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The Effect of Tail Fin Parameters on the Induced Roll of a Canard-Controlled Missile

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Canard-controlled missiles often have adverse rolling moment characteristics that are difficult to predict. Several parameters that affect these rolling moment properties are investigated. An effort has been made to use a semi-empirical aerodynamic prediction code to determine the effects of varying tail geometry on the rolling moment. A generic canard controlled missile based on the NASA Blair configuration was examined at subsonic and supersonic Mach numbers with varying angle of attack and canard deflection angle. The span and area of the tail fins were systematically varied to determine the effects of each parameter alone on the rolling moment of the configuration.

Nomenclature

Ac	=	Canard Area
AR	=	Aspect Ratio
At	=	Tail Area
bc	=	Canard Semi-span
bt	=	Tail Semi-span
C_{LL}	=	Rolling Moment Coefficient
CNF	=	Fin Normal Force Coefficient
C_R	=	Root Chord
C_T	=	Tip Chord
M	=	Mach Number
YCP	=	Spanwise Center of Pressure
α	=	Angle of Attack
δ	=	Deflection Angle
δ_r	=	Roll Command Deflection
δ_y	=	Yaw Command Deflection
φ	=	Roll Angle

I. Introduction

CANARDS are attractive devices for guided missile control. They allow for a compact size, a high degree of maneuverability and low hinge moments. However, the use of canards as control devices complicates the rolling moment characteristics. As canards are deflected in pitch, roll, and/or yaw, vortices emanating from the canards stream aft and interact with the tail section which typically induces an adverse rolling moment. The adverse rolling moment can result in a roll reversal if the induced roll from the tail fins exceeds the direct canard roll control. Oftentimes, a roll mechanism is used in a canard-controlled system to mitigate the adverse roll properties. This has been accomplished with free-spinning tail sections,[1,2] and in the case of the Sidewinder missile, with rollerons or

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gyroscopically driven tail fin flaps.[3] However, if mechanisms to minimize induced roll effects are not used, then the missile roll characteristics must be accurately determined.

Several parameters affect the induced roll of a canard-controlled missile. Previous efforts have focused on the effects of varying tail span on the missile roll properties[2,4,5]. However, other studies have shown that tail area also has an impact[5]. This study examines both of these effects as well as the effect of tail placement. In particular, the roll control authority and the roll induced by a yaw command at angle of attack are studied in this effort. This effort is based on the study presented by Blair[4]; however, the effects of span and area were isolated in the current work by holding all other variables constant where possible. The previous efforts referenced did not make attempts to isolate any variables. This paper expands upon previous effort and provides a more complete evaluation of the tail parameters due to the isolation of specific variables.

II. Canard Controlled Vortex Interactions

Much of the complexity surrounding canard controlled missiles is attributable to the interaction of the canard vortices with the aft tail fins. These interactions can be both beneficial and detrimental to the control of the missile. One of the more favorable characteristics of a canard controlled system is the pitch coupling[2]. When the canards are deflected to produce a nose-up pitch command, the canard vortices induce a downwash on the tail fins which reduces their typical nose-down pitching moment at angle of attack. This is depicted in Figure 1 at a freestream angle of attack of zero where the tail fins loads are induced only by the canard shed vortices. This adds more control authority than what the canards alone produce. This vortex interaction is not studied in this effort as it does not affect the rolling moment of the airframe.

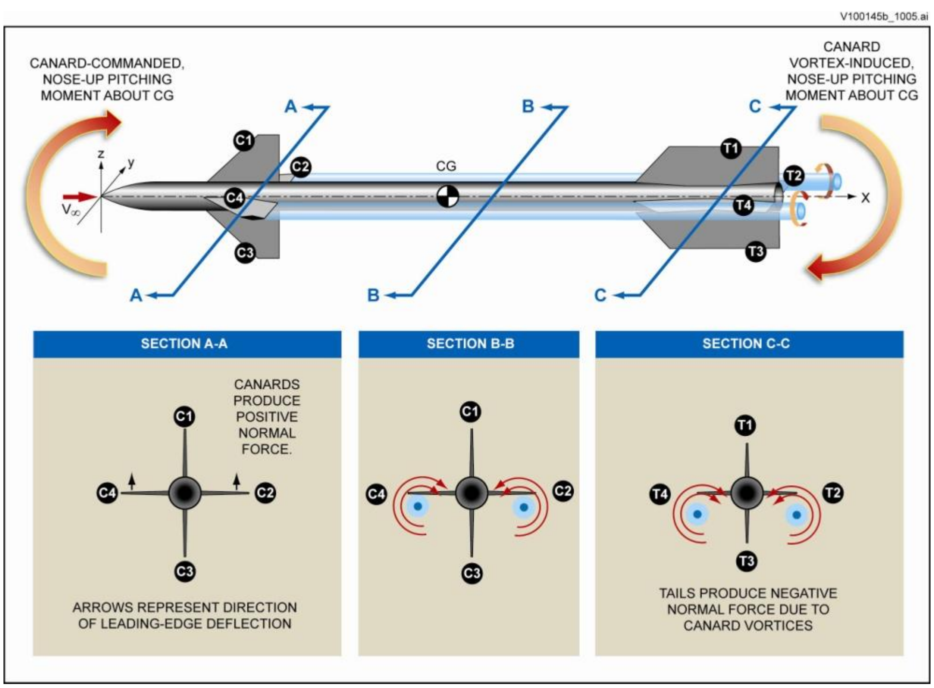


Figure 1. Canard Pitch Coupling

For other, non-pitch control deflections, the canard vortex interactions create adverse rolling moment effects. Two different types of roll interactions are possible and presented in this paper. The first deals with the roll control authority, or the ability of the canards to control the missile in roll. For this type of roll, the canards are deflected to generate a rolling moment. The canard vortices stream aft and influence the tail fins. These vortices induce a flowfield which generates a *negative* rolling moment on the tail fins, thereby reducing the effectiveness of canards to provide roll control. If a large enough rolling moment is generated by the tails, it is possible to negate or even reverse the rolling moment generated by the canards. In such cases, all effective roll control authority is lost. Figure 2 provides a graphical explanation of this process.

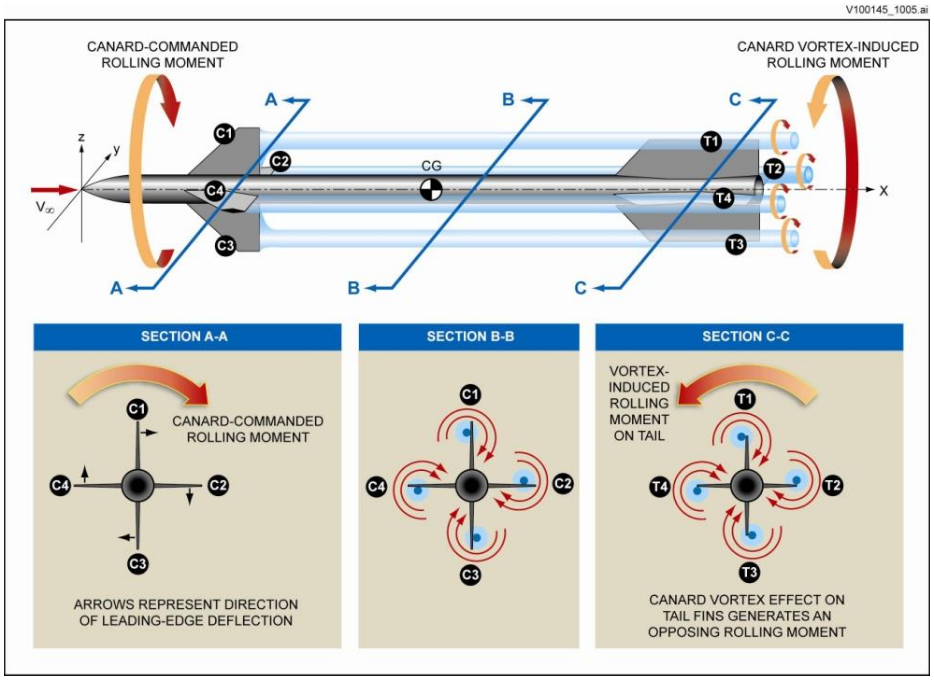


Figure 2. Canard Roll Coupling

The second type of rolling moment studied in this effort is yaw-control induced rolling moment. This type of roll occurs when canards are set in a yaw command at a non-zero angle of attack. Again, the canard vortices stream aft interacting with the tail surfaces. In turn, a rolling moment is generated, as shown in Figure 3. The rolling moment was not commanded by the canards and may cause a significant spin in the airframe. The magnitude of this induced rolling moment is also dictated by the size of the tails fins, and the ability to mitigate it is determined by how well the missile retains direct canard roll control authority with the presence of the tails.

