A New Approach to Structure of Aerodynamic Fin Control System for STT Missiles

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Abstract: In order to control the missiles by aerodynamics, control surfaces sometime called fins are used. Deflection angles of these fins are the right control variables of the aerodynamics, but aerodynamicists prefer to use analytic variables called aileron, elevator and rudder instead of these physical variables, because these three analytic variables dominantly influence on the roll, pitch and yaw channels of the missile maneuver, respectively, and each can be assumed a linear combination of four fin deflection angles. On that basis, roll, pitch and yaw autopilots for controlling the attitudes or lateral acceleration of the missile are designed, and as a consequence outputs of each autopilot are aileron, elevator and rudder commands, respectively. In the existing fin control scheme for the typical tail-fin controlled cruciform missiles, firstly these outputs are distributed to four fin defection commands, and after that four fins are actuated by fin controllers so that their deflections follow the commands. This paper shows that performance of such control schemes can be degraded significantly when fin actuators have certain physical constraints such as slew rate, voltage or current limit, uncertainty of actuator dynamics, and so on, and propose a new control scheme which alleviates such problems. This scheme can be widely applied to various fin actuation systems. But in this paper, for convenience, tail-fin controlled cruciform missile is taken as an example, and it is shown that a proposed control scheme gives better performance than the existing one.

Keywords: STT missile, actuator, non-linearities, fin controller, conversion logic

1. INTRODUCTION

In order to control the missiles by aerodynamics, control surfaces sometime called fins are used. There are many different types of fins, but they are largely categorized into three types, i.e., canard type located in the front part, wing type located in the middle part, and tail-fin type located in the rear part of the missiles. Regardless of their types, these fins need suitable actuation systems.

The right control variables of the aerodynamics are fin deflection angles, but aerodynamicists prefer to use analytic variables called aileron, elevator and rudder instead of physical variables of fin deflection angles, because these three analytic variables dominantly influence on the roll, pitch and yaw channels of the missile maneuver, respectively, and each can be assumed a linear combination of four fin deflection angles. On that basis, roll, pitch and yaw autopilots for controlling the attitudes or lateral acceleration of the missile are designed, and as a consequence outputs of each autopilot are aileron, elevator and rudder commands, respectively.

In the existing fin control scheme for the typical tail-fin controlled cruciform missiles, firstly these outputs are distributed to four fin defection commands, and after that four fins are actuated by fin controllers so that their deflections follow the commands. This paper shows that performance of such control schemes can be degraded significantly when fin actuators have certain physical constraints such as slew rate, voltage or current limit, uncertainty of actuator dynamics, and so on, and propose a new control scheme which alleviates such problems. This scheme can be widely applied to various fin actuation systems. But in this paper we take, for convenience, tail-fin controlled cruciform missile, and show that with a proposed control scheme we can get better performance than the existing scheme.

An optimal conversion logic between four fin deflection angles and three control deflection angles of aileron, elevator and rudder is presented in section 2. Section 3 introduces a new control structure of fin actuators which have severe non-linearities such as voltage saturation and limitation of angular rate. In order to investigate the performance of new fin-control structure, a simple example for a STT missile which has a typical electromechanical actuator model with voltage saturation is dealt with in section 4. Finally, we give concluding remarks on the new structure of actuation system and further studies are descrived in section 5.

2. CONVERSION LOGIC

In this section, we consider the conversion logic between four fin deflection angles and three control deflection angles of aileron, elevator and rudder. Cruciform tail fins of STT missiles with a rear view are depicted in Fig. 1. Here, δ_1, δ_2, δ_3 and δ_4 denote fin deflection angles.

