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Estimation of the Damping Derivative in Pitch for a Wedge at Supersonic Mach Numbers using Design of Experiments

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ABSTRACT

This work primarily focuses on numerically modelling the damping derivative over the 2D wedge at different pivot points for considerable values of Mach number and incidence angles. The damping derivative is numerically simulated using regression model analysis. The two-dimensional piston theory of Ghosh is applied to obtain the analytical findings. The current study considers the variables Mach number, wedge angle and pivot location. In the present investigation, the wedge angle (θ) varies between 2° and 20°, while the Mach number (M) spans 2.2 to 4.0. The results of the damping derivatives are derived by analysing different Mach numbers (M) and angles of incidence (θ) at various pivot positions (h) ranging from 0.0 to 1.0. This study evaluates the damping derivative results against theoretical predictions, revealing a significant alignment between the two. Both the research findings and the theoretical forecasts show a striking similarity. This research demonstrates that the variation in damping derivative is influenced by factors like the Mach number (M), wedge angle (θ) and pivot position (h). At each pivot position, the magnitude of the damping derivative decreases with a rise in Mach number, which increases as the angle of incidence increases.

Keywords:

Mach number; supersonic flow; angle of incidence

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1. Introduction

Studying high-speed flow conditions is a critical and fundamental aspect of space exploration. The study of space, advanced weapons and space transportation are among the most essential research areas. Tsien [1] is credited with developing the theory of hypersonic similitude by studying the irrotational equation of motion in two dimensions and axis symmetry. Lighthill [2] first established the "Piston Theory" through the expansion of Tsien's [1] hypersonic similitude by Hayes

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[3]. Ghosh [4] has advanced in studying hypersonic similitude and piston theory, specifically in large incidence angles. This work incorporates the piston theories proposed by Lighthill [2] and Miles [5].

Additionally, Ghosh *et al.,* [6] explored the aspects of hypersonic similitude and the behaviour of oscillating nonplanar wedges. Ghosh [7] obtained the similarity of delta wings with attached shock waves in hypersonic flow at significant incidences. Khan *et al.,* [8] simulated using computational fluid dynamics (CFD). They employed approaches and theoretical evaluations to confirm the flow patterns associated with the wedge. In hypersonic flow, the various elements of the aerodynamic derivative of a delta wing have been explored by Bashir *et al.,* [9]. Pathan *et al.,* [10] found that with their streamlined shape, boat tail helmets can reduce aerodynamic drag. Shaikh *et al.,* [11-13] studied the different flow parameters on wedge and cone surface pressure distribution in high-speed flows. Azami *et al.,* [14] investigated wall pressure and micro-jets influence. Pathan *et al.,* [15] investigated how base pressure varied in interior and external flows by employing CFD simulation. Khan *et al.,* [16] and Pathan *et al.,* [17-19] studied various methods for overseeing base pressure. Pathan *et al.,* [21] research focused on duct length optimization inflows that suddenly expand. Pathan *et al.,* [20,21] underscored that optimizing the expansion geometry significantly improves base flow characteristics and diminishes reattachment length. Fiqri *et al.,* [22] illustrated how the design of cavities in sonic Mach flows can function as an effective passive control strategy, enhancing flow reattachment and base pressure. Asadullah *et al.,* [23] presented a cost-efficient passive technique for base drag reduction. Although Azami *et al.,* [24] and Khan *et al.,* [25] demonstrated that optimizing duct lengths and nozzle configurations boost flow management, they also noted that this supports passive control in supersonic scenarios. Furthermore, Pathan *et al.,* [26] employed variable wall thickness in nozzle design to improve performance and lessen weight, thereby highlighting the diverse benefits of geometric optimization in aerospace engineering.

The potential of passive design modifications to optimize flow without the need for active controls was studied in multiple studies [27-34]. Computational Fluid Dynamics (CFD) serves a vital function in the progression of these designs, providing insights into their diverse applications. Chaudhari *et al.,* [35] explored catalytic converters, establishing a connection between combustion strategies and fluid dynamics, specifically in sonic flows. Jain *et al.,* [36] and Shaikh *et al.,* [37-39] investigated thermal and flow optimization in heat sinks and catalytic converters. They emphasized the importance of uniform flow [40-42]. However, while these studies offer valuable perspectives, they also reveal the complexities inherent in fluid dynamics.

