Optimal Location and Size of Canards for Aeroelastic Actuation in Aerospace Vehicles

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The present study investigates the problem of locating and resizing canard control surfaces in order to achieve a desired trim flight control force. The problem of a generic flexible aerospace vehicle having canard as the main flight control surface is formulated and a simplified analytical model is developed which demonstrates the feasibility of determining the geometric configuration and location of the canard that recovers the desired control force by relocating and resizing the existing canard. Next, the above concept is extended to a practical aerospace vehicle configuration using an in-house software tool for performing the static aeroelastic load analysis and these results are obtained for the supersonic flight regime, by also considering variation in the structural stiffness of the body of the aerospace vehicle. The results are obtained for a trim analysis, with inertia force corrections taken into account, and plots are generated for the required canard location as a function of the vehicle body stiffness factor, for two different values of the canard size and for a typical supersonic Mach number. Lastly, the effect of canard structural flexibility on the overall control derivative is investigated, through an equivalent lumped torsional stiffness approach. These results clearly show that it is possible to locate and resize the canard such that the desired control force is recovered, using the favourable aeroelastic effects of the body of the aerospace vehicle. These results are considered to be applicable both for the multidisciplinary design of aerospace vehicle as well as for on-board implementation as a part of the flight control algorithm.

I. Introduction

Aerospace vehicles require control surface actuation to achieve the desired trajectory related manoeuvres. The control forces and moments required for carrying out these manoeuvres are generated using the rigid body deployment of conventional control surfaces such as fins, elevators, canard and flaps. However, as modern aerospace vehicles are becoming more and more flexible, many of the conventional control actions are getting modulated by the aeroelastic efficiencies, which are not only significantly different from unity but also different in different flight regimes. It is well known that the aeroelastic effects associated with the vehicle body flexibility enhance the effectiveness of the control surfaces ahead of vehicle centre of gravity and reduce that of control surfaces behind the centre of gravity. Similarly, the aeroelastic effects of a control surface enhance the effectiveness of leading edge control flaps and reduce that of trailing edge control flaps. In general, the overall aeroelastic efficiency of a control surface, which is a part or whole of a lifting surface, will depend on its location with respect to the elastic axis of the control surface and the location of the control surface with respect to overall centre of gravity of the vehicle. The present study explores the possibility of arriving at a methodology for achieving a specified canard control force through an aeroelastic approach.

In recent times, a number of studies have proposed the use of structural flexibility for improving the maneuvering performance of different types of aerospace vehicles. One of the earlier studies is by Ehlers & Weisshar† who have looked at the concept of an adaptive lifting surface using static aeroelasticity. Khot et al² in 1996 have proposed a method based on a prescribed anti-symmetric twist and camber distribution for enhancing the rolling manoeuvre of a flexible wing, which is achieved through the definition of a ‘Fictitious’ Control surface for re-twisting the wing to its original shape. In this study, the authors have demonstrated that lost roll performance could be recovered using this technique.

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Recently, Sandeep et al\textsuperscript{3}, have mooted the concept of a conformal control surface to enhance roll rate for a morphing aircraft and to provide inputs for design of wings for such an application. Lee and Chopra\textsuperscript{4} and others\textsuperscript{5, 6} have used the concept of a smart actuation for enhancing/compensating the loss of performance in conventional control surfaces. It has been established that all control surfaces that are ahead of centre of gravity and elastic axis have an increased effectiveness due to favourable elastic bending of the body and therefore, are better options for providing actuation for trajectory related manoeuvres. In fact, a study by Dowell et al\textsuperscript{7} has used this beneficial location of leading edge control surfaces (which are located ahead of the elastic axis of the wing structure) to counteract the reversal of trailing edge control surfaces by having a combined deployment of both leading edge and trailing edge control surfaces. The above study has demonstrated that simple control algorithms used in situations as described above, can also minimize the actual control rotations. One of the attractive options of leading edge control surface is the canard that has found use in many aerospace vehicle applications for (i) providing better longitudinal stability\textsuperscript{8}, (ii) compensating for inadequacy of the horizontal tail to trim aircraft configurations using blown flaps as high lift devices\textsuperscript{9} and (iii) controlling the aerospace vehicle motion\textsuperscript{10}. However, it should be kept in mind that such control surfaces can lead to aeroelastic instabilities at higher dynamic pressures and therefore there is a need to understand the behaviour of canards as flight control surfaces, in greater detail. The present study investigates the usage of typical aerospace vehicle canard configurations, in conjunction with their least possible size and optimum location, for arriving at solutions that either prevent or minimize the loss of control force in the supersonic flight regime. A typical aerospace vehicle configuration is used to demonstrate the concept and also to arrive at generic trends that can be applied to a wide variety of aerospace vehicle configurations.