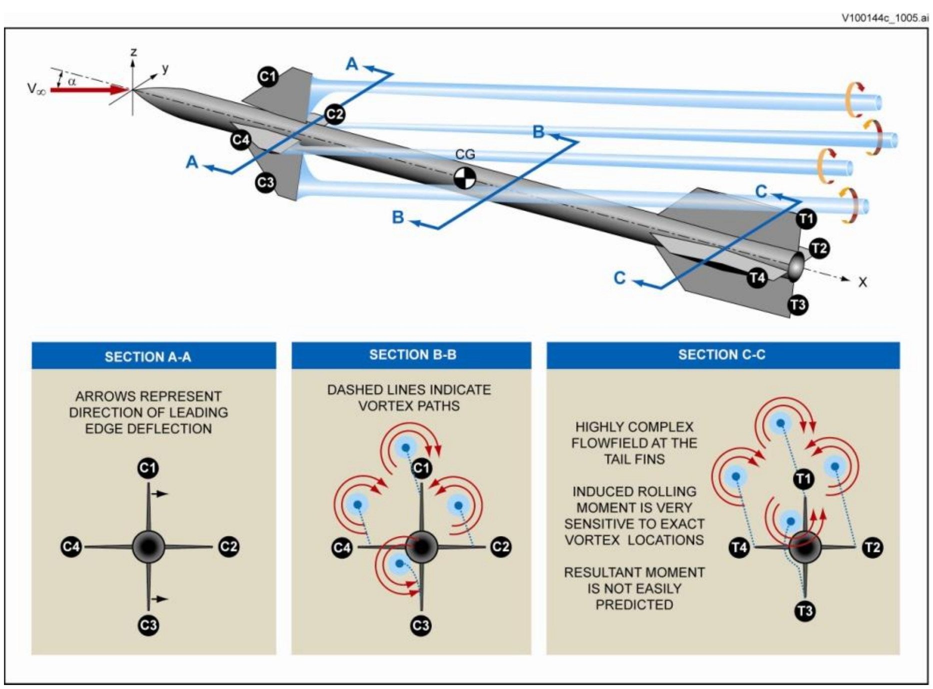


Figure 3. Canard Yaw Induced Roll

The roll control authority and induced rolling moment are both affected by vortex interactions between the canards and tails. However, they do not represent the only types of rolling moment or vortex interactions that can occur for a canard controlled missile. For this study, only results for a zero degree roll angle are presented. Asymmetric orientations will induce a rolling moment separate from those induced by canard deflections. Additionally, body shed vortices will impact the roll properties of the airframe; particularly at high angles of attack. Only results for a zero-degree roll angle are evaluated in this effort.

It should be stressed that the vorticity and its effects are complex; especially, as related to affecting overall rolling moment. The overall rolling moment is the summation of the rolling moments produced by eight individual fins for a canard-body-tail configuration. These individual fin rolling moments depend on the fin force produced and its spanwise center of pressure. At zero angle of attack the induced flow field is from the canard vorticity only and all four tail fins experience an induced roll in the same direction, opposite to the commanded canard roll. With increasing angle of attack the flowfield becomes more complex. The horizontal canards experience an angle of attack effect, including body upwash effects, combined with their command deflection settings. The vertical canard fins have their direct control effect as well as loading due to fin-on-fin interference, etc. At angle of attack, the resulting induced flow field at the tails is stronger than the $\alpha = 0°$ case because the canard vortices are stronger. The horizontal tail fins are at angle of attack and experience body upwash effects, and all four tail fins experience the canard induced flow and fin-on-fin interference loadings. The tail rolling moment is then the sum of the loadings from the four fins which can involve large terms which often nearly cancel one another. As a result of these many complex factors, rolling moments can be difficult to predict. Figure 4 depicts tail section individual fin forces as a function of AOA for Mach 0.8, bt/bc = 1.0, and a canard roll command. This graph illustrates the complexity of the rolling moment computation. Fin 21 and Fin 23 are the upper and lower vertical tail fins, respectively. The large variations in the spanwise centers of pressures are associated with the vortex from the lower vertical canard fin passing along the edge of the vertical tail fins.

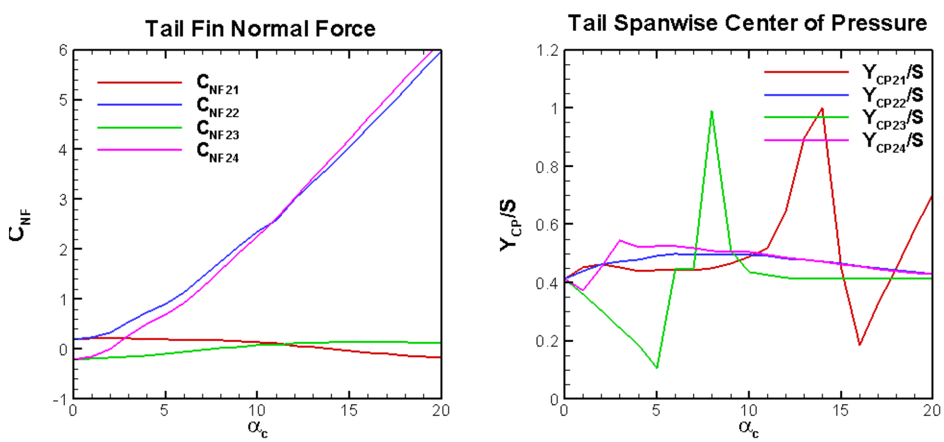


Figure 4. Tail Fin Normal Force and Spanwise Center of Pressure

III. Analysis Procedure

A. Geometric Definition

All of the configurations considered in this study were based on the Blair sidewinder configuration discussed in Reference 4. That study varied the tail span and looked at the effects the tail to canard span ratio, defined as bt/bc, had on the induced rolling moment. Variations in area, aspect ratio, and/or taper ratio were not considered in the Blair study. The canards and body were identical for every configuration and the tails were altered for the geometric variations.

The referenced body is 24 calibers (42.28 inches) in length and has a 2.25 caliber tangent ogive nose. The canard leading edges are located 6.22 inches aft of the nose tip. They have a 4.379 inch root chord, a 1.314 inch tip chord, and a 2.847 inch exposed semi-span. All tail geometries have an unswept trailing edge which is located at the base of the body. Detailed tail geometries are discussed in subsequent sections as they are specific to the parameter that is being varied. Unless otherwise specified, all analyses are for fins in the "plus" configuration. Sign conventions for forces and moments are shown in Figure 5. The configuration shown in this figure represents one of the Blair configurations.

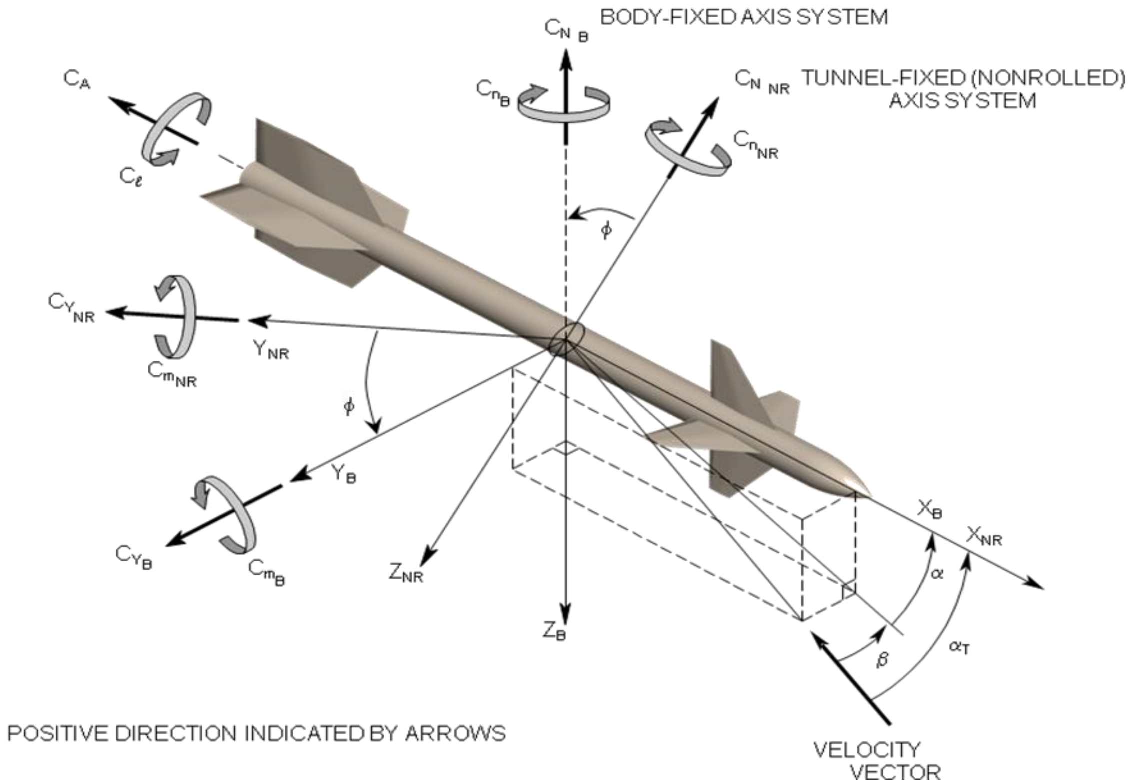
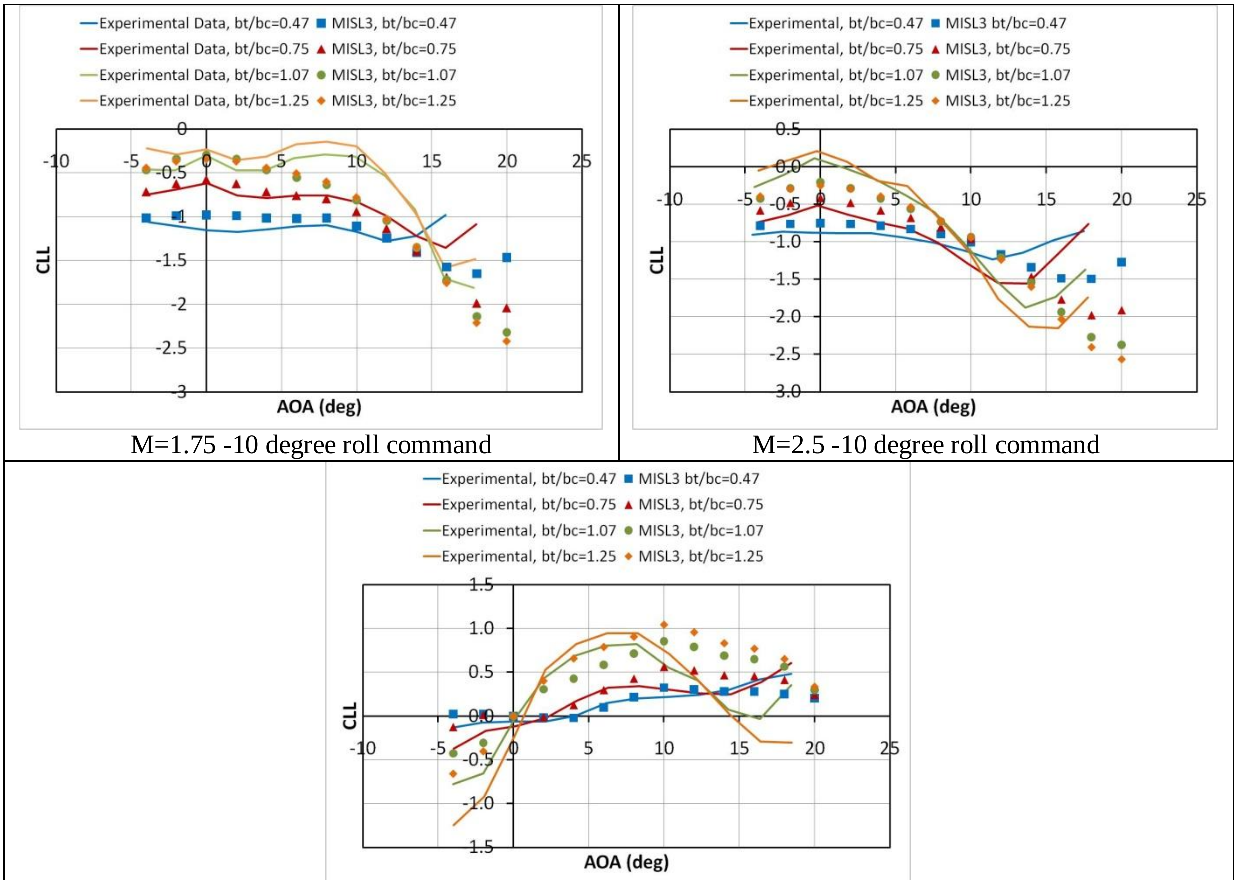