Although progress has been achieved in understanding supersonic and hypersonic flow, there is still a research gap in the current studies. Many studies in the literature concentrate on shapes like slender aerofoils, wedges and delta wings. Further research is required to investigate a broader range of configurations in greater depth. The potential of utilizing advanced statistical techniques in aerodynamics research is emphasized through comparative studies using regression analysis and Design of Experiments. Research is conducted on the lack of utilizing interdisciplinary methods to analyse and forecast intricate aerodynamic phenomena. Improving our understanding of supersonic and hypersonic flows will benefit the design and performance of aerospace vehicles and long-range weapons by addressing this gap.

2. Methodology
2.1 Analysis

Our concern is to evaluate the aerodynamic damping derivative over the 2D planar wedge. In the present research, we concentrate on the analytical results of damping derivatives within a sizable variety of incidence angles and Mach numbers. The Mach number is considered on the scale of 2.2

to 4.0, whereas the angle of incidence is from 2° to 20°. The geometry of the planar wedge is displayed in Figure 1.

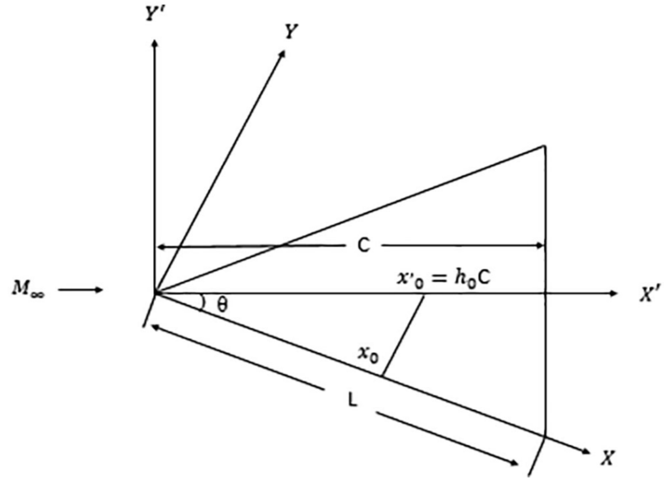


Fig. 1. Wedge geometry

The flat plate aerofoil should observe the small pitch oscillations near the pivot point, determined by its length (L) and wedge angle (θ). The variable x_0 denotes the distance from the apex. Eq. (1) gives the velocity of the piston at any instant, taking into account the distance x and the angle of attack α.

$$U_P = U_\infty \sin\alpha + q(x - x_0) \tag{1}$$

Eq. (2) gives the Mach number 'Mp' of the piston as,

$$M_P = M_\infty \sin\alpha + \frac{q(x - x_0)}{a_\infty} \tag{2}$$

Lighthill [2] examined the precise isentropic formula for piston pressure outlined in Eq. (3), a power series linked to velocity. The speed of the piston must be equal to or lower than the speed of sound in a free stream to keep the isentropic condition. The concept aligns with Lighthill's Piston theory, which emphasizes the importance of minor disturbances.

$$\frac{P}{P_\infty} = 1 + \gamma\frac{U_p}{a_\infty} + \frac{\gamma(\gamma+1)}{4}\left(\frac{U_p}{a_\infty}\right)^2 + \frac{\gamma(\gamma+1)}{12}\left(\frac{U_p}{a_\infty}\right)^3 \tag{3}$$