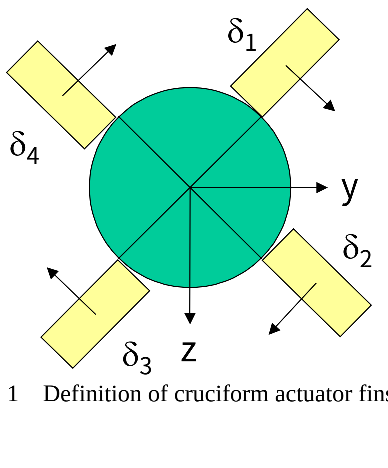

Fig. 1 Definition of cruciform actuator fins

As shown in the Fig. 1, positive rolling moment is generated by positive $\delta_1, \delta_2, \delta_3$, and δ_4. Furthermore, positive pitching moment is generated by positive δ_1, δ_2 and negative δ_3, δ_4, and positive yawing moment is generated by positive δ_2, δ_3 and negative δ_1, δ_4. Thus roll control deflection angle δ_r, pitch control deflection angle δ_p and yaw control deflection angle δ_y can be expressed as eqns. (1)-(3). These equations will be called mixing logic.

$$\delta_r = \frac{1}{4}\left(\delta_1 + \delta_2 + \delta_3 + \delta_4\right) \quad (1)$$

$$\delta_p = \frac{1}{4}\left(\delta_1 + \delta_2 - \delta_3 - \delta_4\right) \quad (2)$$

$$\delta_y = \frac{1}{4}\left(-\delta_1 + \delta_2 + \delta_3 - \delta_4\right) \quad (3)$$

Control deflection angle commands can also be written in a form similar to the above mixing logic. Let us introduce a new control deflection angle δ_{x_c} which can be defined arbitrarily by control designer. Then we can get an eqn. (4).

$$\begin{bmatrix} \delta_{r_c} \\ \delta_{p_c} \\ \delta_{y_c} \\ \delta_{x_c} \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 \\ k_1 & k_2 & k_3 & k_4 \end{bmatrix}\begin{bmatrix} \delta_{1_c} \\ \delta_{2_c} \\ \delta_{3_c} \\ \delta_{4_c} \end{bmatrix} \quad (4)$$

Here, k_1, k_2, k_3 and k_4 are constant to be determined. Manipulating matrix inversion, we get the following equation of four fin deflection commands

$$\begin{bmatrix} \delta_{1_c} \\ \delta_{2_c} \\ \delta_{3_c} \\ \delta_{4_c} \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & -c_1 & d_1 \\ a_2 & b_2 & c_1 & -d_1 \\ a_1 & -b_2 & c_2 & d_1 \\ a_2 & -b_1 & -c_2 & -d_1 \end{bmatrix}\begin{bmatrix} \delta_{r_c} \\ \delta_{p_c} \\ \delta_{y_c} \\ \delta_{x_c} \end{bmatrix} \quad (5)$$

where,

$$\Delta = k_1 - k_2 + k_3 - k_4$$

$$a_1 = \frac{-2(k_2 + k_4)}{\Delta}, \quad a_2 = \frac{2(k_1 + k_3)}{\Delta}$$

$$b_1 = \frac{-2(k_2 - k_3)}{\Delta}, \quad b_2 = \frac{2(k_1 - k_4)}{\Delta}$$

$$c_1 = \frac{2(k_3 - k_4)}{\Delta}, \quad c_2 = \frac{2(k_1 - k_2)}{\Delta}$$

$$d_1 = \frac{4}{\Delta}$$

From eqn. (5), we see that conversion logic from the three control deflection commands to the four fin deflection commands is not unique, because δ_{x_c} is composed of arbitrary constant k_1, k_2, k_3 and k_4.