Figure 5. Sign Convention

B. Prediction Code

Due to time and cost constraints, experimental and full computational testing were not an option for this study. Instead, an acceptable engineering level code was needed. It was desired that the chosen code predict the proper trends with respect to varying tail span, area, etc.; however, it was not required that the code exactly predict the magnitude of the induced rolling moment. The overall trends were what were considered significant. Data from Blair, et al[4] was used as the baseline for determining a prediction code as it represented the most comprehensive data available. These data points were manually digitized from plotted data and thus have a rather large uncertainty. However, the trends were considered more important than the exact values.

The MISL3[6] semi-empirical aerodynamic prediction code provided the most consistent results compared to test data, and was thus used to determine the rolling moments for this study. This code is an engineering level prediction tool for the design of conventional missiles with cruciform fins and was chosen due to its extensive vortex modeling capabilities. Data acquired by Blair[1] was used to verify that the code could accurately predict the trends shown in that report. Figure 6 illustrates that MISL3 is indeed able to determine the appropriate trends. In addition, Lesieutre, et. al[6,7] presents additional verification of MISL3's ability to predict canard vortex-induced tail fin forces and moments. These references include cases for non-zero roll angles and several additional missile configurations[6,7].



M=1.75 -10 degree roll command

M=2.5 -10 degree roll command

M=2.5 -5 degree yaw command

Figure 6. MISL3 comparison with Blair data

C. Rolling Moment Analysis

To evaluate the effect of tail fin geometry on canard roll control authority, a normalized rolling moment, C_{LLnorm}, is defined as follows.

$$Cll_{norm} = \frac{Cll_{ind}}{Cll_{canard}}$$

Where C_{LLind} is the rolling moment of the complete body+canard+tail configuration with the same canard deflections, $C_{LLcanard}$ is the direct roll control authority of the canards. The C_{LLnorm} parameter directly indicates the percentage change in roll control authority due to the presence of the tails. If $C_{LLnorm} = 1.0$, the presence of the tail has not affected the canard roll control authority. If C_{LLnorm} falls in the range from 0.0 to 1.0, the tail fins have reduced the canard roll control. For example, $C_{LLnorm} = 0.5$ indicates that the roll control authority has been reduced by 50%. Negative values of C_{LLnorm} indicate a roll reversal, and values greater than 1.0 indicate "increased" effectiveness. Values greater than 1.0 can be seen at higher angles of attack and often involve body generated vorticity. For the controls engineer, these induced rolling moments present a challenge.

For the roll control effectiveness analysis in this study, all four canards are deflected five degrees to produce a positive (i.e. clockwise when viewed from rear) rolling moment. For the yaw induced roll analysis in this study, the actual rolling moments produced by the airframe are compared rather than a normalized value. No suitable normalizing term can be defined because the canards alone do not produce a rolling moment. For the yaw control induced rolling moments analyzed in this effort, the vertical canard fins are each deflected 10 degrees.

IV. Effect of Varying Tail Span

In order to isolate the effects of varying tail span, the area of the tail fins was held constant for all configurations under evaluation. A single tail fin area of 15.9 square inches was used, corresponding to the bt/bc=0.75 tail of the

Blair study[1]. For this study, the leading edge sweep angle was held constant and the root and tip chords were adjusted to maintain the appropriate area. A summary of the tail geometries evaluated is presented in Table 1 and Figure 7.

Table 1. Tail Geometry for Varying Tail Spans, Constant Area

Configuration	bt/bc	Tail Exposed Semi -Span (inches)	Leading Edge Sweep (degrees)	Root Chord (inches)	Tip Chord (inches)
T1	0.75	2.135	45.000	8.500	6.365
T2	0.90	2.565	45.000	7.470	4.905
T3	1.00	2.850	45.000	7.000	4.150
T4	1.10	3.135	45.000	6.630	3.495
T5	1.20	3.420	45.000	6.350	2.930
T6	1.30	3.705	45.000	6.140	2.435

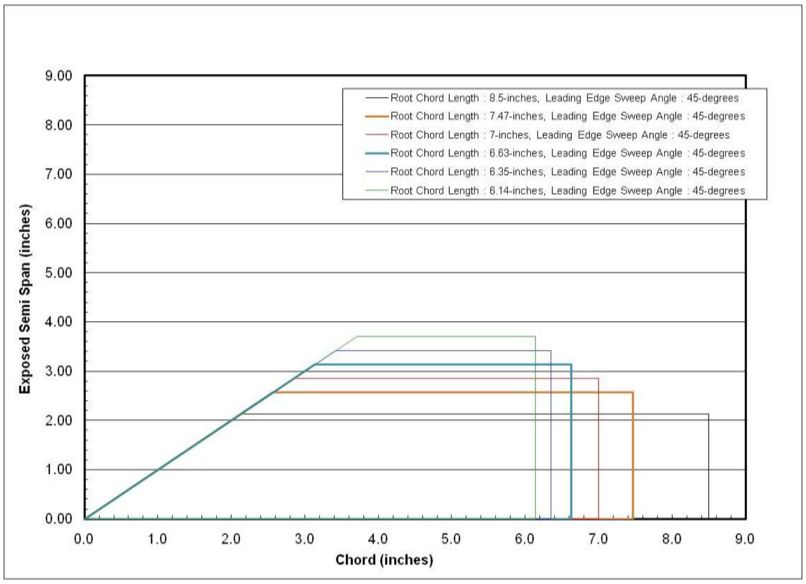


Figure 7. Tail Configurations for a Constant Area

A. Impact on Roll Control Authority

Figures 8 and 9 present the roll control authority results with varying tail span. Data are presented as a function of tail to canard span ratio, bt/bc, at varying Mach numbers and angles of attack. It is clear from these plots that adding the tail surfaces reduces the roll effectiveness of the canards since the normalized rolling moment is less than 1.0. The largest impact is seen at zero degrees angle of attack, as would be expected since the vortices directly impact the tail fins. At subsonic Mach numbers, a minimum of 30 percent of the roll authority that the canards are capable of generating is lost, while at higher Mach numbers, up to 75 percent is lost.

As angle of attack increases to six degrees, the impact of the tails is lessened with 20-40 percent of the roll authority lost at all Mach numbers. There also appears to be less variation with increasing tail span. These trends are expected, as angle of attack increases the vortices' influence on the tail fins is less and adverse effects are smaller. One notable feature that is evident in figure 9 is that at high angles of attack, normalized rolling moment is larger than 1.0. As illustrated in Figure 10, as angle of attack increases, the canard generated rolling moment is decreasing while the tail generated moment increases. This combination results in normalized rolling moment that is greater than 1.0.