2.2 Piston Theory

Lighthill [2] created the piston theory for oscillating air foils at supersonic and hypersonic velocities. Ghosh [4] found a resemblance and two similar features for a shock wave on the edge of vibrating delta wings at high angles of attack. According to Ghosh [6], the z-axis, where the velocity is least, can be seen as separate from the wedge strip aligned with the centreline. The integration of strip theory with Ghosh's [7] similitude method resulted in the creation of the "Piston analogy," specifically focusing on the piston Mach number "Mp." This leads to using Ghosh's piston theory instead of the strong shock expansion concept proposed by Lighthill [2] or Miles [5]. Eq. (4) demonstrates that the surface pressure (P) directly influences the level of inertia at the wing's surface piston.

$$\frac{P}{P_\infty} = 1 + AM_P{}^2 + AM_P\sqrt{1 + BM_P{}^2} \tag{4}$$

where, $A = \frac{\gamma(\gamma+1)}{4}, B = \left(\frac{4}{\gamma+1}\right)^2$ and P_∞ γ are the free stream pressure and the specific heat ratio, respectively.

The strips are processed independently at various points along the span, with the wedge angle representing the wing. At this point, the piston Mach number and the flow deviation are allowed to increase. The incidence and wing angles are equivalent. The piston analogy has been widened to include supersonic flow past, as seen in Eq. (5). The related expression is below. With a uniform incidence angle and wing angles, the angle 'ø' here denotes the shock angle.

$$\frac{P}{P_\infty} = 1 + A\left(\frac{M_P}{\cos\phi}\right)^2 + A\left(\frac{M_P}{\cos\phi}\right)\sqrt{1 + B\left(\frac{M_P}{\cos\phi}\right)^2} \tag{5}$$

2.3 Pitching Moment Derivative

When a wedge rotates about its axis and moves forward by a distance along the x direction, the angle of attack is referred to as α_0. The pressure and piston motion remain consistent on the wing side across a strip, with a length of 2L at point x. Eq. (5) describes the nose-down moment, assuming no pressure on the lee surface.

$$m = -\int_0^L P(x - x_0)\,dx \tag{6}$$

The aerodynamic damping derivative is of the form as,

$$-Cm_q = \frac{1}{\frac{1}{2}\rho_\infty U_\infty L^3}\left(\frac{-\partial m}{\partial q}\right)_{\alpha=\alpha_0,\, q=0} \tag{7}$$

Here ρ_∞ denotes the density of the free stream.

By combining Eq. (2) and Eq. (5) in Eq. (6) and applying DUIS in Eq. (6). Also defining $x_0 = hL\cos^2\alpha_0, C = L\cos\alpha_0$ $S_1^1 = \frac{M_\infty \sin\alpha_0}{\cos\phi}$, the desired relation of the damping derivative of a plane wedge is in the form of

$$-Cm_q = \left[\frac{\gamma+1}{M_\infty}\right]\left[\frac{F\left(S_1^1\right)}{\cos\phi\cos^3\alpha_0}\right]\left[\frac{1}{3} - h\cos^2\alpha_0 + h^2\cos^4\alpha_0\right] \tag{8}$$

Where,

$$F\left(S_1^1\right) = 2S_1^1 + \frac{B + 2\left(S_1^1\right)^2}{\sqrt{B + \left(S_1^1\right)^2}} \tag{9}$$

2.4 Methodology of Design of Experiment

A structured approach using experiments, known as Design of Experiments (DOE), is employed to understand the impact of factors on a process and its outcomes. This method is crucial for creating, enhancing and refining processes. Below are the principles and stages involved in DOE:

i. Setting the objective which clearly states the problem.
ii. Identifying the factors to be tested with their specific values and desired range.
iii. Select the appropriate experimental design, such as full factorial or fractional factorial design, to test all possible combinations.
iv. Conduct experiments to implement randomization, replication and blocking to reduce bias and variability.
v. Systematically collect accurate and precise data.
vi. Statistical analysis of the collected data was performed using ANOVA, regression analysis and factorial analysis to interpret the data.
vii. Interpret the results to understand the main and interaction effects and find the optimal conditions.
viii. Verify the results and validate the model against the actual results.
ix. Apply the optimal conditions or changes to the process or product to implement the model.