II. Problem Definition and Formulation

Figure 1 schematically shows the concept of trimmed flight of a typical aerospace vehicle, maneuvering in x-z plane such that F is the net control force provided by the canard.

![Figure 1. Schematic of a typical aerospace vehicle](image)

The dotted line in the above figure depicts the deformed centreline of the aerospace vehicle under the equilibrium of the aerodynamic, the elastic and the inertia forces acting on the aerospace vehicle, considering the free-free boundary condition, as encountered in flight. If $\theta_e$ is the equilibrium elastic slope at the canard location, it can be shown, in a conceptual sense, that the aeroelastic control force at the aerospace vehicle centre of gravity, in terms of the corresponding rigid value, is given by,

$$F_{ce} = F \left( \delta_c + \theta_e \right) / \delta_c$$  \hspace{1cm} (1)  

$$\theta_e = F x_c / \left( K_e - F x_c \right)$$ \hspace{1cm} (2)

Here, $\delta_c$ is the rigid deflection of the canard, F is the corresponding control force if the aerospace vehicle body is taken as rigid, $K_e$ represents an equivalent elastic stiffness of the aerospace vehicle body and $F_{ce}$ is the aeroelastic control force obtained from the canard. It can be seen that the denominator term in the expression for the elastic deflection $\theta_e$ reduces as dynamic pressure increases so that aeroelastic efficiency can be much larger than unity at higher dynamic pressures.
The above formulation is based on an equivalent representation of the basic aerodynamic and structural effects, in order to bring out the possibility of preventing loss of flight control force, due to unfavourable aeroelastic effects, under all flight conditions. Further, it is assumed that changes in trim forces are small enough to be ignored. In order to also explicitly include the influence of the size of the canard control surface, $S_c$, it is necessary to define the actual control surface lift force $F$, based on rigid assumption, as,

$$F = F_{cr}' \left( \frac{S_c}{S_o} \right)$$  \hspace{1cm} (3)

Where, $F_{cr}'$ is the rigid aerodynamic force magnitude, corresponding to the canard control surface of the surface area equal to the reference area, where $S_o$ is the reference area over which the lift coefficient derivative is defined. Substituting relations (2) and (3) into (1), we get an expression for the aeroelastic control force as,

$$F_{ce} = F_{cr}' \left[ 1 + \left\{ \frac{\overline{S_c} F_{cr}'}{K_e - \overline{S_c} F_{cr}'} \right\} / \Delta_c \right]$$  \hspace{1cm} (4)

The objective of present approach is to ensure that aeroelastic control force is equal to the control force demand from a specific manoeuvre and this can be interpreted as the multiplier of demanded control force being equal to unity. Imposition of this condition gives the following constraint relation.

$$\overline{S_c}^2 \overline{F_{cr}'} \overline{x_c} = (1 - \overline{S_c}) (1 - \overline{S_c} \overline{F_{cr}'} \overline{x_c}) \delta_c$$  \hspace{1cm} (5)