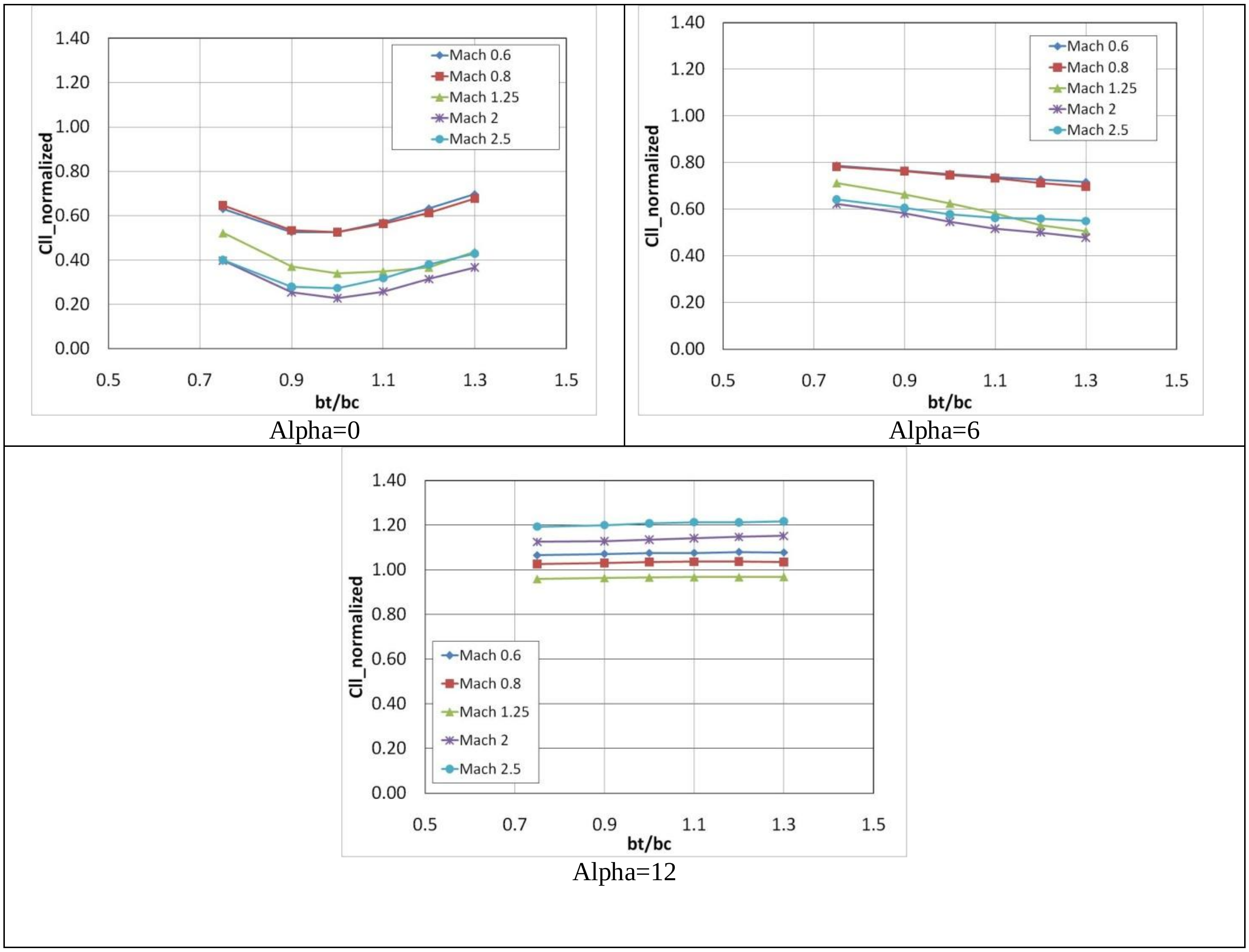


Figure 8. Normalized Roll for a Five Degree Roll Command (constant area)

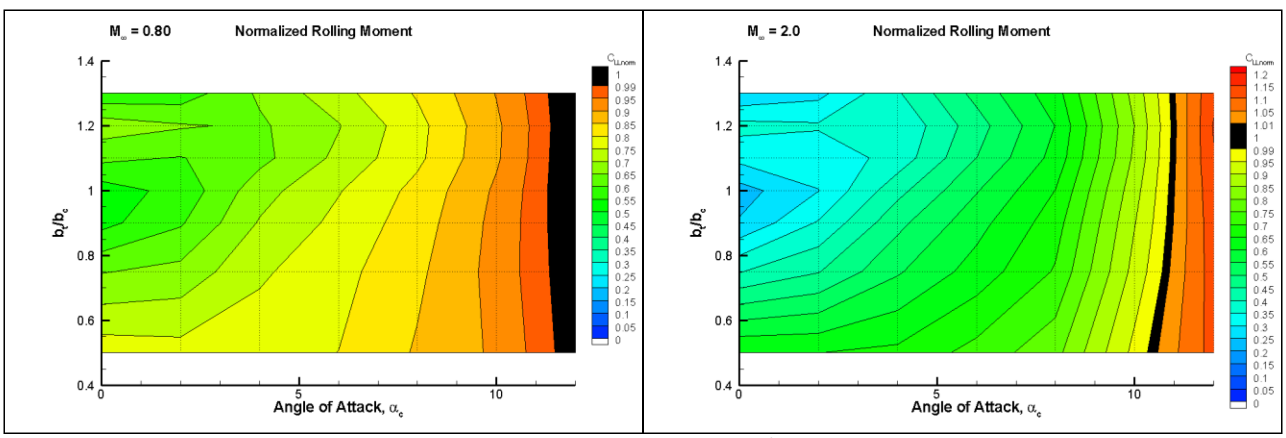


Figure 9. Normalized Roll for δ_r=5° (constant area)

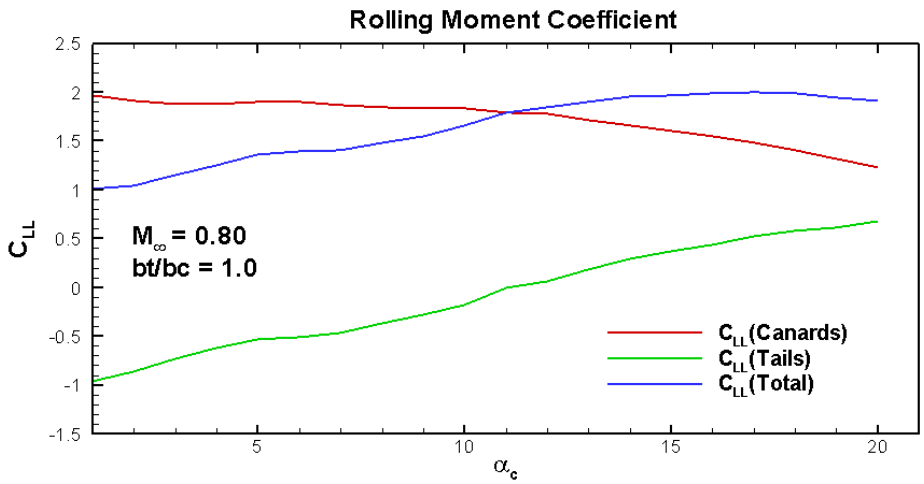


Figure 10. Component Rolling Moment Variation with Angle of Attack

Another method for illustrating why larger tail spans have a greater impact on the roll control authority is to examine the path of the vortices generated by the canards. Figure 11 shows the vortex paths and the crossflow velocity vectors in the vicinity of the tails. Radii are shown for varying tail spans. These plots illustrate the complexity involved in calculating the rolling moment on the tails due to the complex flowfield. As span increases, there is a larger tail region that is affected by the canard vortices. The resulting spanwise center of pressure is further outboard, creating a larger rolling moment.