Now, let's try to get a unique conversion logic from the three control deflection commands to the four fin deflection commands by considering the following minimization problem:

$$\text{Min.} \quad J = \sum_{i=1}^{4}\left(\delta_{i_c}\right)^2 \quad (6)$$

If we can get a solution δ_{x_c} which minimizes the cost function, it will be an optimal conversion logic which makes the smallest fin deflection commands for given control deflection commands. Manipulating the following calculation,

$$\frac{dJ}{d\delta_{x_c}} = 0 \quad (7)$$

$$\frac{d^2 J}{d\delta_{x_c}^{\ 2}} > 0 \quad (8)$$

we get the solution given in eqn. (9).

$$\delta_{x_c} = \frac{1}{4}\begin{bmatrix} (k_1 + k_2 + k_3 + k_4)\delta_{r_c} + (k_1 + k_2 - k_3 - k_4)\delta_{p_c} \\ +(-k_1 + k_2 + k_3 - k_4)\delta_{y_c} \end{bmatrix} \quad (9)$$

Inserting eqn. (9) into eqn. (5), we obtain

$$\delta_{1_c} = \delta_{r_c} + \delta_{p_c} - \delta_{y_c} \quad (10)$$

$$\delta_{2_c} = \delta_{r_c} + \delta_{p_c} + \delta_{y_c} \quad (11)$$

$$\delta_{3_c} = \delta_{r_c} - \delta_{p_c} + \delta_{y_c} \quad (12)$$

$$\delta_{4_c} = \delta_{r_c} - \delta_{p_c} - \delta_{y_c} \quad (13)$$

This implies an optimal conversion logic from the three control deflection commands to the four fin deflection commands in a sense of the smallest fin deflection. Eqn. (10) will be called division logic.

3. A NEW STRUCTURE OF FIN ACTUATTION SYSTEM

We assume a STT(skid-to-turn) missile with four tail-fins driven by electromechanical actuators. As mentioned before, autopilots for the missiles generate three desired control deflection commands, i.e., roll control deflection angle δ_r, pitch control deflection angle δ_p and yaw control deflection angle δ_y. Autopilots are designed based on the assumption that fin actuators are linear systems, but real electromechanical actuators have non-linearities such as voltage limit in electrical part and limitation of angular rate in mechanical part. Degradation of actuator performance due to such non-linearities have been an important factor adversely affecting the stability and performance of missile autopilot. In particular, even if just one of the 4 fin actuators is saturated by large voltage or large angular rate, the saturation can bring forth bad control performances of all control deflection angles, δ_r, δ_p and δ_y because one fin deflection is connected to all control deflection angles via conversion logic.

Now, we present a new control structure of fin actuators which have severe non-linearities such as voltage saturation and limitation of angular rate. In fig. 2, a block diagram of existing fin- actuation system for STT missiles is shown. Here, a fin-actuator and its controller are denoted by ACT and CON, and the division logic and mixing logic are expressed as DIV and MIX, respectively. Each fin controller produces a voltage command V_c using fin command and feedback variables such as angle, angular rate, etc. As shown in fig. 2, existing actuation system is simply composed of four fin-actuators with four corresponding controllers which control $\delta_1, \delta_2, \delta_3$ and δ_4. If one fin-actuator is saturated, it affects all control deflections which results in very slow response to all autopilots.

Fig. 3 shows a new structure of fin actuation system for STT missiles. In this structure there are three controllers corresponding to autopilot commands, respectively, instead of four fin controllers. These 3 controllers are designed so as to control analytic inputs, i.e., aileron δ_r, elevator δ_p and rudder δ_y directly. These variables are calculated in linear combination of fin deflections (see eqn. (10)). The performance of the new structure is exactly same as the existing one when 4 fin actuators and controllers have same dynamics and all linear, but the new structure will give better performance than the existing one when afore-mentioned non-linearities exist. Such an expectation comes from the fact that roll, pitch and yaw deflection angles are directly feedback.