Statistical software programs such as Minitab, Statistica, SPSS, SAS, Design-Expert, Stat graphics, Prisma, R and Action for Microsoft Excel can simplify DOE design and analysis. Mach Number (M), Wedge angle (θ) and Pivot Position (H) are the factors used by DOE. Creating the experiment requires taking into account the six different levels of pivot position (H) at level 10 while also factoring in Mach number (M) and incidence angle (θ). Table 1 depicts the data's factor, factor level and values.

Table 1
Full factorial: Level and the factors of the design of experiments

Factor	Type	Levels	Values
Mach Number (M)	Fixed	10	2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0
Wedge Angle (T)	Fixed	10	2, 4, 6, 8, 10, 12, 14, 16, 18, 20
Pivot Position (H)	Fixed	6	0.0, 0.2, 0.4, 0.6, 0.8, 1.0

3. Results and Discussion

3.1 Major Impact Plots of Mach Numbers for the Damping Derivative ($-C_{m_q}$)

In Figure 2, the primary influence of the damping derivative on the wedge is illustrated. Figure 2 presents the average damping derivative values across speed ranges from Mach 2.2 to 4.0. These measurements were taken at angles of incidence, ranging from 2° to 20° and for pivot positions varying from h = 0.0 to 1.0. The findings indicate that the damping derivative values exhibit a specific trend as the Mach number increases. Additionally, there is a notable difference in the mean damping derivative values observed between Mach numbers 3.0 and 4.0 compared to those at Mach numbers 2.2 and 2.8. Overall, the damping derivative values gradually decline with the increase in Mach number.

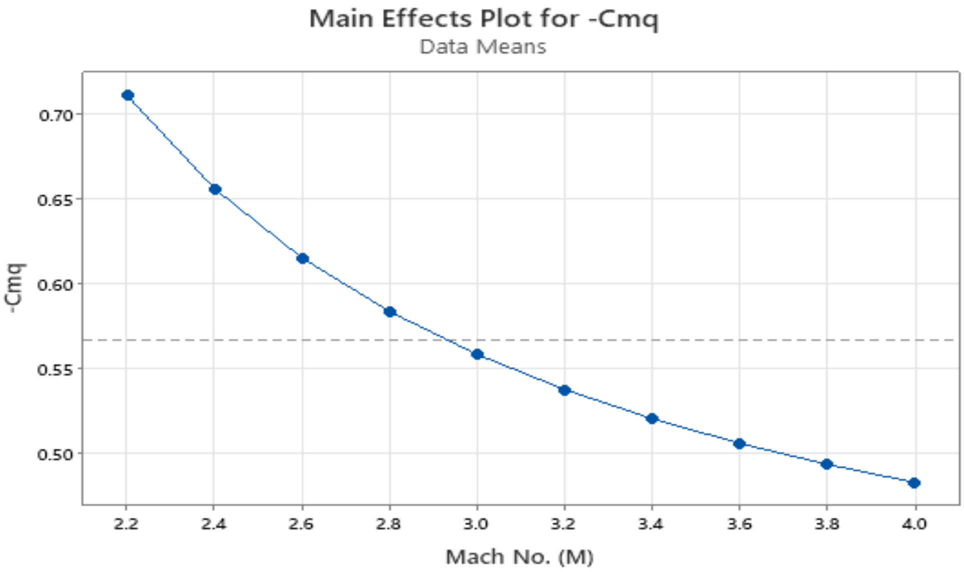


Fig. 2. Major effect of Mach numbers on the damping derivative for the wedge

3.2 Major Impact Plots of the Angle of Incidence for the Damping Derivative ($-C_{m_q}$)

Figure 3 vividly showcases how changes in damping along the wedge impact the overall performance. This figure depicts the correlation between mean damping derivative values and the angle of incidence (θ) spanning from 2° to 20°. The Mach numbers in the diagram range from 2.2 to 4.0, while the pivot locations vary between 0.0 and 1.0. The findings reveal that the damping derivative tends to increase with the angle of incidence. Notably, this variation is more pronounced for incidence angles between 10° and 20° than those between 2° and 8°. In essence, the damping derivative progressively rises as the incidence angles increase.