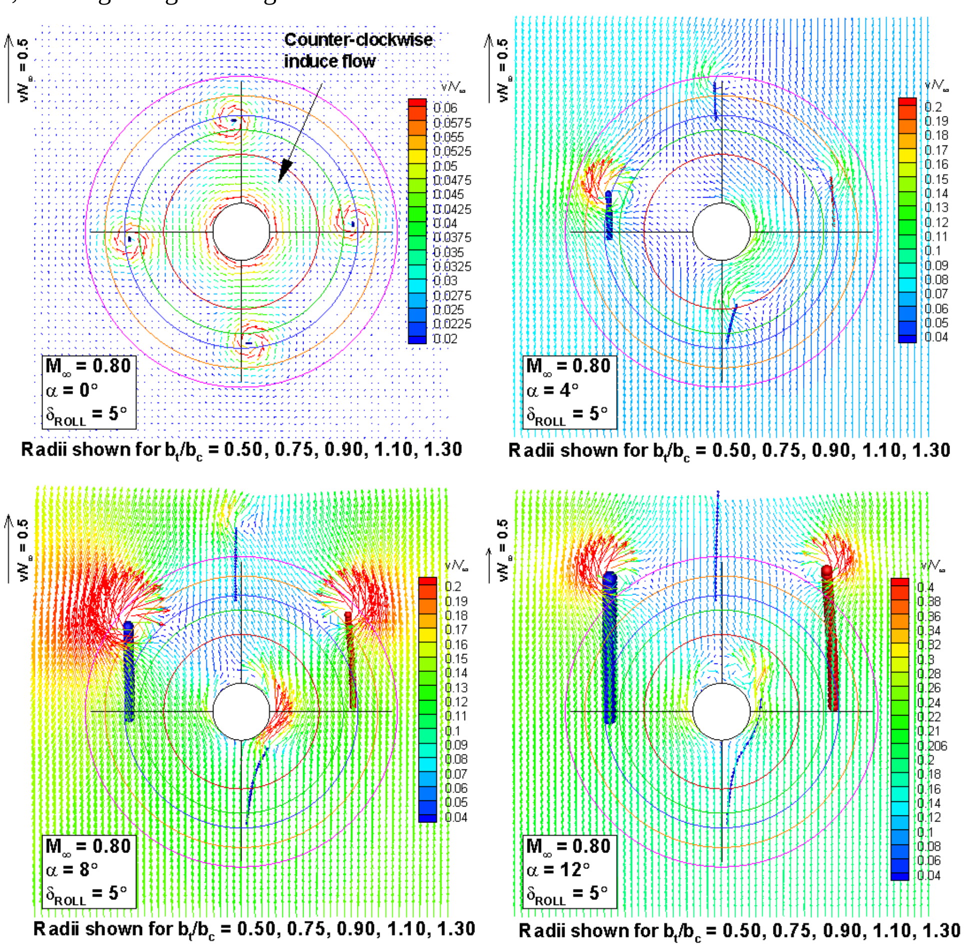


Figure 11. Roll Control Velocity Maps

B. Impact on Yaw Control Induced Roll

In general, the flowfield mechanisms discussed in the previous section are similar for the yaw-control induced rolling moment. The vertical canards are deflected 10 degrees and produce stronger vortices. The horizontal canard vortex strengths are reduced due to the lack of deflection, though they still generate vortices that increase strength with angle of attack due to both angle of attack and body upwash effects. These vortex effects produce increased rolling moments with increasing angles of attack. Figure 12 shows a velocity map of the yaw control configuration that illustrates the stronger vortices on the vertical fins when compared with the roll control configuration of Figure 11.

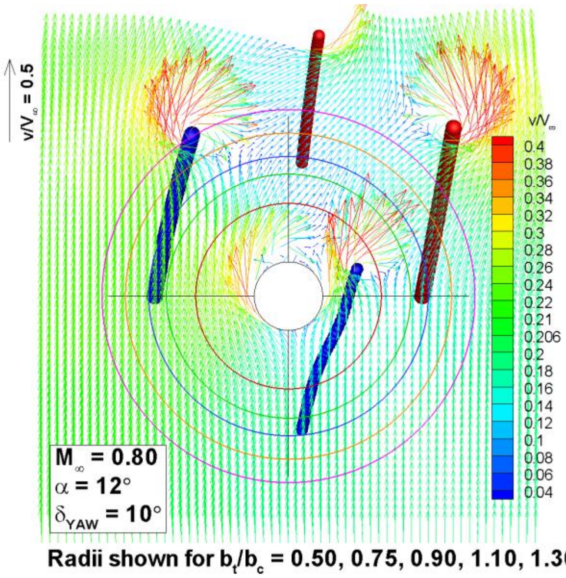
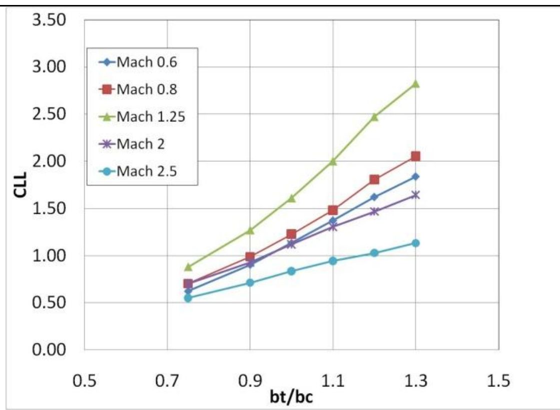


Figure 12. Yaw Control Velocity Maps

Figures 13 and 14 present the yaw command induced roll results with varying tail span. There is a large increase in the induced rolling moment as the tail span is increased. The largest induced rolling moments occur at Mach 1.25 and the smallest at Mach 2 and 2.5. At the highest Mach numbers, the increase in yaw control induced roll is less with increasing span ratio. At low angles of attack, there is very little rolling moment generated by the yaw command because the vortices impact the tails in a symmetric fashion and body-shed vortices are not a significant factor. As angle of attack increases, there is a significant increase in rolling moment as the flow becomes more asymmetric. Generally, the largest rolling moments appear around 10 degrees angle of attack. At these angles, the flowfield is asymmetric and complicated by the presence of the body-shed vortices.



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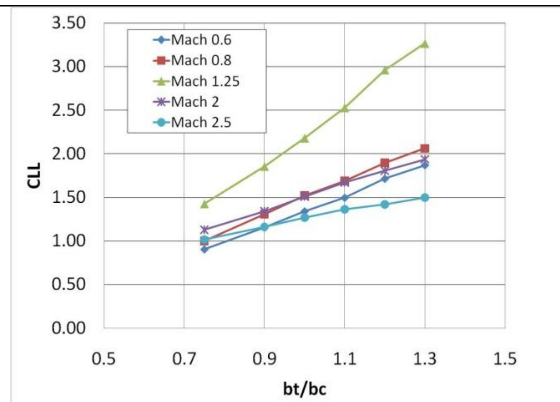

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Figure 13. Induced Rolling Moment for δ_y=10^o (constant area)

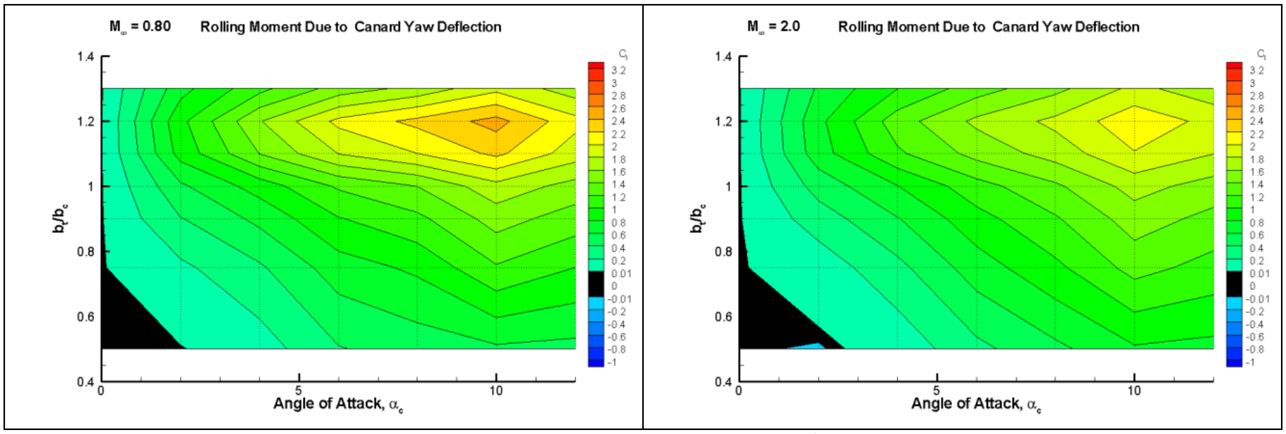


Figure 14. Induced Rolling Moment for δ_y=10^o (constant tail area)

V. Effect of Varying Tail Area

The previous section isolated the effect of tail span on the roll characteristics by holding the tail area constant. To analyze the effect of tail area on roll characteristics, three tail spans were chosen, as shown in Table 2. For each tail span, the aspect ratio and taper ratio were varied to change the area. The same values of aspect ratio and taper ratio were used for each span. This provides common parameters between the three tail spans for comparisons. A complete listing of the tail geometries used for this evaluation is shown in Table 2, and sketches of the tail fins are shown in Figure 15.

Table 2. Tail Geometry for Varying Tail Areas

Configuration	bt/bc	b/2 (in)	Λ (deg)	C_R (in)	C_T (in)	C_T/C_R	A (in^2)	AR	At/Ac
T1_A1	0.75	2.1375	0.000	4.9038	4.9038	1.000	10.48	0.872	1.293
T1_A2	0.75	2.1375	24.648	4.9038	3.9231	0.800	9.43	0.969	1.163
T1_A3	0.75	2.1375	45.000	4.9038	2.7663	0.564	8.20	1.115	1.011
T1_A4	0.75	2.1375	45.542	4.9038	2.9423	0.600	8.39	1.090	1.034
T1_A5	0.75	2.1375	54.003	4.9038	1.9615	0.400	7.34	1.245	0.905
T1_A6	0.75	2.1375	61.416	4.9038	0.9808	0.200	6.29	1.453	0.776
T2_A1	1.10	3.1350	0.000	7.1923	7.1923	1.000	22.55	0.872	2.781
T2_A2	1.10	3.1350	24.648	7.1923	5.7538	0.800	20.29	0.969	2.503
T2_A3	1.10	3.1350	45.000	7.1923	4.0573	0.564	17.63	1.115	2.175
T2_A4	1.10	3.1350	45.542	7.1923	4.3154	0.600	18.04	1.090	2.225
T2_A5	1.10	3.1350	54.003	7.1923	2.8769	0.400	15.78	1.245	1.947
T2_A6	1.10	3.1350	61.416	7.1923	1.4385	0.200	13.53	1.453	1.669
T3_A1	1.30	3.7050	0.000	8.5000	8.5000	1.000	31.49	0.872	3.884
T3_A2	1.30	3.7050	24.648	8.5000	6.8000	0.800	28.34	0.969	3.496
T3_A3	1.30	3.7050	45.000	8.5000	4.7950	0.564	24.63	1.115	3.038
T3_A4	1.30	3.7050	45.542	8.5000	5.1000	0.600	25.19	1.090	3.107
T3_A5	1.30	3.7050	54.003	8.5000	3.4000	0.400	22.04	1.245	2.719
T3_A6	1.30	3.7050	61.416	8.5000	1.7000	0.200	18.90	1.453	2.330