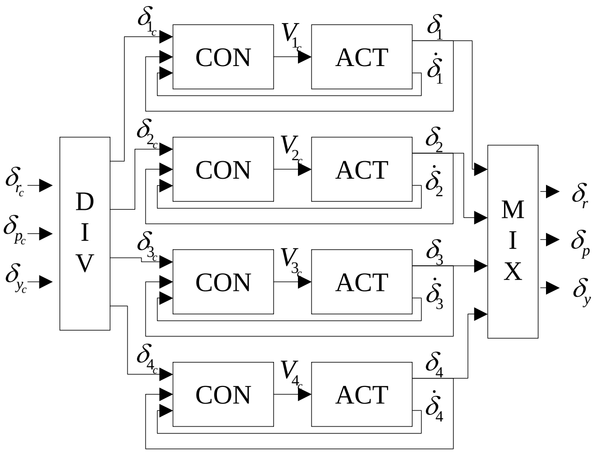

Fig. 2 Block diagram of existent actuating system

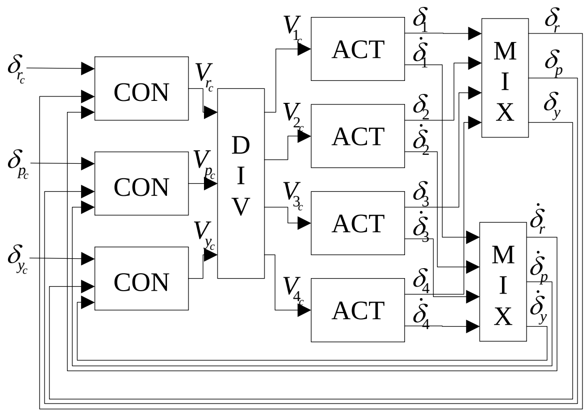

Fig. 3 Block diagram of proposed actuating system

4. EXAMPLE

In order to investigate the performance of new fin-control structure, a typical electromechanical actuator model is taken as fig. 4. For its control, a classical PD controller as in fig.5 is used. In fig. 4, we can see that there is a saturation block implying a voltage limiter.

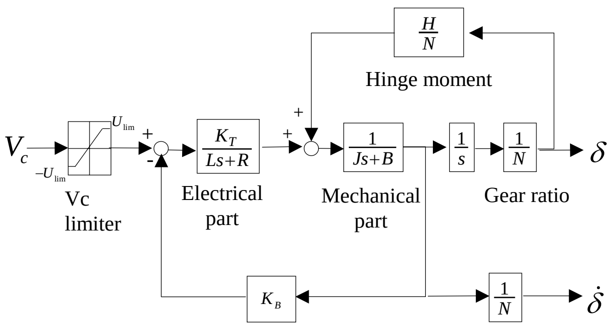

Fig. 4 Block diagram of electromechanical actuator

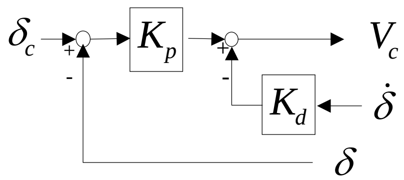

Fig. 5 Block diagram of simple controller

The numerical values of parameters in fig. 4 - 5 are given in table 1.

Table 1. Numerical Values

Parameters	Values	Parameters	Values
K_T	0.303125	K_B	5.7333e-4
L	0.35e-3	H	0
R	0.933	K_P	6
J	8.5354e-7	K_d	0.02
B	2.0835e-6	$U_{\lim}$	28
N	274		

Figs. 6-9 show aileron responses when all aileron, elevator, rudder command are applied to the actuation system by 1deg, 5deg, 10deg, 20deg, respectively. Here, only aileron responses are shown because responses of elevator and rudder are not so much affected by aileron response. In these figures, NEW implies simulation results from the new structure of actuation system given as fig. 3, and OLD implies the results from the existing one given as fig. 2. Ref. implies the results obtained when only aileron command is applied without elevator and rudder commands.

According to fig. 6, all responses coincide with each other when 1 deg. command is applied. In other cases as shown in figs. 7-9, the performance of reference is better than those of the new structure and the existing one, but it is notable that the performance of the new structure is superior than that of the existing one.