Here, $\overline{F_{cr}'}$ is the non-dimensional manoeuvre force demand and $\overline{x_c}$ is the non-dimensional canard location parameter. It is seen from equation (5) that the problem of finding a location and size of canard that prevents aeroelastic related loss of control force, is nonlinear in $\overline{S_c}$, $\overline{F_{cr}'}$ and $\delta_c$ inasmuch as that the size and location of the canard depends on the magnitude of desired control force and the corresponding rigid deployment of the canard. It is interesting to note that when body has infinite elastic stiffness (i.e. $\overline{F_{cr}'} = 0$), equation (5) reduces to the form $\overline{S_c} = 1$, which is the value of $\overline{S_c}$ for the rigid case and that there are no constraints on the location of the canard. Thus it is clear that presence of body flexibility provides a mechanism for coupling the size and location of canard, for achieving a desirable control force. The above constraint relation is shown in figures 2 as plots of $\overline{S_c}$ versus $\overline{x_c}$, for representative values of $\overline{F_{cr}'}$ and $\delta_c$.

Figure 2(a). Effect of small flexibility on desired canard areas and locations
Figure 2 (a) above shows the variation of canard area with canard location for a fairly rigid vehicle body and it is found that while there is only a marginal decrease in the canard area, there is a large change required in the canard location (away from the centre of gravity), to maintain the prescribed control force. Figure 2(b), given below shows a similar trend for slightly higher body flexibility. It is seen from both these plots that the variation is primarily linear while the effect of increasing the rigid control deployment $\delta_c$, is to increase the slope of the curve further.

![Graph showing effect of medium flexibility on desired canard areas and locations](image)

**Figure 2(b). Effect of medium flexibility on desired canard areas and locations**

Figure 2 (c) & (d) below show the effect of slightly and moderately higher body flexibilities, which make the variation of canard area with canard location, deviate from linear variation as seen earlier. In addition, there is also a higher sensitivity of canard area with respect to the canard location. Further, it is seen that a small change in canard location now requires a larger change in the canard surface area.

![Graph showing effect of higher flexibilities on desired canard areas and locations](image)

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III. Solution Methodology for a Practical Aerospace Vehicle

Formulation presented in previous section establishes the feasibility of achieving a desired flight control force by suitably re-sizing and re-locating the canard control surface. However, in practical aerospace vehicles, the body elasticity is non-uniformly distributed along its span. Further, it is necessary to represent the aerodynamic and inertia forces, realistically, so that correct deformations of the vehicle body axis are available for further processing. In the present study, a typical aerospace vehicle configuration, as shown in figures 3, is chosen.
In practical aerospace vehicles, while it is simple to change the position of the canard, by moving with the help of a linear motion actuator, the requirements on changing the canard area are more difficult to meet. One of the main constraints on changing canard size is the restriction that its aspect ratio should be maintained so that aerodynamic effects related to aspect ratio are not altered. One way to achieve such a change in canard surface area is to move the surface in and out of a cavity in the body, so that a smaller, or larger, part of the surface is exposed to the air stream. This can be practically implemented by using a curved rack inside the body, on which the canard can be mounted, so that when the canard is moved forward, it also moves inside, thereby reducing its exposed surface area in a predetermined fashion. The design of such a mechanism will be dictated by the requirements on the desired flight control force and the overall vehicle flexibility.

The following analysis, using in-house software FLEXMODL, is carried out on the typical vehicle configuration, described earlier. Firstly, the rigid aerodynamic analysis is performed for a supersonic Mach number of 1.4, for establishing the baseline control forces that are to be obtained in the flexible version of the same aerospace vehicle. This involves selecting a set of two canard areas and, for each of the selected areas, then selecting a fixed and predetermined number of locations of the canard, for which the trimmed static aeroelastic control force analysis is carried out using the above software tool. These results are plotted as a family of curves, for the reference stiffness of the aerospace vehicle body. Next, structural stiffness distribution, as shown in figure 3, is scaled down by factors 0.7 and 0.4, in order to simulate a more flexible aerospace vehicle, but having the same span wise distribution of the flexibility, and the above analyses are repeated. The normalized results in respect of the aeroelastic control force, as a function of canard location and body flexibility, are presented in figures 4 (a) & (b).