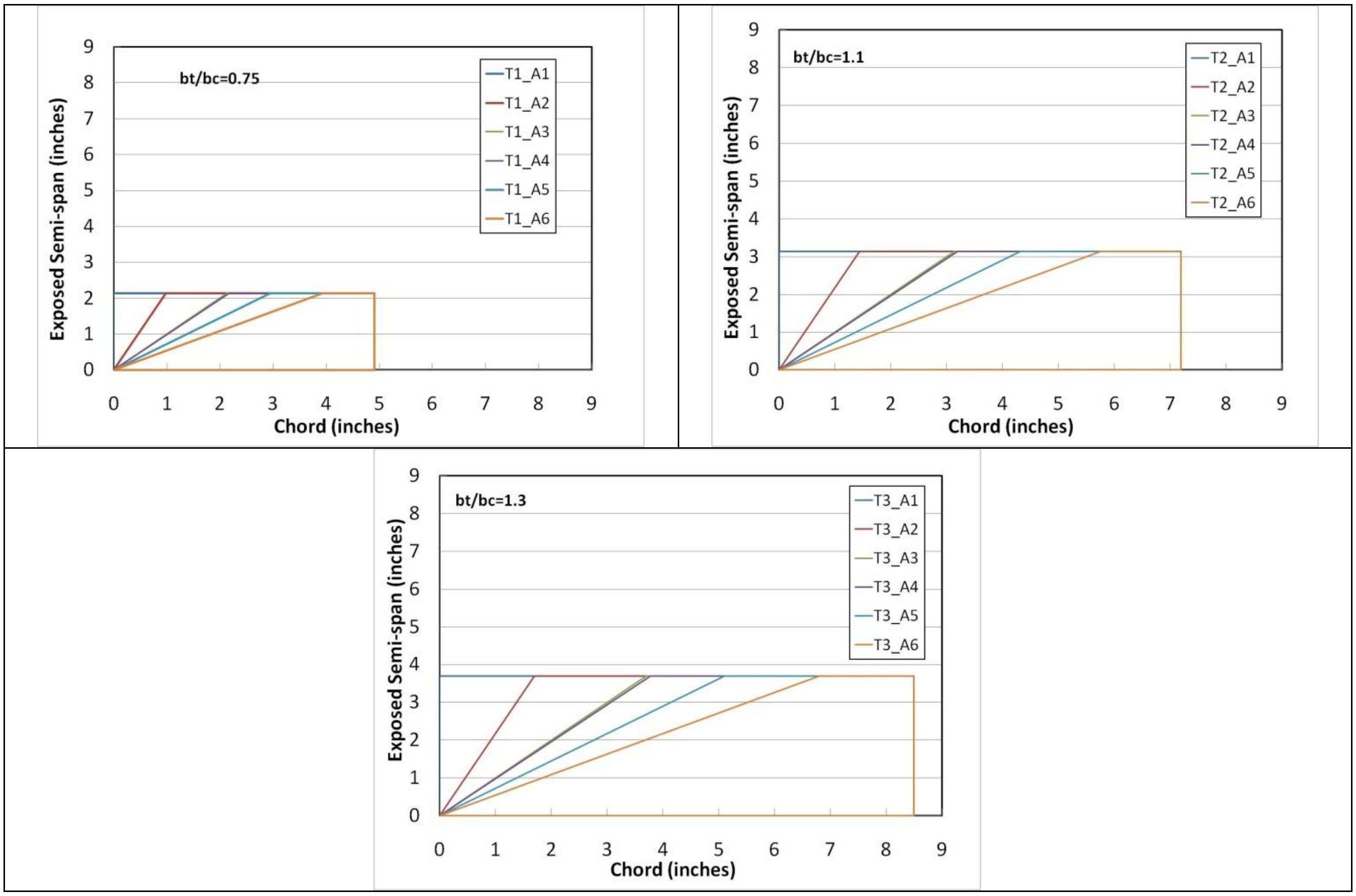


Figure 15. Tail Geometries for Varying Area

A. Impact on Roll Authority

Figures 16 and 17 present the roll authority results with varying tail aspect ratio or tail to canard area ratio. Figure 16 shows the results as a function of aspect ratio as these are the same for all tail spans. Figure 17 presents the results as functions of tail to canard area ratio and angle of attack in order to present a more complete overview of the results. The flowfield characteristics discussed with the varying tail spans are the same since the canard geometry has not changed. However, there are additional influences to the roll control authority due to the varied tail area. As previously noted, the largest reductions in roll control authority occur at low angles of attack. The contour plots presented in figure 16 confirm that there are significant similarities in trends at the selected tail spans. In particular, the areas chosen for the span ratios of 1.1 and 1.3 overlap and the normalized rolling moment presented is very similar in the region of overlap.

Figure 16 indicates that at subsonic Mach numbers, there is reduction in roll control authority of 25-45 percent with increased area (or decreased aspect ratio as shown in figure 14). This trend implies that the span ratio has more of an impact than the area at these Mach numbers where there was a reduced control authority of 30-50 percent. However, at supersonic Mach numbers, there is a 30-90 percent reduction with increased area at a given span ratio. Keeping in mind that the variation in aspect ratio is the same for all three spans presented, even though the area ratios vary, this indicates that aspect ratio may be the dominant factor at these Mach numbers.

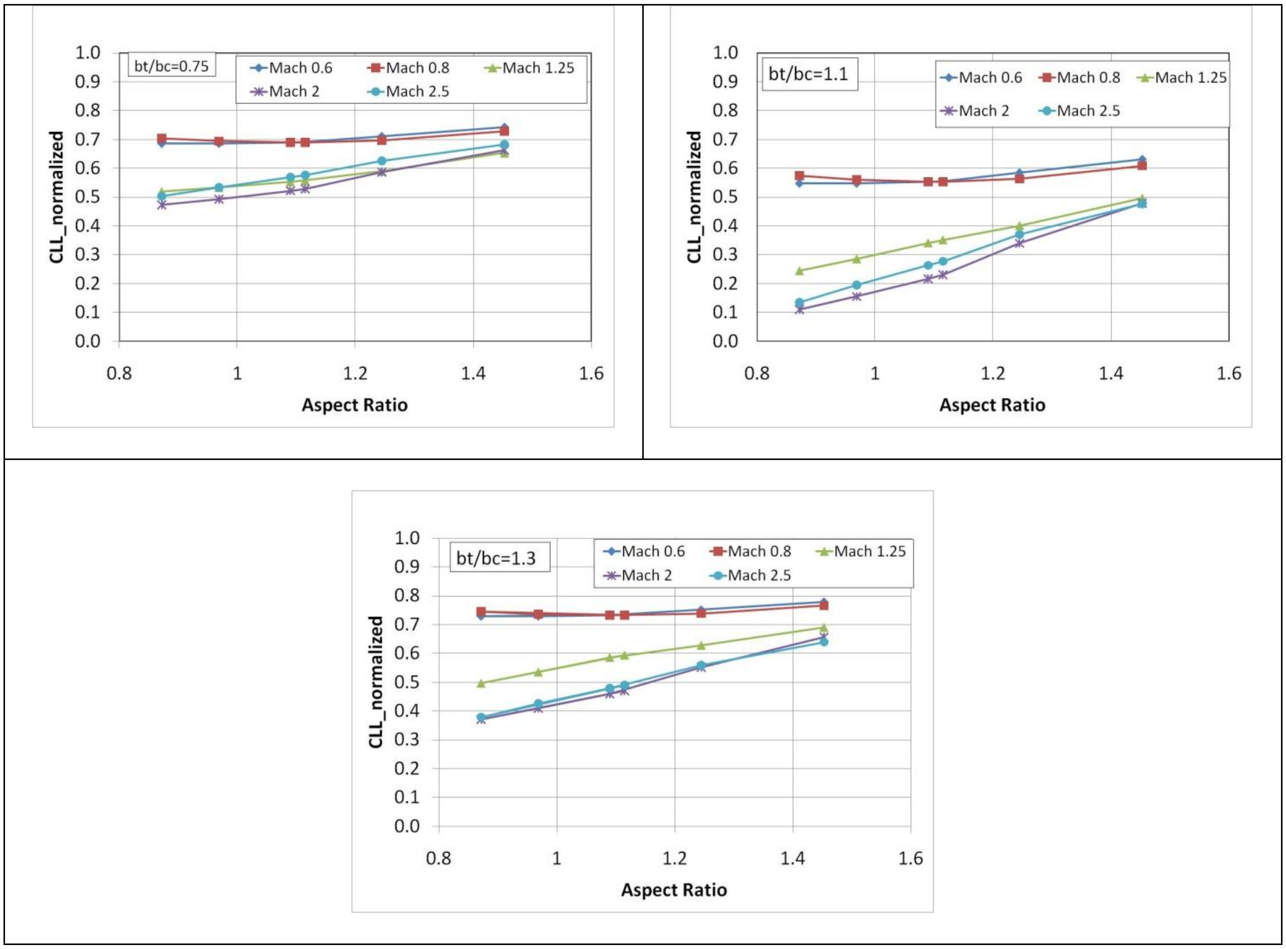


Figure 16. Normalized Roll for δ_r=5^o, α=0^o(Varying Tail Area)