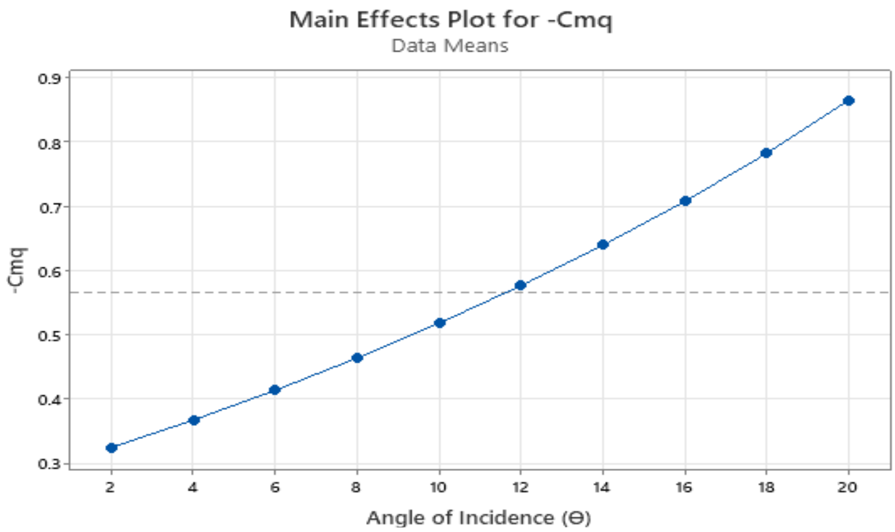


Fig. 3. Major effect of incidence angle on damping derivative for the wedge

3.3 Major Impact Plots of Pivot Position for the Damping Derivative ($-C_{m_q}$)

Figure 4 illustrates the influence of the damping derivative on the wedge. The graph showcases the average values of the damping derivative at pivot positions of 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0. These values are derived from a range of Mach numbers (M) from 2.2 to 4.0 and incidence angles (θ) varying from 2° to 20°. The results indicate a decrease in the damping derivative when transitioning from the pivot point h = 0.0 to h = 0.6. In contrast, the damping derivative increases from the pivot position h = 0.6 to h = 1.0.

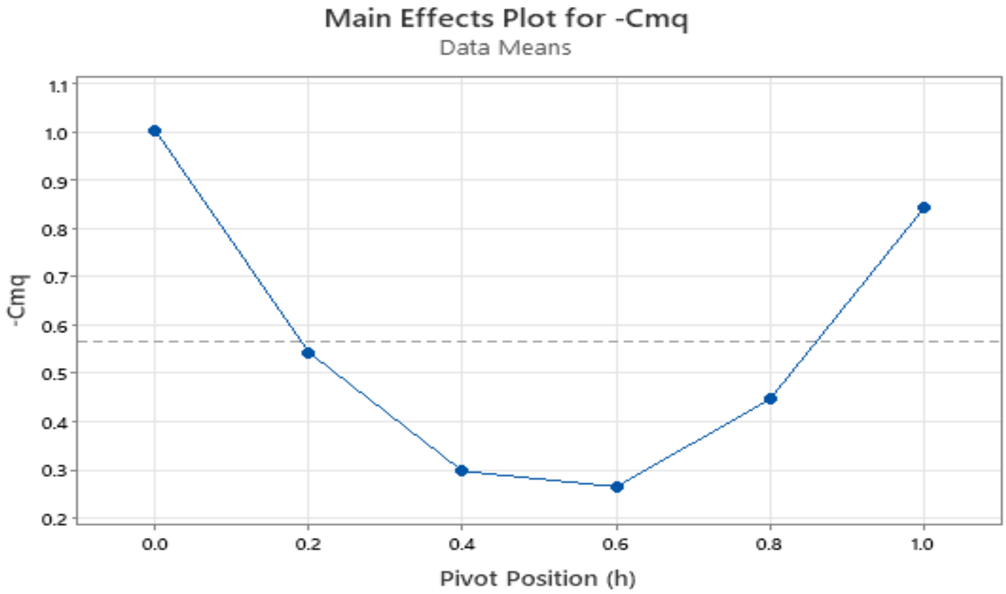


Fig. 4. Major effect of the pivot position on the damping derivative over the wedge

