AN ENGINEERING LEVEL PREDICTION METHOD FOR NORMAL-FORCE INCREASE DUE TO WEDGE SECTIONS

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Abstract

An engineering level prediction method for the increase of normal-force curve slope caused by wedge sections has been proposed and validated. The method uses both generalized slender body theory and oblique shock wave relationships so it is applicable throughout the tri-sonic range of Mach numbers. The validation was done by comparing predictions by the Missile Datcom code with test data, using corrections based on the new method, as well as without these corrections. The benchmark configurations include two wings with wedge sections and three body-tail configurations. The validation covers Mach numbers from subsonic to high supersonic. In all cases the application of the new method considerably improves the agreement between analysis and test data.

Nomenclature

be	exposed span
$C_{m\alpha}$	pitching-moment curve slope
$C_{N\alpha}$	normal-force curve slope
d	body diameter, reference length
Kw	amplification of normal-force curve slope due to wedge cross-section
M	Mach number
t	thickness of wedge section
Xcp	center of pressure location relative to moment reference point

Notation of the Components

B	body alone
B-T	body-tail combination
T	planar thin tail
T^w	tail with wedge section
TU	tail unit; tail and mutual influences with the body

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1 Introduction

It is known, e.g. Chapman [1], [2] that wings with wedge sections have a larger normal-force curve slope than matching wings with thin trailing edges. This finding has the potential to increase the efficiency of stabilizing fins and control surfaces. Indeed, a variety of aerodynamic configurations utilize such sections. For example, the vertical tail of the X-15 research aircraft and the second stage of the Pershing missile feature wedge fins.

Moore and Hymer [3], [4] added the capability to account for thick airfoils, including wedge sections, to the 2005 version of their Aeroprediction code. They use the shock-expansion method, which is applicable in the supersonic region.

The objective of the present study is to devise a tri-sonic, easy to implement, method to estimate the increment of the normal-force of lifting surfaces due to wedge sections, and to validate it. The validation is done by comparing predictions to available test data with and without the wedge effect as predicted by present method.

2 Analysis

The main prediction tool used is the 1997 edition of the Missile Datcom code (M-Dat) [5]. The code was run to obtain the stability derivatives of the components and those of the configurations. For body-tail configurations the contributions of the tail units (tails and mutual interactions with the body) are obtained from the output files using:

$$C_{N\alpha}(TU) = C_{N\alpha}(B\text{-}T)-C_{N\alpha}(B) \quad (1)$$

$$C_{m\alpha}(TU) = C_{m\alpha}(B\text{-}T)-C_{m\alpha}(B) \quad (2)$$

These two stability derivatives are valid for thin wings. The correction that accounts for the effect of wedge sections consists of two branches, in an attempt to cover the entire tri-sonic Mach numbers range:

1. In the subsonic and transonic regions, Sacks [6] application of the generalized slender body theory to thick slender wings is used. His governing parameter is the thickness-to-span ratio. (t/be) The pertinent design chart from [6] is shown as Fig. 1.
2. For supersonic Mach numbers, the results of the analysis of McLellan, [7] based on exact oblique shock relationships, are used. This method is equivalent to the shock-expansion method for small angles of attack. His working chart is presented in Fig. 2. The governing parameters are Mach number and wedge angle. Reference [7] was used by Yuska [8] who found that it improved the accuracy of the estimation of the longitudinal characteristics of a body-tail configuration. (His configuration and test data are also used in this paper.)

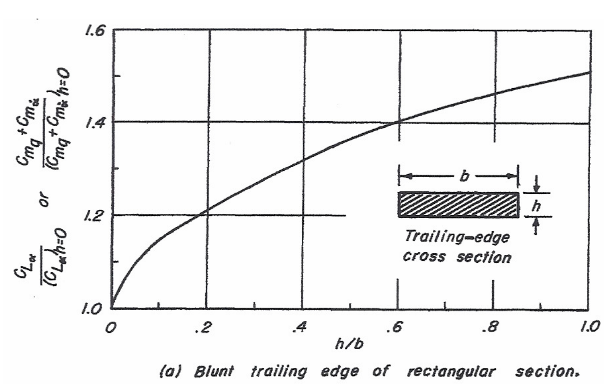


Fig. 1. Normal-force gain due to thick trailing edge, from Sacks. [6]

