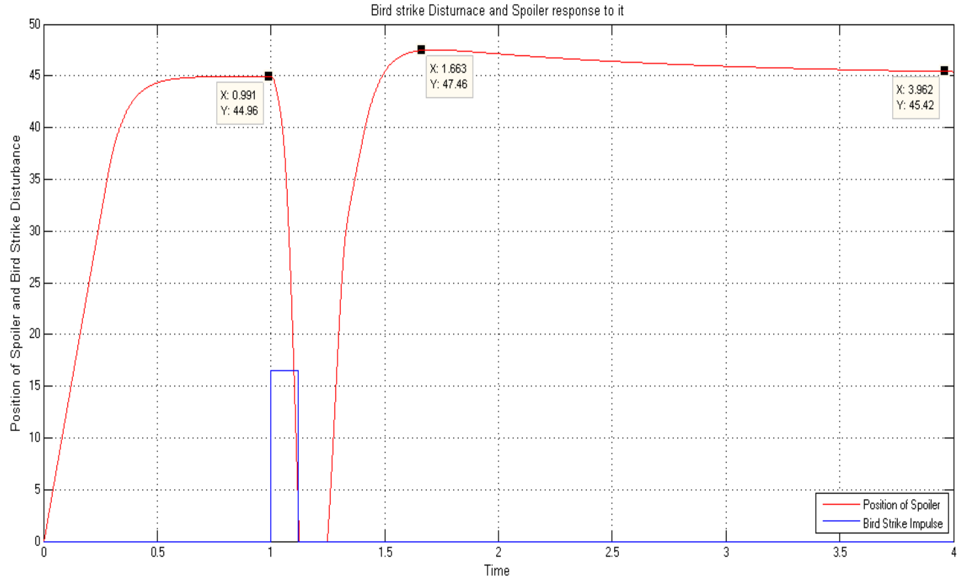

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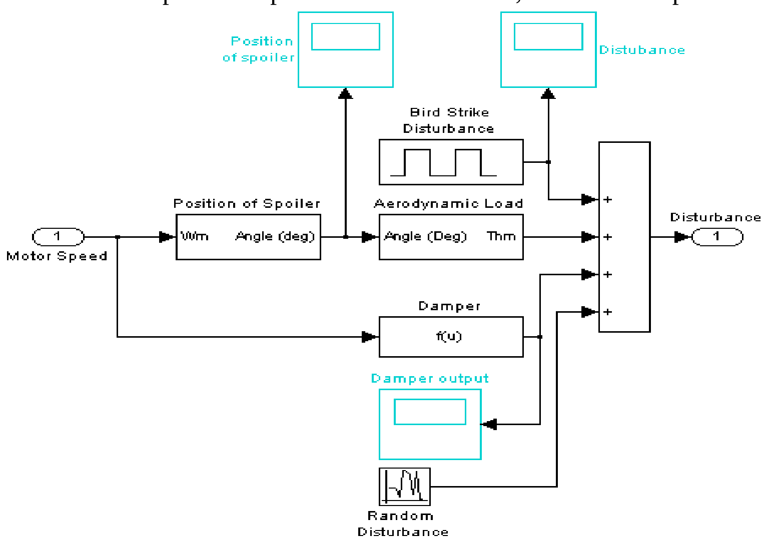
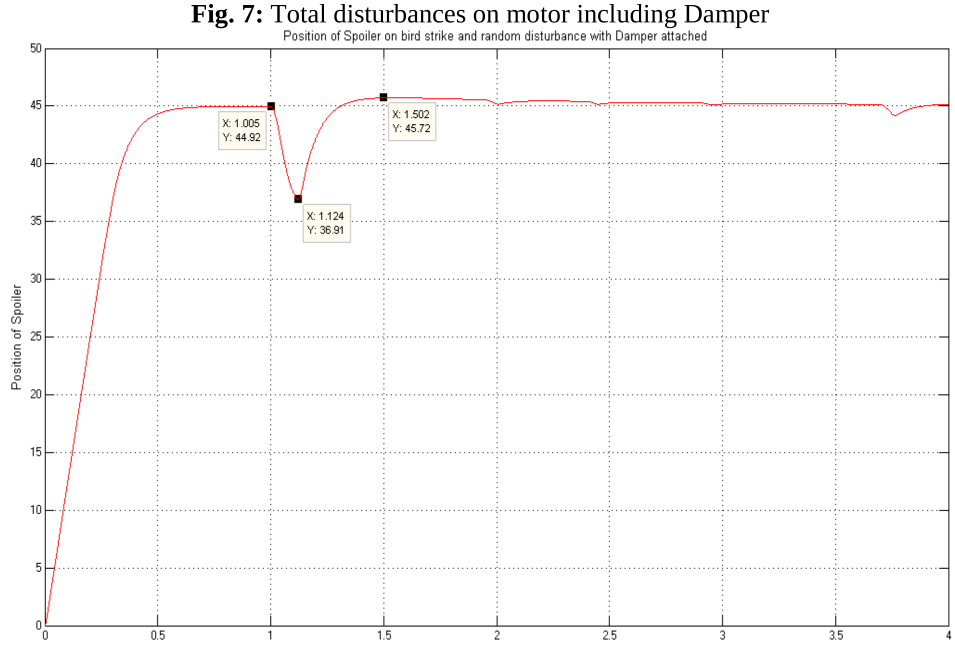