3.4 Graph of Interaction among Incidence Angle (ϑ), Mach Number (M) and Pivot Position (h) for Damping Derivative ($-C_{m_q}$)

Figure 5 illustrates the interaction diagram of the damping derivative showcasing the relationship among Mach number (M), angle of incidence (θ) and pivot position (h). The data reveals that the damping derivative initially decreases, reaching its minimum value at the centre of pressure before rising again from the pivot position h = 0.6. This trend persists across angles. Additionally, it is noted that the centre of pressure falls within the range of h=0.4 to 0.6. Moreover, as the incidence angle increases, the damping derivative's magnitude grows at pivot positions.

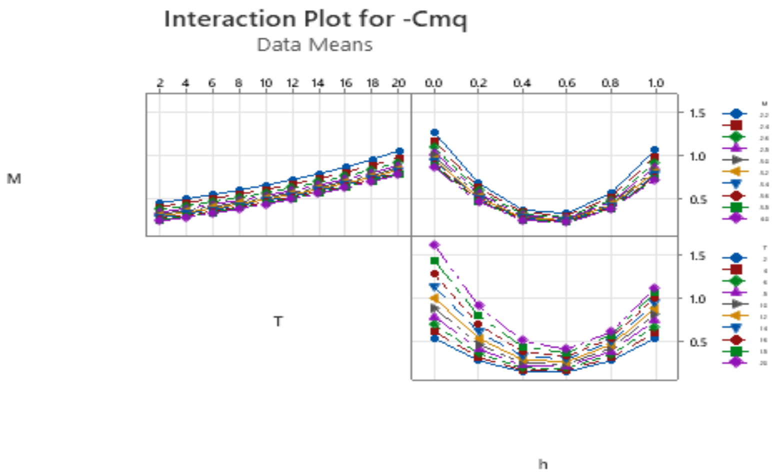
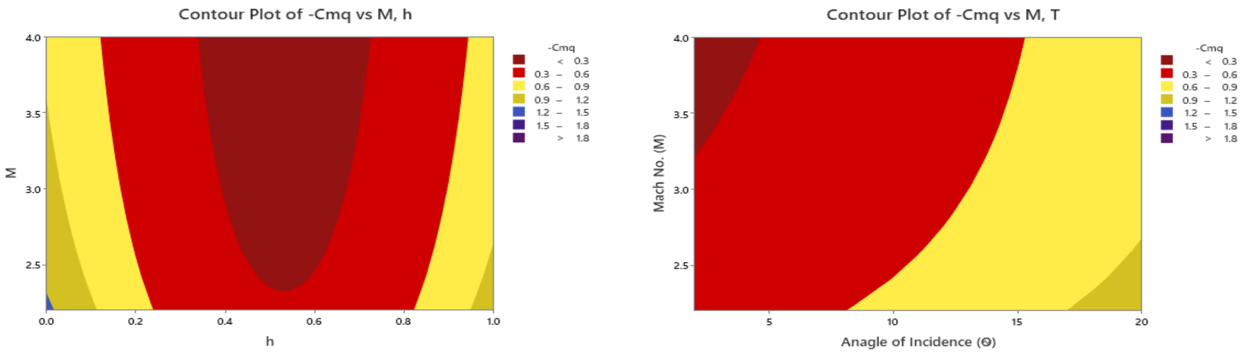