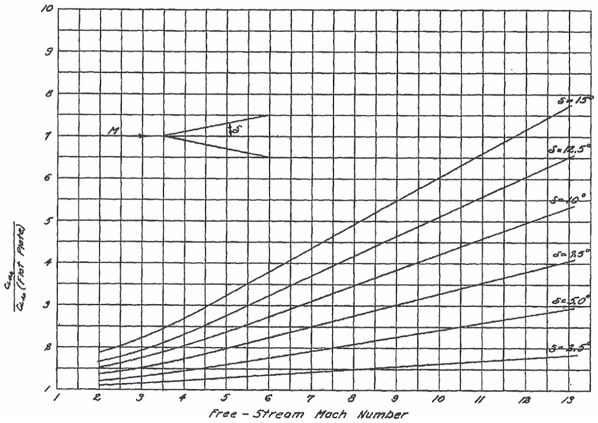


Fig. 2. Normal-force gain due to wedge section, from McLellan. [7]

Define the gain in the normal-force curve slope due to wedge section by

$$\boldsymbol{Kw} = C_{N\alpha}(\text{wing with wedge airfoil}) \,/\, C_{N\alpha}(\text{matching thin wing}) \quad (3)$$

The cross-over between the two methods is that Mach number where both predict equal gains.

The corrected stability derivatives, namely those that account for the effect, are:

$$C_{N\alpha}(B\text{-}T^{w}) = C_{N\alpha}(B)+\boldsymbol{Kw}\cdot C_{N\alpha}(TU) \quad (4)$$

$$C_{m\alpha}(B\text{-}T^{w}) = C_{m\alpha}(B)+\boldsymbol{Kw}\cdot C_{m\alpha}(TU) \quad (5)$$

$$Xcp/d = -C_{m\alpha}(B\text{-}T^{w})/C_{N\alpha}(B\text{-}T^{w}) \quad (6)$$

3 Validation I – Wings Alone

Blake [9], [10] and McLellan et al.[11] experimentally studied aspect-ratio 1.0 square wings that feature wedge airfoils. Table 1 shows a summary of their test conditions and results of $C_{N\alpha}$ and results of the M-Dat code with and without the application of the present method.

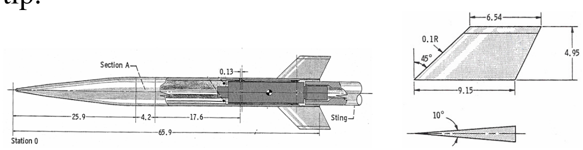
Table 1: Comparisons between predictions and test data

Reference		**Blake [9], [10]**	**McLellan [11]**
Mach number		0.7	6.86
Aspect-ratio		1.0	1.0
t/c		0.175	0.05
Ref. for Kw		Sacks [6]	McLellan [7]
Kw		1.20	1.24
$C_{N\alpha}$	**Test data**	**1.76**	**0.67**
	M-Dat	**1.48**	**0.55**
	Present	**1.78**	**0.68**

It is apparent that the present correction greatly improves the match of the predictions to the test data, in both cases.

4 Validation II – Body Tail Configurations

Benchmark 1: Yuska [8] tested body-tail combinations at Mach numbers of 1.77 to 3.43. The configuration with the swept tail and the 10° wedge section was selected for this study. Schematics of the configuration and details of the selected stabilizer are depicted in Fig. 3. The reference point for pitching-moment is the nose tip.



a) The configuration b) The wedge tail

Fig. 3. Schematics of Benchmark 1, from Yuska. [8]

The wedge gain factor ranges between 1.16 for M≤1.6 to 1.41 for M=3.6. Comparisons between analysis and test data are shown in Fig. 4 and Fig. 5.