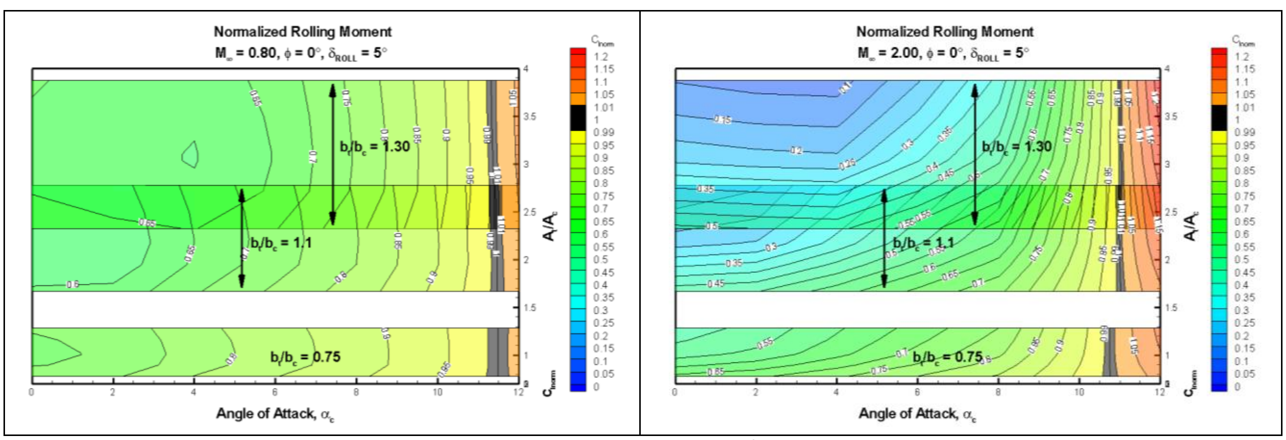


Figure 17. Normalized Roll for δ_r=5^o (Varying Tail Area)

B. Impact on Yaw Induced Roll

Figures 18 and 19 present the effects of yaw control induced rolling moments as a function of varied tail area. Again, the flowfield characteristics are the same as for the varied tail span analysis. As expected, higher span ratios produce higher induced rolling moments. At subsonic Mach numbers, there is little increase in induced rolling moment with increased area (decreased aspect ratio). This again indicates that span ratio is the dominant factor at subsonic speeds. However, there is slightly greater variation for supersonic Mach numbers. Across the aspect ratio range presented here, there is an approximate 40 percent rise in induced rolling moment at Mach 1.25 and a 70 percent increase at Mach 2.5. This is true regardless of the span ratio. Although significant, this much smaller than the doubling or tripling of the induced rolling moment that was seen with increasing tail span. However, the results do indicate that tail area must be considered when evaluating the roll characteristics.

Again examining the region of overlap between the span ratios of 1.1 and 1.3 in Figure 18, there is little difference in the results. For all three of the span ratios shown here, the peak rolling moment appears to occur near 10 degrees angle of attack regardless of the Mach number. At 10 degrees, the vortex from the lower vertical canard directly impacts the right horizontal tail fin; at 8 degrees the vortex passes below the fin while at 12 degrees the vortex passes above. Although the peak occurs near this angle, the value of the rolling moment is greatest at larger tail spans. Increased area does not appear to have as significant an effect as the span. For all of these configurations, the distance between the canards and the tails has been kept constant. Due to the importance of canard fin vortex locations on the induced rolling moment, the distance between canard trailing edge and the tail leading edge is expected to have a significant effect. This effect is evaluated in the following section.

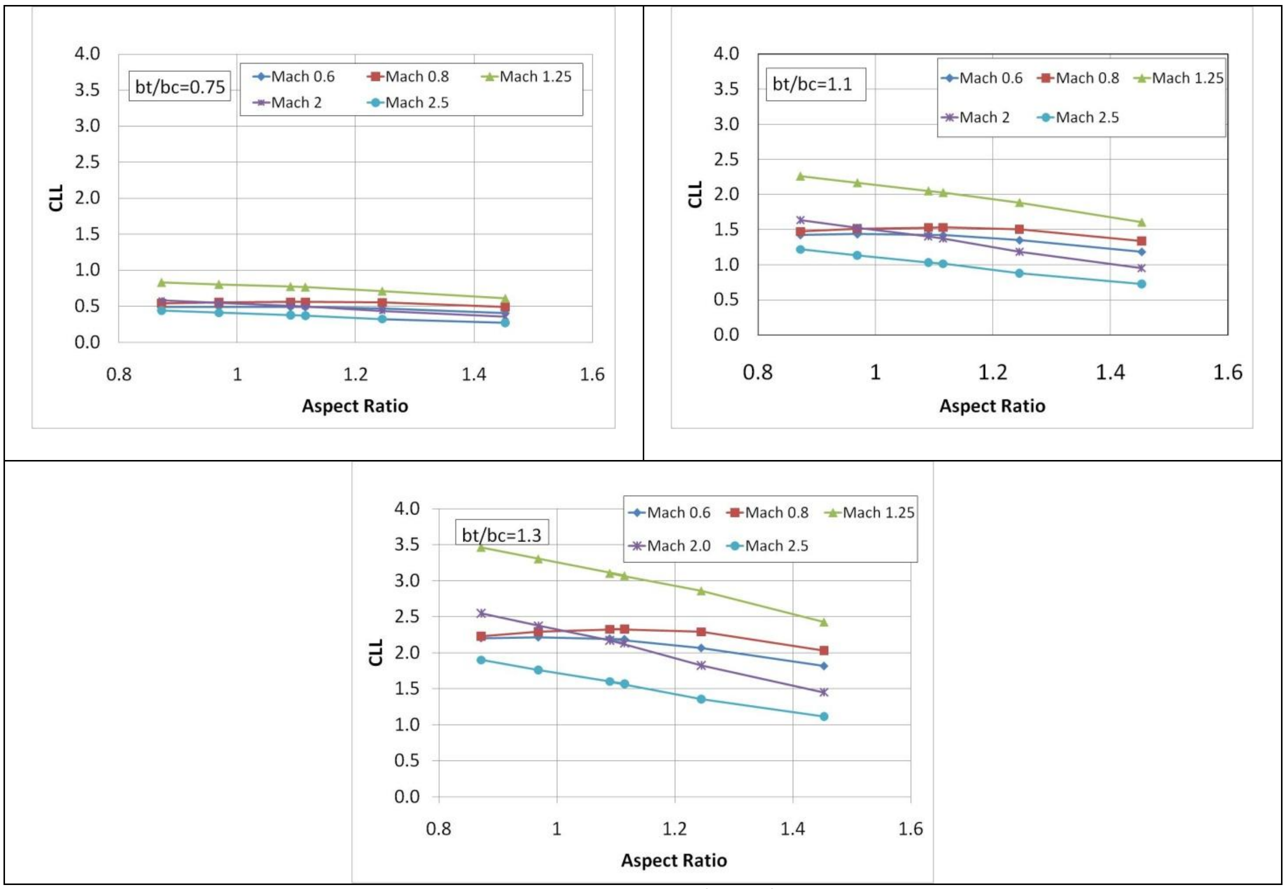


Figure 18. Rolling Moment δ_y=10^o, α=6^o (Varying Tail Area)