Fig. 5. Interaction plot on damping derivative over the 2D wedge

3.5 The Contour Plot for the Damping Derivative ($-C_{m_q}$) over Wedge

Figure 6(a) and Figure 6(b) present a contour plot illustrating the damping derivative across a wedge-shaped structure. In Figure 6(a), the plot showcases how the damping derivative varies, with changes in the Mach Number (M) and pivot position (h). The data reveals that as the Mach number increases at positions, the magnitude of the damping derivative diminishes. Furthermore, it indicates that the damping derivative attains its minimum value when h falls within the range of 0.4 to 0.6, where the centre of pressure is situated. Additionally, for each Mach number, the damping derivative initially decreases to its value within h values of 0.4 to 0.6 before rising again from the pivot position of h=0.6 to 1. The contour plot depicted in Figure 6(b) illustrates the relationship between the damping derivative Mach number (M) and the angle of incidence (θ). A thorough examination of the plot shows that with an increase in the angle of incidence, there is a corresponding increase in the magnitude of the damping derivative across different Mach numbers and locations. Moreover, it is noted that at angles of incidence and high Mach numbers, the damping derivative attains its value. While the Mach number and angle of incidence influence the damping derivative, the angle of incidence seems to impact its variations significantly.



(a) (b)

Fig. 6. (a) Contour plot for damping derivative with Mach number and pivot position (b) Contour plot for damping derivative with Mach number and angle of incidence

4. Model of Regression

The assessment of damping derivatives through a regression model is carried out using Minitab software, taking into account variables like position (h), angle of incidence (θ) and Mach number (M). Eq. (10) outlines the regression structure for calculating the damping derivative.

$$-Cm_q = \begin{pmatrix} 2.770 - 1.712\,M + 0.04151\,T - 3.499\,H + 0.4298\,M*M + 0.001415\,T*T + 2.9058\,H*H \\ - 0.00600\,M*T + 0.8995\,M*H - 0.12850\,T*H - 0.03841\,M*M*M + 0.000012\,T*T*T \\ + 0.0893\,H*H*H + 0.000720\,M*M*T - 0.0583\,M*M*H - 0.000097\,M*T*T + 0.002486\,M*T*H \\ - 0.5593\,M*H*H - 0.001755\,T*T*H + 0.12727\,T*H*H \end{pmatrix} \tag{10}$$

4.1 Model Summary

Table 2 provides an overview of the regression analysis model that examines the relationship between pivot location (h) angle of incidence (θ) and Mach number (M). In this study, the adjusted R^2, a statistical measure, is employed to assess the effectiveness of the regression model in representing damping derivatives at supersonic speeds. This metric reflects the degree to which the independent variables can explain the variability in the dependent variable. With an R^2 value of 99.35%, the research suggests that the regression model effectively captures the underlying data.

Table 2
Summary of regression model

S	R-square	R-square(adj)	R-square(pred)
0.0279476	99.37%	99.35%	99.31%

4.2 Validation of Current Work with Literature

The results of the current study have been confirmed by comparison with data from previous studies, as shown in Figure 7(a), Figure 7(b) and Figure 7(c). The results of the analytical expression of the damping derivative, as determined by Eq. (8) and studied by Ghosh *et al.,* [6], are shown in Figure 7(a), Figure 7(b) and Figure 7(c), the damping derivative results, as determined by Eq. (10), using the regression model. Figure 7(a), Figure 7(b) and Figure 7(c) show an excellent agreement between the results of the damping derivative with analytical analysis and the current research activity, as indicated by the obtained results.