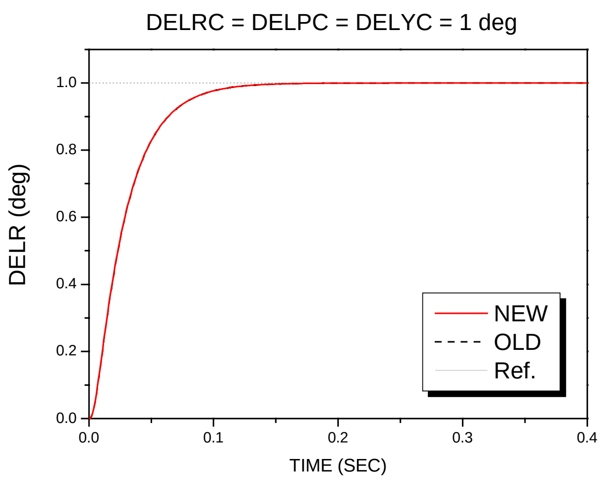

Fig. 6 Comparison of aileron response ($\delta_{r_c} = \delta_{p_c} = \delta_{y_c} = 1^\circ$)

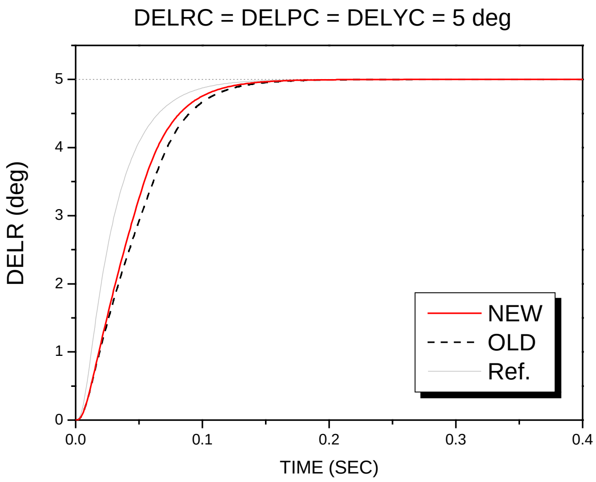

Fig. 7 Comparison of aileron response ($\delta_{r_c} = \delta_{p_c} = \delta_{y_c} = 5^\circ$)

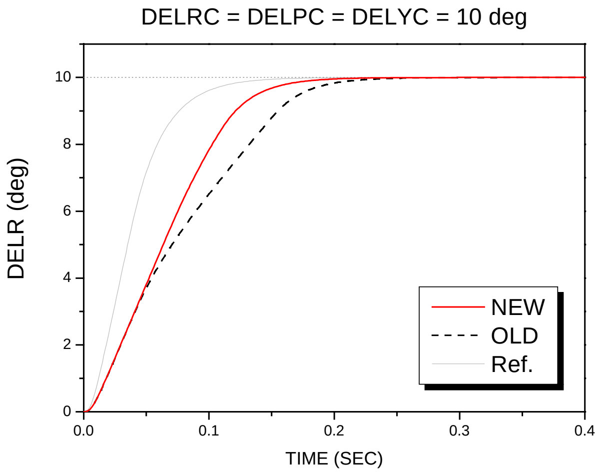

Fig. 8 Comparison of aileron response ($\delta_{r_c} = \delta_{p_c} = \delta_{y_c} = 10^\circ$)

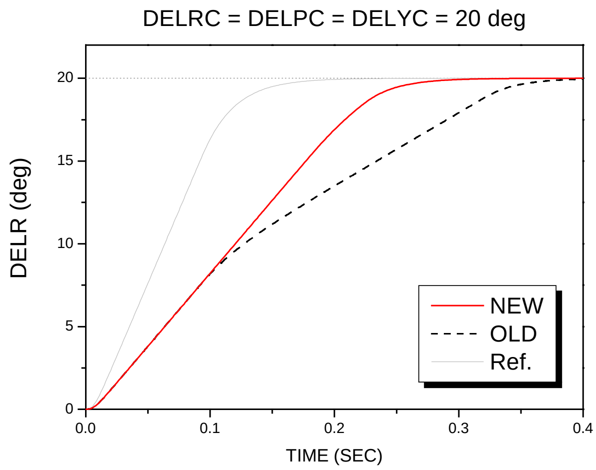

Fig. 9 Comparison of aileron response ($\delta_{r_c} = \delta_{p_c} = \delta_{y_c} = 20^\circ$)