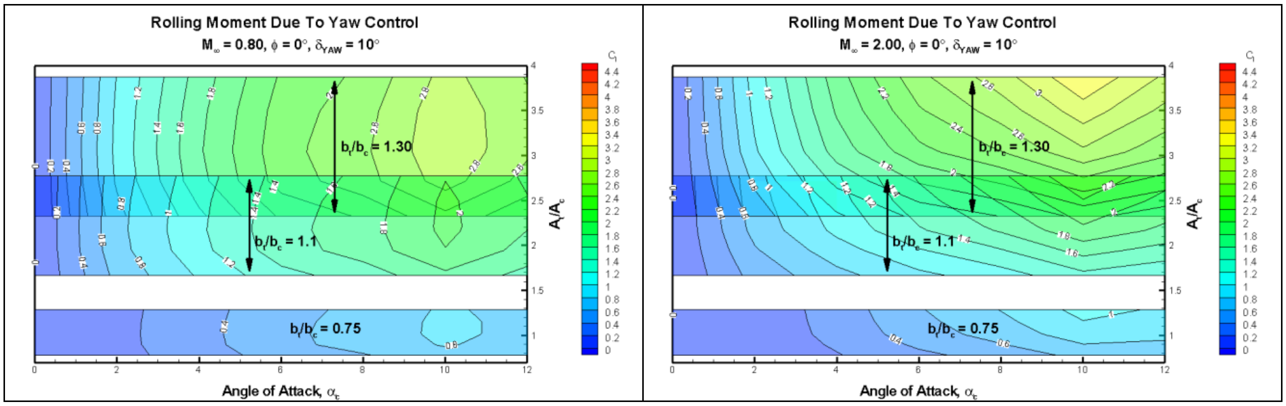


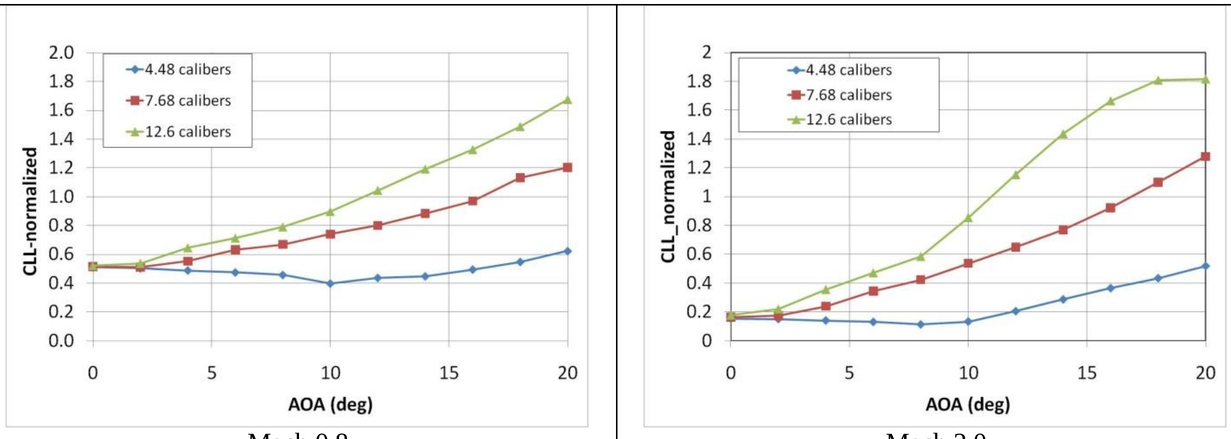
Figure 19. Rolling Moment for δ_y=10° (Varying Tail Area)

VI. Effect of Tail Leading Edge Location

A third factor that influences the roll properties of a canard controlled missile is the proximity of the tail to the canard. To evaluate this effect, the Blair configuration with bt/bc=1.07 was chosen as a baseline. This configuration was chosen because it places the tail well within the canard vortex wake without producing excessive adverse roll properties. The baseline configuration has the tail leading edge approximately 12.6 calibers aft of the canard trailing edge. Two other configurations were considered with the identical tail. The first had the leading edge of the tail 7.68 calibers behind the canard and the second was 4.48 calibers behind the canard.

A. Impact on Roll Authority

Figure 20 illustrates the impact the tail location has on the direct roll control authority at Mach 0.8 and 2.0. At low angles of attack there is little difference between the three configurations presented. Previous results have shown that increasing angle of attack will improve the roll control authority. Figure 19 indicates that placing the tails at larger distances from the canards will cause this improvement to happen at a lower angle of attack than when the tails are located in close proximity to the canards. An explanation for this can be seen by examining the vortex paths in figure 21. At larger angles of attack, moving the tail fin aft moves the fin out of the vortex wake at large angles of attack, thereby restoring roll authority. For fins close to the canards, a higher angle of attack is necessary before the tails move under the vortex wake.



Mach 0.8 Mach 2.0

Figure 20. Impact of fin placement on roll authority, δ_r=5°

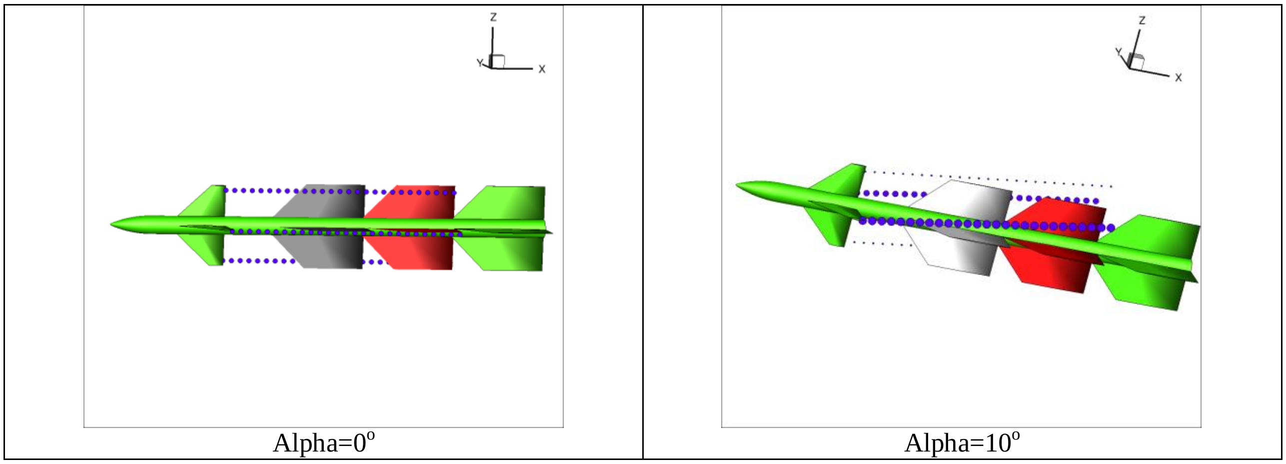


Figure 21. Vortex Tracks for Roll Authority

B. Impact on Yaw Induced Roll

The impact of tail placement on the yaw control induced rolling moment is shown in Figure 22. An improvement in yaw control induced roll would mean that the rolling moment decreases. These changes are, however, much smaller than the effects due to varying span or area. As with the roll authority, tails placed farther from the canards show a drop off in induced rolling moment at lower angles of attack than those closer to the canard. The reasons for this behavior are the same as for the roll authority improvements. It is also noted that the closer tail fins experience lower induced rolling moment than those that are farther from the canards. However, the induced rolling moment becomes larger with increasing angle of attack rather than decreasing. While it is unlikely that some of these configurations are feasible from a stability point of view, the tail placement must still be considered when evaluating the potential impacts to the airframe roll characteristics.

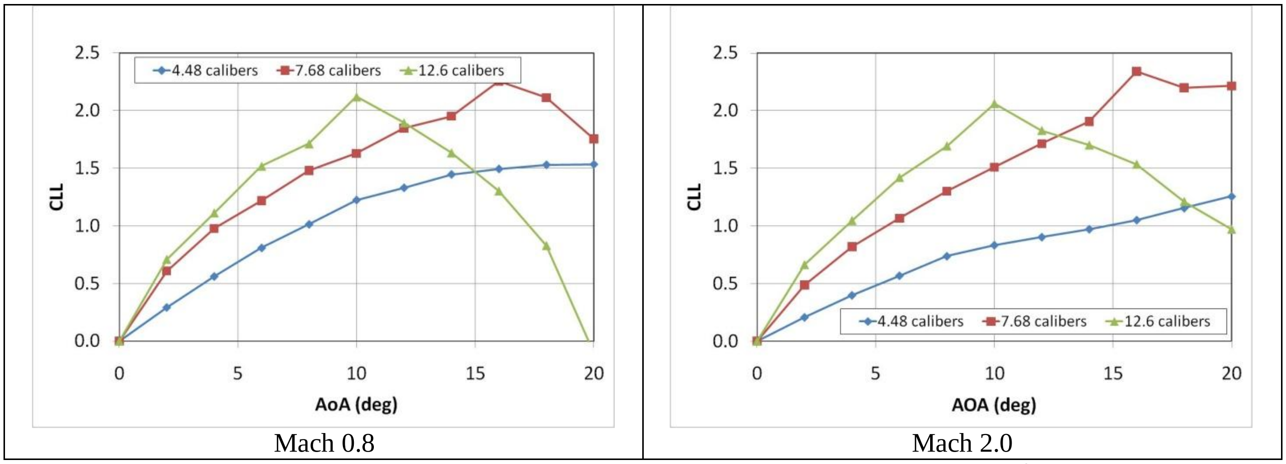


Figure 22. Impact of Fin Placement on Yaw Induced Roll, δ_y=10°

VII. Conclusions

Canards offer attractive control advantages for missiles; however, the adverse roll properties can prove difficult for the aerodynamicist and the controls engineer. The calculation of these roll properties is, however, complicated due to both the canard induced vortex influences and the body shed vortices. Two types of roll must be considered for a canard controlled missile – the roll induced by a yaw command and the roll control authority. For this effort, the effect of tail span, tail area, and tail placement on these commands has been investigated. In general terms, any increase in tail geometry (span or area) results in adverse roll properties. Direct canard roll control authority is typically reduced by the presence of tail surfaces. One could propose to correct this by a larger roll command; however, this would induce stronger vortices whose influence could be more detrimental, netting little benefit. In addition, a directed yaw command induces flowfields that produce undesirable rolling moments. Typically, an induced rolling moment would be countered through the use of a roll command to mitigate the induced roll;

however, the canard-tail interactions complicate the use of such a command. This creates a design loop that must be considered by the engineer. This study indicates that varying tail span has a larger effect on the rolling moment generated than changing the tail area. However, the effects of varying tail area cannot be neglected, particularly at supersonic Mach numbers.

The work presented in this paper is meant as an extension to the work performed by Blair. An effort was made to hold all tail parameters constant except those whose effect was being studied. For both the canard roll and yaw commands, any increase in tail span or area produces an adverse effect on the rolling moment. Although experimental data were not available, the trends of varying span, area, and aspect ratio were analyzed with aerodynamic prediction codes that accurately predict the trends shown in prior studies to provide insight into the expected characteristics of canard-controlled missiles. This work did not fully investigate all aspects associated with canard induced rolling moments. Additional important parameters include: nonzero missile roll angles and combined pitch, yaw and roll commands.

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