Fig. 7: Total disturbances on motor including Damper



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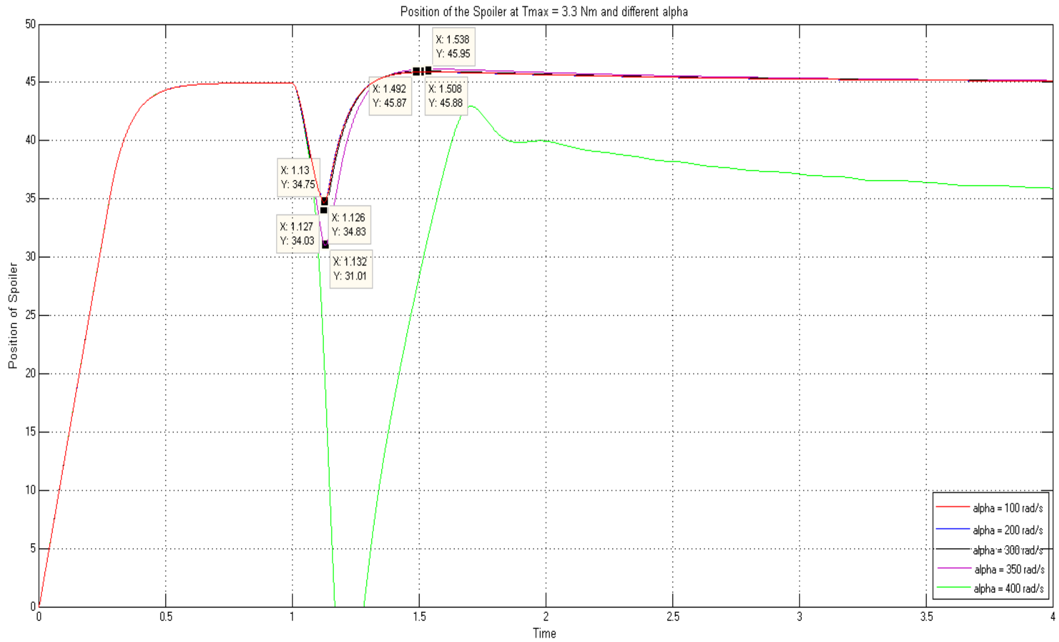

Fig. 9: Position of spoiler for different values of α while keeping T_{max} = 3.3 Nm

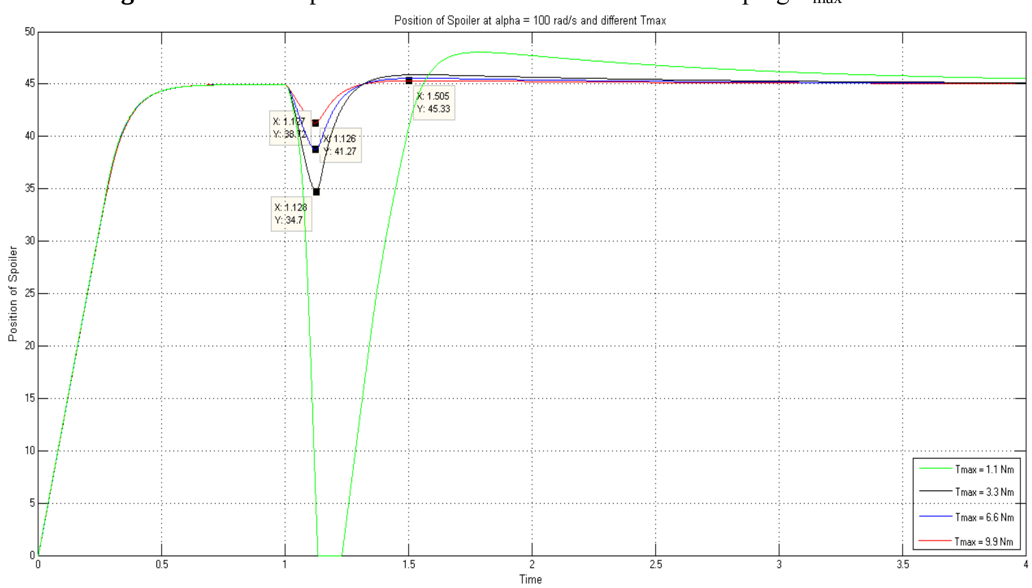

Fig. 10: Position of spoiler for different values of T_{max} while keeping α = 100 rad/s