Fig. 10 shows the responses when 5deg, 20deg and 10deg, are applied as aileron, elevator and rudder commands, respectively. Similar to the previous case, we can see that the performance of the new structure is superior to that of the existing one. Now, assume that certain disturbances exist probably caused by body bending modes or flutter of the actuation system. Then, we obtain the results given as fig. 11. In this simulation, disturbances were assumed to be a sine function with magnitude 1 deg. and frequency 20Hz applied to all fin angle measurements so that oscillation occurs in the pitch channel only.

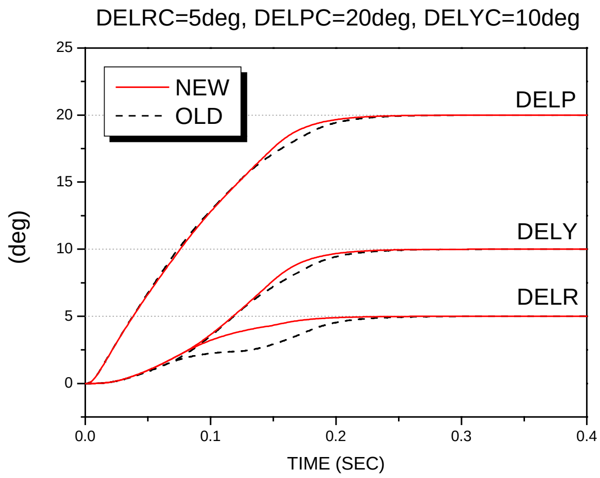

Fig. 10 Comparison of aileron, elevator and rudder response ($\delta_{r_c} = 5^\circ$, $\delta_{p_c} = 20^\circ$, $\delta_{y_c} = 10^\circ$)

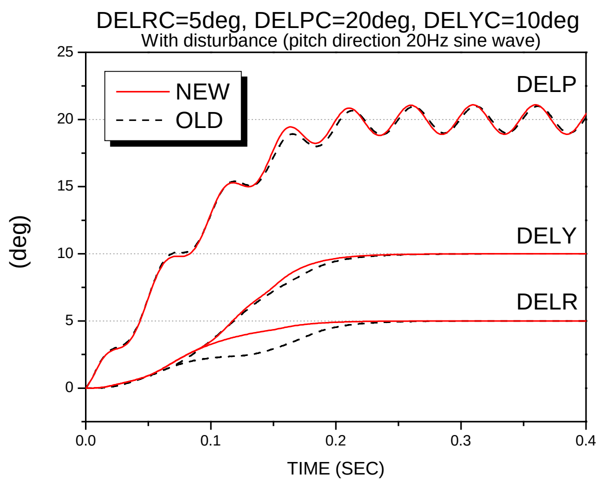

Fig. 11 Comparison of aileron, elevator and rudder response in case of considering additional disturbance ($\delta_{r_c} = 5^\circ$, $\delta_{p_c} = 20^\circ$, $\delta_{y_c} = 10^\circ$)

5. CONCLUSION

So far, for the typical tail-fin controlled cruciform missiles we showed that performance of the existing fin-actuation system can be degraded significantly when fin actuators have certain physical constraints such as slew rate, voltage or current limit, uncertainty of actuator dynamics, and so on. And, a new control scheme was proposed with which such problems can be alleviated. Finally, via computer simulations, it was shown that the proposed control scheme gives better performance than the existing scheme when certain non-linearities exist in actuator dynamics.

Certain issues were not covered in this paper, for example, how to utilize an additional analytic control fin δ_x in other purpose such as alleviation of body coupling or fin blanket effect, and how to suitably limit the fin deflection angle commands in advance so that they are not mechanically saturated in any cases, and so on. We leave them to further study.

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