The results presented in figure 4 (a) are for the case when full canard area is used for control and in this case it can be seen that as against a rigid value of 1.292, the aeroelastic derivative is higher for all the cases and increases with decrease in the body stiffness. In addition, the aeroelastic control derivative increases with the shifting of the control surface towards the nose of the vehicle. This shows that it is possible to augment the control force from canard, through aeroelastic means by suitably locating it on the vehicle longitudinal axis, and obtain a better manoeuvre performance at the design stage itself. The results presented in figure 4 (b) are for a canard with 85% of the area of the original canard and it is seen that, as against the rigid control derivative of 0.873, shifting the canard closer to the nose even without changing the vehicle body flexibility, increases the control force by more than 5%. Significantly larger control force augmentations are feasible if the vehicle body structure is made more flexible at the design stage, using formal optimization tools.
It should be noted here, as shown in figures 4, that the aeroelastic benefit of the body bending flexibility does not increase monotonically as the canard is shifted closer to the nose of the vehicle and in fact it flattens beyond a specific location and even starts dropping after that. This can be attributed to the fact that in a free-structure, the elastic deformation, and hence the slope, is a result of the equilibrium between the aerodynamic and inertia forces which kind of saturates in the nose portion of the vehicle for a certain level of the lateral force.
In addition, it should be noted that in the present study the stiffness scale has been applied uniformly along the vehicle length. However, it may be more practical and beneficial to make only the nose portion of the vehicle, more flexible and derive the greater magnitudes of the aeroelastic benefits described in this investigation. Lastly, figure 5 below brings out the additional effect of the structural flexibility of the canard surface itself, on the overall control force generation capability, using both canard and vehicle body aeroelastic contributions.

![Figure 5: Aeroelastic normal force and moment derivatives versus canard stiffness](image)

In this case, the canard structural flexibility is lumped as an equivalent torsional stiffness at its centre of twist so that the elastic deformations of the canard result only in a change in its effective total angle of attack and no change in the canard camber, due to distributed elastic deformation, is taken into account. This is considered to be a justifiable assumption because in practical aerospace vehicles, the canards are short aspect ratio stiff structures so that their inplane bending, responsible for change in camber, is negligible. These results clearly bring out the fact that it is possible to design suitable canard stiffness distribution in order to achieve the desired control force. In this analysis it is assumed that the centre of pressure of canard is ahead of its centre of twist (or the elastic axis).

**IV. Conclusions**

The problem of recovering or enhancing the desired flight control force, using the body flexibility of a typical aerospace vehicle, through re-sizing and relocating the canard, is investigated. Firstly, a conceptual formulation is presented in which the effect of vehicle body bending flexibility is coupled with the size and the location of a canard control surface, in order to model the effective aeroelastic control force. A condition for recovering the desired rigid control force is imposed which results in a nonlinear algebraic equation relating the canard surface area and its location on the body. Non-dimensional results are obtained for the surface area factor as a function of the location factor, which clearly bring out the feasibility of the concept. Next, the problem of a practical aerospace vehicle operating in the supersonic regime is taken up and the results are obtained for the location and size of the canard, together with the vehicle flexibility as well as flexibility of the canard structure, that recovers the desired flight control force. The results presented in this paper validate the hypothesis that canards have greater potential as smart flight control surfaces, and also clearly bring out the possibility of achieving a desired control force using a canard of smaller size, by suitably locating it and taking advantage of the vehicle body and canard structure related aeroelasticity. It should however be kept in mind that canards work on the basic principle of positive aeroelastic feedback and, therefore, the issues related to static and dynamic stability must be addressed adequately. The present study clearly brings out the possibility of aeroelastically designing the canard, which has lesser weight and can perform the required manoeuvres.
References