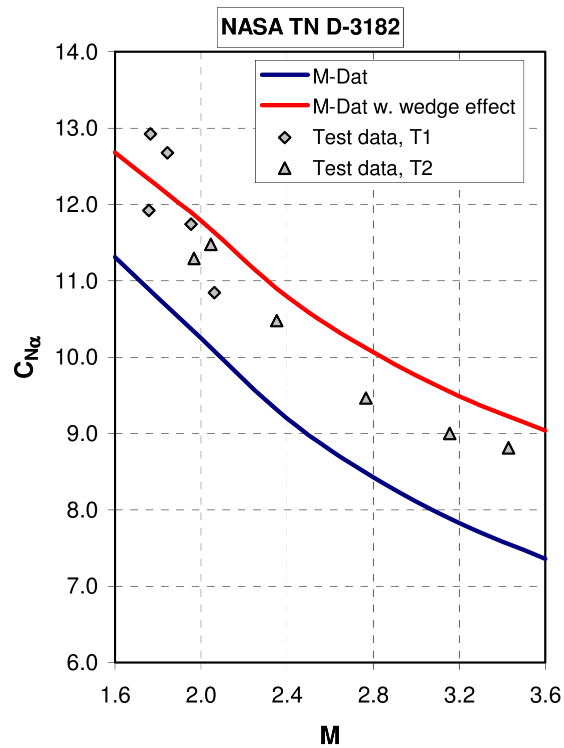


Fig. 4 Analysis and test data for benchmark 1 - Normal-force curve slope

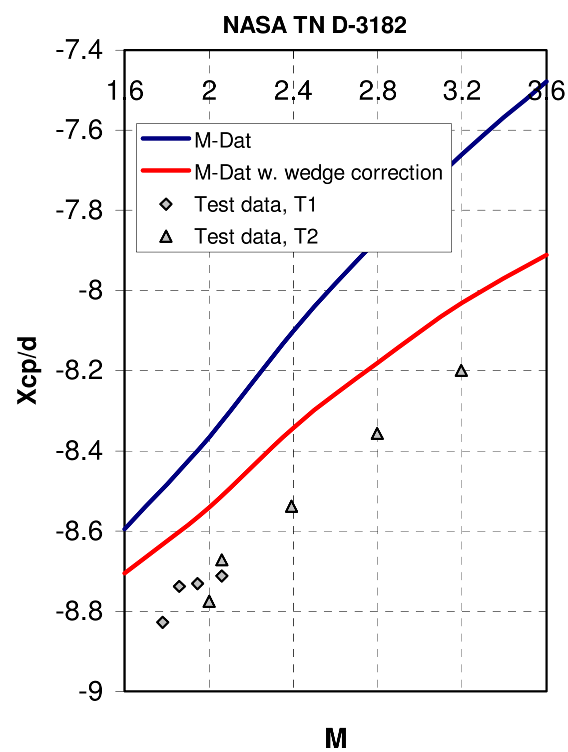
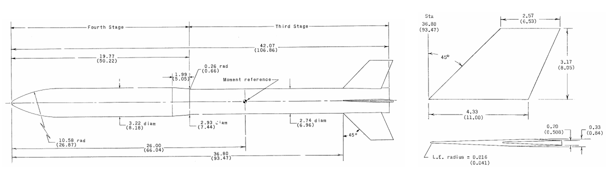


Fig. 5 Analysis and test data for benchmark 1 – Center of pressure location

It is apparent that accounting for the normal-force gain due the wedge section improves the agreement between predictions and test data, for both stability derivatives. It should be noted that the calculated results of [8] are slightly different from the present ones. However, the estimated effect of the wedge section is about the same.

Benchmark 2: Hayes and Corlett [12] tested a model of the upper two stages of the ARGO D-4 sounding rocket. Their configuration features a thickened forebody as shown in Fig. 5. The moment reference point is body station 26", namely 9.49 diameters from the nose tip. The range of test Mach numbers is 2.3 to 4.63 and included the body alone, making it possible to identify the contributions of the tail unit. The M-Dat code was run using the SOSE option for the analysis of the contributions of the body. The inclusive wedge angle of the tail is 4.36° yielding a wedge gain factor that range between 1.11 at M≤2.2 to 1.26 at M=4.8.



a) The configuration b) Tail details

Fig. 6 Benchmark 2 schematics from Hayes and Corlet [12]

A comparison of the normal-force curve slopes showed that the experimentally obtained data is much larger than predicted. Also, the center of pressure location of the tail unit, as obtained from the test data, is several body diameters ahead of the tail. It was concluded that C_N data is not reliable. Thus, the validation of this case is done only for C_m and for the tail unit, rather than for the entire configuration, in order to avoid uncertainties related to the thickened forebody. Comparison between analysis and test data is shown in Fig. 6. It is clear that the present correction improves the agreement between prediction and test data.

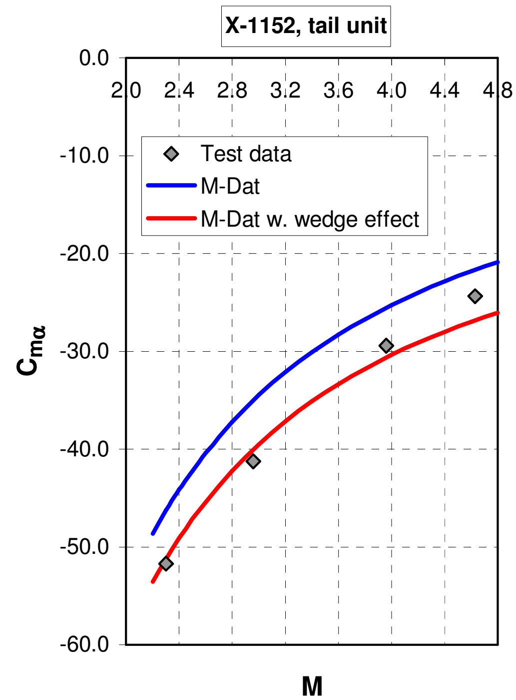
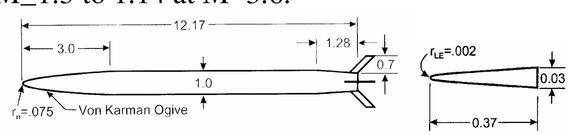