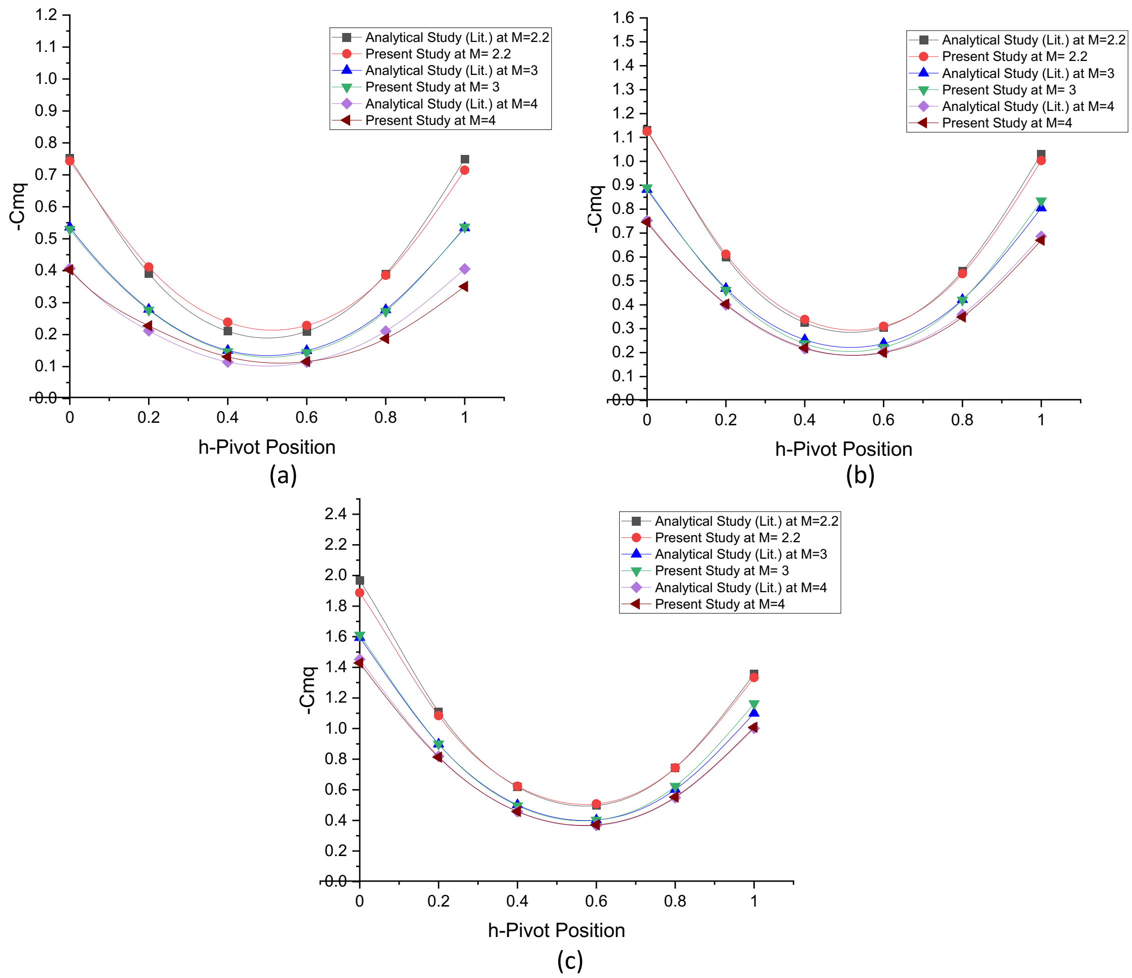


Fig. 7. (a) Damping derivative ($-Cm_q$) variation with pivot position (h) at θ = 2° (b) Damping derivative ($-Cm_q$) variation with pivot position (h) at θ = 10° (c) Damping derivative ($-Cm_q$) variation with pivot position (h) at θ = 20°

4. Conclusion

Applying the Ghosh piston theory, an analytical calculation of the damping derivative is conducted and its findings are contrasted with the conclusions of previous research. There is a high level of consistency between the results from the current study and the analytical discoveries. The research results show various uses for angle of incidence (θ) and Mach number (M). The variation of the damping derivative is significantly influenced by both the semi-vertex angle and the Mach number, according to the obtained data. The value of the damping derivative decreases at each pivot position as the Mach number increases. It is found that the magnitude of the damping derivative increases as angle incidence rises. The findings reveal that the damping derivative exhibits a high magnitude at lower Mach numbers and high angles of attack.

Conversely, the damping derivative shows a decreased value at lower angles of attack and higher Mach numbers. These insights play a role in advancing the progress of aerial vehicle design due to the high costs associated with wind tunnel testing. They hold the potential to enhance the design of aerospace crafts. The present study produces excellent outcomes with significant computational ease. This notion only holds if the shock wave is connected. This theory can consider the effects of viscosity and wave reflection to broaden its application and make it more accurate.

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