Fig. 7 Comparison between predictions and test data for benchmark 2

Benchmark 3: Moore and Hymer [3], [4] used test data of an 8-wedge-fin tail-stabilized missile for their study. A schematic of the configuration is presented in Fig. 7. The base diameter equals 0.75 body diameters and the moment reference point is the nose tip. The test data covers Mach numbers from about 0.6 to 3.5. The thickness ratio of the fins is 0.081 and the wedge gain factor ranges between 1.053 for M≤1.3 to 1.14 at M=3.6.



a) General view. b) tail fin cross section.

Fig. 8 Benchmark 3 schematics from Moore and Hymer [3] [4]

The predicted $C_{N\alpha}$ features a peak at M=1.0, thus it is not shown. Comparisons between analysis and test data are shown in Fig. 9 and Fig. 10. The test data shows scatter at high supersonic Mach numbers. Therefore, conclusions are based on findings at the transonic and low supersonic regions. In this case too, applying the present method improves the match of the calculated results to the test data.

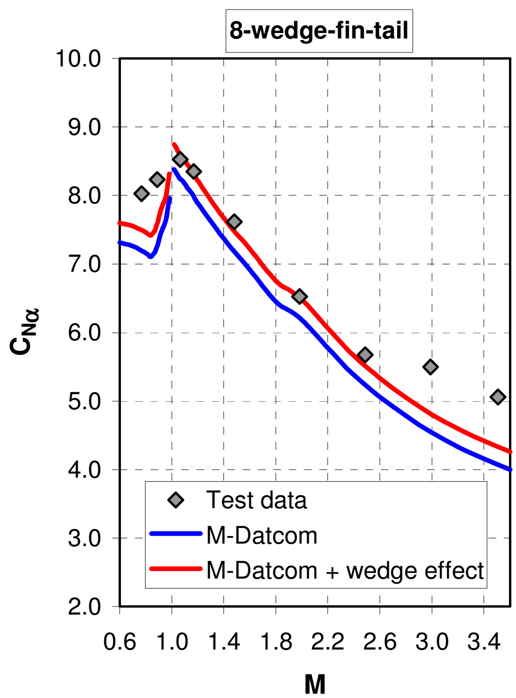


Fig. 9 Predication and test data for benchmark 3 - Normal-force curve slope

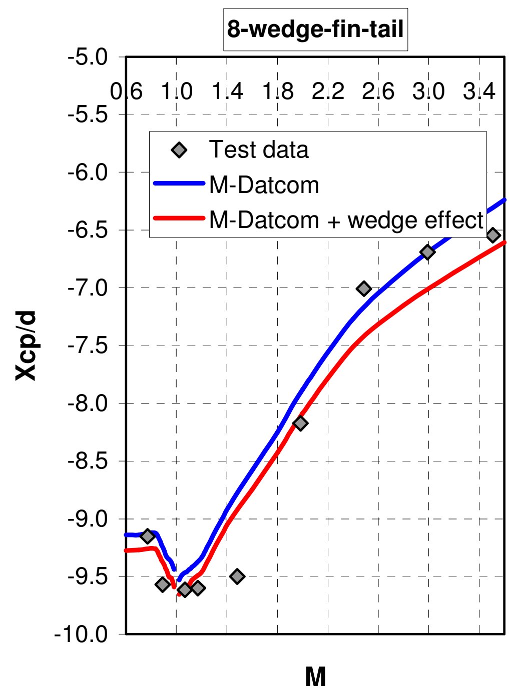


Fig. 10 Predication and test data for benchmark 3 -Center of pressure location

5 Concluding Remarks

An engineering level prediction method that accounts for the increase of the normal-force due to wedge sections is proposed. It is based on two classic methods and covers the tri-sonic range of Mach numbers.

The method was validated for variety of wings alone and for configurations, in a wide range of Mach numbers. In all cases, applying the proposed method significantly improves the agreement between analysis and experimentally obtained data.

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